BRITISH ANTARCTIC EXPEDITION 1907-9
UNDER THE COMMAND OF SIR E.H. SHACKLETON, C.V.O.

REPORTS ON THE SCIENTIFIC INVESTIGATIONS

GEOLOGY

VOL. 1.

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Vol. II. GEOLOGY

To be published later, will contain Papers by the following authors on the Petrology of the rocks collected by the Expedition:

THE LIMESTONES OF SOUTH VICTORIA LAND
Professor E. W. SKEATS, D.Sc.

THE ALKALINE ROCKS OF ROSS ISLAND
H. I. JENSEN, D.Sc.

THE ROCKS OF THE NORTH COAST OF VICTORIA LAND
DOUGLAS MAWSON, D.Sc.

THE DOLERITES OF SOUTH VICTORIA LAND
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Also Papers on the Fossils collected by the Expedition:

FORAMINIFERA AND OSTRACODA FROM UPTHRUST MARINE MUDS
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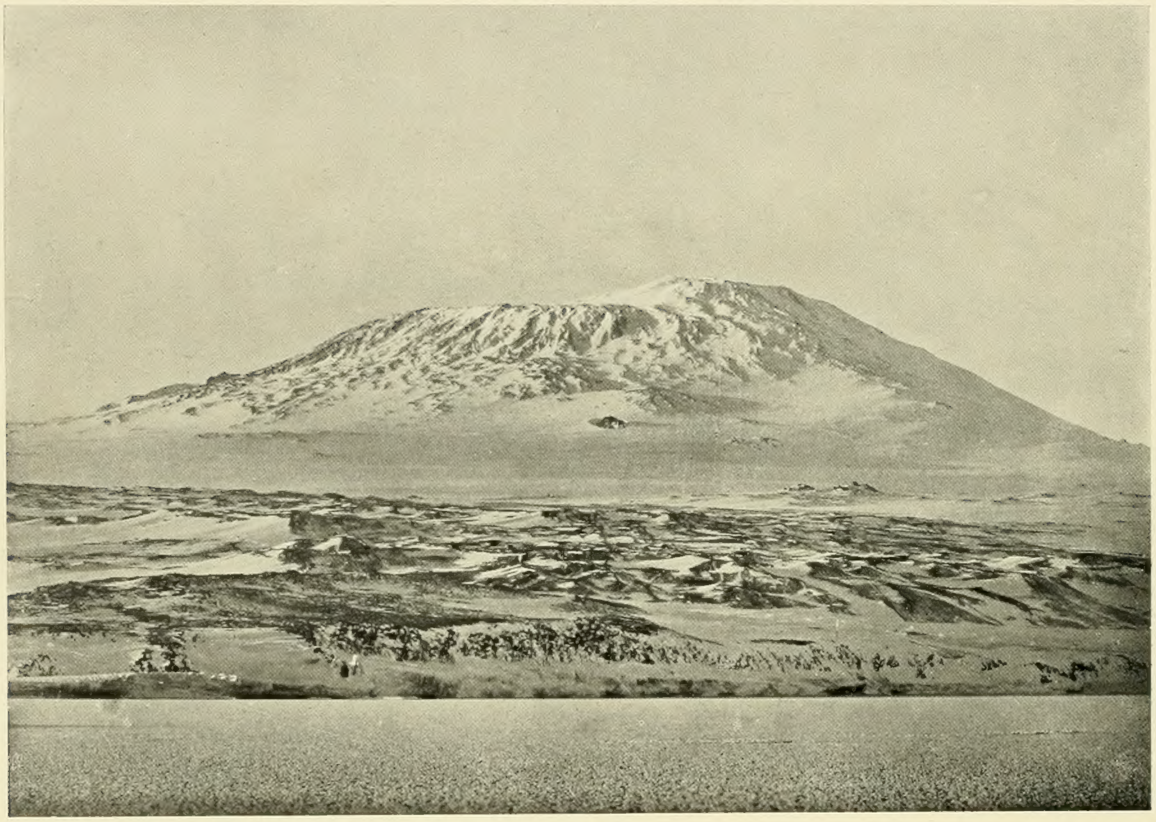
PLATE I



MOUNT EREBUS AND THE FOOTHILLS IN THE NEIGHBOURHOOD
OF THE WINTER QUARTERS

[*Frontispiece*

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GEOLOGY

VOL. I

GLACIOLOGY, PHYSIOGRAPHY, STRATIGRAPHY, AND TECTONIC GEOLOGY OF SOUTH VICTORIA LAND

BY

PROFESSOR T. W. EDGEWORTH DAVID, C.M.G., F.R.S., M.A., Hon. D.Sc.(Oxon.)
AND RAYMOND E. PRIESTLEY, F.G.S.

WITH SHORT NOTES ON PALÆONTOLOGY

BY

T. GRIFFITH TAYLOR, B.A., B.E., B.Sc., AND PROFESSOR E. J. GODDARD, D.Sc.

(*WITH 95 PLATES AND 67 FIGURES IN THE TEXT*)

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TO

SIR JAMES KEY CAIRD, BART.

IN GRATEFUL ACKNOWLEDGMENT
OF HIS GENEROUS SUPPORT OF THE
IMPERIAL TRANSANTARCTIC EXPEDITION
AND IN RECOGNITION OF HIS KEEN
INTEREST IN ALL SCIENCE

PREFACE

A DISTINGUISHED Norwegian geologist has remarked : * " While we know fairly well the effect of running water from glaciated lands with a wet climate, we practically do not know anything of the way in which a continuous ice covering pure and simple may sculpture a land." Herein lies one of the many charms of that great white continent—so vast that even where narrowest it would stretch from Calais to the Caspian—viz. that its ice covering, except for the Antarctic Horst in the Ross Sea region, is nearly continuous. One might, therefore, imagine that in Antarctica Reusch's ideal is at present realised ; and so it is, but to a comparatively limited extent. Man has arrived in Antarctica too late, just as civilised man has been in Europe too late, has gone to North America too late, and still goes to Greenland and Spitzbergen too late, to observe anything like the full effect of a continuous ice covering in sculpturing land. Probably everywhere to-day the ice-fields of the world are on the wane, in spite of what appear to be exceptions in the case of local advancing glaciers. De Geer has suggested that ice does not necessarily flow evenly and steadily, as water does, but is subject probably to intermittent outrushes followed by short epochs of retreat. These outrushes may be due to prolonged accumulation of inland ice setting up a critical pressure ultimately sufficient to overcome frictional resistance and resistance to shearing. The ice then moves away rapidly towards lower levels, and in polar regions thrusts itself into the sea, and across the sea-floor, until its seaward edge floats and breaks away as bergs. Such an epoch of activity may be followed by a resting stage, when ablation of ice, partly through the breaking away of bergs, partly through thaw and evaporation, exceeds what is added through ice flow and snow precipitation. Thus in one and the same district one glacier may be rapidly advancing while an adjacent glacier is retreating, as is the case in Spitzbergen with the Sefström Glacier and the Von Post Glacier respectively.† With the exception of such glaciers as are in a stage of temporary advance all the ice masses in the world are probably dwindling. Certainly the Antarctic ice sheet is decreasing rapidly, and this ice shrinkage has been general, as far as we know, over the whole area of the Antarctic Continent, from circle to pole. We can no more judge of the work that the Antarctic ice has accomplished by what it is accomplishing now in sculpturing the local land than we can measure the erosive action of a river when in flood by what

* Congrès Geologique International, XI. Session, Stockholm, 1910. " A Few Words on the Effects of Glacial Erosion in Norway," H. Reusch.

† We are indebted to G. W. Lamplugh, F.R.S., for kindly calling our attention to this feature.

we know of its work when it is at its lowest level. Frequently a river alternately erodes or aggrades its course according as to whether it is in flood or at lowest level; so that if we saw such a river at its lowest level, or at any rate during the ebbing of the flood, and noted that then it had no appreciable erosive force, we should not be justified in concluding that it had not accomplished erosion in the past. And as with water so it is with ice, with the exception of the phenomenon explained as above by De Geer. The Antarctic ice is certainly not now in flood, and its power to sculpture land is enormously diminished as compared with what it was when the outlet glaciers were about 2500 feet thicker than now, the Ross Barrier 800 feet thicker and 200 miles longer, and much of the island ice perhaps 1000 feet thicker than at present. Nevertheless there is much to learn from present Antarctic ice conditions which helps towards the interpretation of the phenomena of a past glaciation in Pleistocene times in both hemispheres. For example, the Ross Barrier may be compared with the North Sea ice sheet; the glaciation of Gerlache Channel and Bransfield Strait with that of the Irish Sea and of the Isle of Man; the upthrust marine muds on the flanks of Erebus with some of the British marine deposits pushed up from the bottom of the Irish Sea, &c. Some details of this will be given in the summary at the end of the second volume. No less entrancing than the glacial problems of Antarctica is the enigma of its lost Andes. In West Antarctica the Andean rocks, both sedimentary and eruptive, are typically developed and as typically folded, attaining heights of 6000 to 8000 feet. In East Antarctica, with the exception, perhaps, of the grano-diorites of King Edward VII. Land, Andean rocks and Andean structures are absent, but there emerges from near the South Pole a mighty block-faulted range from 8000 to 15,000 feet high, with eruptive rocks typically alkaline, and upper Palæozoic coal measures, not folded, resting partly on Devonian, partly on Cambrian, or in places on Pre-Cambrian rocks. Have the Andean faults swerved away from the Andean fold lines and the Andean petrological belt, so as to yield a block-faulted range meeting in a sort of tectonic virgation the true Andean fold lines of West Antarctica; or is the range of the Antarctic Horst entirely distinct from the Andes, and does it trend to Prince Regent Luitpold Land and Coats Land, on the eastern side of the Weddell Sea? If the latter view is correct, a sea channel, as suggested by Penck, may divide Antarctica into two portions, leaving Graham Land with all West Antarctica and Carmen Land and King Edward Land in the condition of a festooned archipelago. A physiographic feature of great interest in the part of Antarctica to which these notes relate is the development of an "ice divide" to the west of the Antarctic Horst of Ross Sea. Though considerably lower than the ranges of the Horst, the "ice divide" sends mighty glaciers through low gaps in the Horst eastwards to Ross Sea. Is this "ice divide" at all analogous to the Pleistocene "ice divide" of the Baltic Sea at a time when it sent ice westwards across the summit of Areskutan, 5000 feet above the level of the Baltic, across the main range of Scandinavia into the North Sea? Greenland has obviously such an ice divide at the present day.

Petrologically the rocks of the Ross Sea region constitute a distinct province. The reports by our colleagues, published in the second half of this Memoir, make it clear that the region has been a province for alkaline rocks from Palæozoic time. The relation of these rocks to one another, that of the alkaline granites to the vast sills of dolerite, and the latter to the great variety of effusive rocks produced by Erebus and adjacent volcanoes; and the relations of the products of eruption of the smaller parasitic cones to those of the parent cones present problems of unique interest. Biologically the deglaciated region of Cape Royds with its glacially-formed lakes has proved most interesting on account of the rich harvest of various forms of microscopic life, especially *Rotifera* and *Tardigrada*, already described by our colleague James Murray in the biological memoirs of our expedition. The occurrence of beds of algal peat on the floors of some of these lakes has furnished material for analysis and for notes given later in this volume.

Palæontologically Antarctica is proving a veritable treasure-house. To a lower Cambrian fauna, contained in as yet almost untouched massive limestone, must now be added the Devonian rocks, with the fossil fish plates discovered by F. Debenham and T. Griffith Taylor on Scott's last expedition at Granite Harbour. These Old Red Sandstone fish are shortly to be described by Dr. A. S. Woodward. Most fascinating also are the many problems presented by the vastly extensive, horizontally bedded coal measures and their associated fossil flora. This great field extends certainly from at least as far south as the Beardmore Glacier, in 85° S., to certain nunatakker recently discovered by Madigan's party, on the Mawson Expedition, to the east of Adélie Land near the Antarctic circle, a distance of at least 1300 miles. The seven coal seams discovered by F. Wild and Sir Ernest Shackleton, together with fossil wood and rootlets, proved for the first time that the "Beacon Sandstone" of H. T. Ferrar is a coal-bearing formation and that trees formerly flourished there, within 5° of the South Pole, in an area which is now in almost total darkness for five months in the year. As a result of a preliminary examination of the fossil plants, so heroically carried by Captain Scott and his comrades to the very end of their terrible journey, Mr. Debenham has stated * that he considers them to be of Upper Palæozoic Age. A detailed report of these plant remains is about to be published in connection with the Scientific Report of the Scott Expedition 1910–1913.

So far no trace of the Jurassic strata, like those of Hope Bay, from which J. Gunnar Andersson and Dr. Nordenskjöld reaped the rich harvest of fossil plants, which have been described by Nathorst, has been discovered in East Antarctica. Neither has any evidence been found there of the extensive marine cretaceous strata developed in West Antarctica at James Ross Island, Cockburn Island, and Snow Hill Island; nor again of the Oligocene or Lower Miocene strata, like those of Seymour Island, from which Nordenskjöld obtained bones of penguin and leaves like those of *Fagus* and *Sequoia*. The Pliocene Pecten Conglomerates of Cockburn Island also appear to be wanting in East Antarctica.

* "Scott's Last Expedition," vol. ii. p. 437.

It would seem, therefore, that in East Antarctica the great "Schild" has formed a land surface, subsequent to the extensive lower Cambrian transgression, from Devonian times down to the present.

The late Cainozoic, including recent, Palæogeography of Antarctica, based on palæontological and biological evidence, has been well summarised by C. Hedley in the "Proceedings" of the Linnean Society, London, for 1913.*

A feature of the greatest possible interest in connection with Antarctica is the recent discovery by R. C. Mossman that there is a causal connection between the state of the ice in Weddell Sea, the height of the barometer in the South Orkneys, and the rainfall in Chili and in the Paraná region, together with the depth of water in the Paraná River. Much ice in the Weddell Sea region appears to bring about a high barometer at the South Orkneys, and this high pressure seems to drive the rainy belts of the sub-tropics of the Southern Hemisphere nearer to the equator than usual. Thus, on Mossman's theory, Antarctica acts meteorologically as a great tension screw. Presumably, if the alternations of relatively colder and relatively warmer conditions take place synchronously at either pole, such part of the earth's atmosphere as lies between the polar circles is alternately compressed or expanded, with a concertina-like movement, according as to whether the area of the ice there is above or below the normal in extent. This very suggestive theory induces the hope that it may hereafter be possible, by means of the wireless station established by Dr. Mawson at Macquarie Island (subsequently taken over by the Commonwealth), to trace a connection between the state of the ice in the Ross Sea and the weather of Australasia. To complete the essential observations it would be necessary to establish a wireless meteorological station in Antarctica itself, and there can be no doubt that in course of time this will be an accomplished fact. Thus, by the increased accuracy of the weather forecasts, not only will trade and commerce be promoted, but, it is hoped, many a shipwreck averted. Surely such a result would justify all the cost, hardship, suffering, and even sacrifice of human life which recent Antarctic expeditions have involved!

It is hoped that the second volume of this memoir, with papers relating to petrology by Drs. H. I. Jensen and D. Mawson, Professor Skeats, Professor Woolnough, Dr. Allan Thomson, W. N. Benson, A. B. Walkom, L. A. Cotton, and Miss F. Cohen, and with palæontological papers by F. Chapman and C. Hedley, will be published within a few months of the date of issue of the present volume. The latter will contain the index and bibliography. We are fully sensible of the fact that in the present memoir we have probably fallen into many errors, arising possibly from too hasty generalisation from slender data, too imperfect a review of the many valuable memoirs of previous writers on this region (a shortcoming, however, which has been almost unavoidable in view of the fact that the whole of this memoir has been elaborated in Australia, where we have not had access to many memoirs on the

* "The Palæographic Relations of Antarctica," Chas. Hedley, Proc. Linn. Soc., June 6, 1912.

Antarctic to be obtained only at European libraries). We are also aware of defects arising from the spasmodic working up of our material. The latter drawback has arisen from the fact that it was necessary to break off from time to time from our study in order to raise funds to defray all the cost, other than that of printing, of the preparation of the memoir. By means of lectures a sum of over £800 has been raised in various parts of Australia and Tasmania, and we are very grateful to the audiences who so generously patronised these lectures, and so made the preparation of the two volumes of this memoir possible. We must add that the Royal Society have generously contributed £200 towards defraying the cost of the publication, the remainder of the cost being borne by Sir Ernest Shackleton. In reference to the photographs reproduced herein, whenever possible we have added the name of the photographer. All were taken by members of the expedition, but in many cases it has now been found impossible to trace the name of the photographer. The rough sketches of the coast-line from Cape Bernacchi to Mount Nansen, and inland towards the South Magnetic Pole, were made by one of us (T. W. E. David), and we are much indebted to Mr. K. Craigie for redrawing these for reproduction. He has also redrawn in black and white several of our photographs, which otherwise would have been too inferior for printing. Our acknowledgments are also due to Mr. H. E. C. Robinson for the great care with which he has prepared our maps and sections. We are indebted above all to Sir Ernest Shackleton for the constant sympathetic encouragement which he gave us throughout in our work, and the invaluable collection of fossils brought back from the Beardmore Glacier by himself, Wild, Adams, and Marshall, under conditions of extreme risk and hardship. We have also to thank our colleague James Murray for useful notes about thaw and ocean currents in the neighbourhood of Cape Royds. Valuable assistance was also rendered us by our late colleague Mr. Bertram Armytage, as well as by other members of the expedition. We are particularly indebted to Mr. C. Hedley, of the Australian Museum, for his contributions on the mollusca of the raised beaches and upthrust marine muds; to Mr. Frederick Chapman, of the National Museum, Melbourne, for his account ot the *Foraminifera* and *Ostracoda* derived from these marine muds; as well as to Mr. T. Griffith Taylor for his notes on the *Archæocyathinæ* in the Cambrian limestones of the Beardmore Glacier. Professor Skeats, of the University of Melbourne, has contributed important notes on the Cambrian limestones, a subject on which, of course, few can speak with such authority. What, perhaps, has been a no less laborious, and in some cases certainly a still more tedious and difficult, task has been the elaboration of our large petrological collection. This work has been done by Dr. Jensen, Professor Woolnough, Dr. Allan Thomson, W. N. Benson, A. B. Walkom, and Dr. D. Mawson, to all of whom we beg to express our hearty gratitude, while to Mawson we owe the map of the coast from Cape Bernacchi to Mount Nansen, compiled from his theodolite survey. Mr. Arthur W. Allen has been unremitting in his kind attention to the business side of our work;

Mr. J. A. Tunnicliffe, of the University of Sydney Library, has much assisted us in the matter of arranging and indexing these notes, as well as in the matter of references; and certainly not the least important help that we have received has been given by our colleague, Mr. W. S. Dun, who has been an unfailing source of information in all matters relating to Antarctic Bibliography. Our hearty thanks are due, and are hereby sincerely tendered, to Dr. Charcot, Professor Penck, Dr. J. Gunnar Andersson, Dr. A. Strahan, G. W. Lamplugh, and Professor Sibly for much sympathetic help.

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ANTARCTICA

GEOLOGY

PHYSIOGRAPHIC INTRODUCTION

The name Antarctica, adopted by us, has been given by Balch,* and most other American and English authors, to that great southern continent termed by Elisée Reclus "Antarctide," by Gourdon "L'Antarctique," and by German authors "Antarktis." In the subdivisions of this continent we have followed the system of Charcot and Gourdon † of dividing Antarctica into three sectors corresponding to the three great continents of the Southern Hemisphere :

1. The American Sector, lying between 0° and 120° W.
2. The Australian Sector, ,, ,, 120° W. and 120° E.
3. The African Sector, ,, ,, 0° and 120° E.

Another system is that which divides Antarctica into four quadrants :

1. Enderby Quadrant, lying between 0° and 90° E.
2. Victoria Quadrant, ,, ,, 90° E. and 180°.
3. Ross Quadrant, ,, ,, 180° and 90° W.
4. Weddell Quadrant, ,, ,, 90° W. and 0°.

Area. Dr. W. S. Bruce has estimated the superficial area of the Antarctic Continent as 5,470,000 square miles—an area which, as Hann remarks, is almost as large as Europe and Australia—respectively 3,750,000 and 2,947,000 square miles. It is doubtful if the actual land area of Antarctica much exceeds about 4,500,000 square miles. In this case nearly 1,000,000 square miles of its area, as estimated by Bruce, would be occupied by old pack ice, ancient floe ice, and piedmonts afloat, all probably held in position by islands.

Altitude. It has been estimated that Antarctica has a mean altitude of approximately 6000 feet (1829 metres), in which case, perhaps, it has the greatest mean height of any continent.

* "Antarctica," Philadelphia, 1902.

† "Expédition Antarctique Française," 1903–1905. Dr. Jean Charcot, "Géographie Physique, &c." par E. Gourdon. Paris, Masson et Cie, Editeurs, 1908, p. 2.

Shape. Antarctica is irregularly pear-shaped, with the curved stem directed towards South America, and the "eye" towards the Indian Ocean. Two deep indents are conspicuous, Ross Sea lying between the meridians of 170° E. and 160° W., and Weddell Sea lying between long. 20° W. and 50° W. Some have supposed that the Antarctic Continent is divided into two distinct portions by a wide strait joining Ross Sea and Weddell Sea. The recent brilliant geographical discoveries by Roald Amundsen tend to disprove this view. He found in his wonderful journey to the South Pole a new land, commencing at the intersection of the parallel of 86° S. with the meridian of 160° W. and trending thence in a N.N.E. direction at least as far as lat. 84° S. This land, to which Amundsen has given the name of Carmen Land,* is estimated to be about 4000 feet high, and is thought to be probably, though not necessarily, continuous with the "appearance of land" reported by Amundsen, between lat. 81° S. and 82° S. and also probably with King Edward VII. Land. Thus the Ross Barrier is completely shut off by land to the south, and, if it communicates at all with Weddell Sea, must do so by some very narrow straits, possibly situated between Carmen Land and King Edward VII. Land. The discovery by Amundsen that the great ranges of South Victoria Land continue to the S.E. as far as the Heiberg Glacier and then bend back to S.S.E., resuming further on a S.E. and eventually taking on a nearly due E. direction, is obviously of far-reaching importance. This great range, Queen Maud's Range, may continue without interruption to the high land recorded by Charcot, Arctowski, Nordenskjöld and others in the American Sector of the Antarctic. The land from Terre Louis Philippe, south-westwards through Danco Land, Graham Land, Terre Loubet and Terre Fallières, is high and on the whole of a plateau or peneplain type. It rises to heights of over 2000 m. (over 6560 feet), in Graham Land to 2400 m., and on the island between Isle Adelaide and Terre Loubet to a height of 2500 m. (over 8200 feet).† While we think there can be little doubt that the continuous ranges of South Victoria Land and Queen Maud's Range extend without interruption to the high land of Terre Loubet and Graham Land, &c., as shown on Dr. Mawson's map,‡ and Dr. W. S. Bruce's earlier map,‡ we have preferred to leave the map blank between Mount K. Olsen of Amundsen's map, and Terre Fallières of Charcot's map. There is still the possibility, but remote in our opinion, that the Queen Maud's Range trends towards the land recently discovered by Lieutenant Filchner, which extends to, at least, as far south as 79° S., this land being a continuation to the S.W. of Coat's Land. As there are marked differences in petrographical as well as in tectonic characters between the great ranges of the Ross Sea region and those of the South

* "The South Pole," Amundsen, vol. ii. pp. 170–171.

† See "Carte Provisoire de L'Antarctique Sub-Americaine d'après le lévé fait par 01." Bongrain. "Le Pourquoi-Pas? dans l'Antarctique," Dr. Jean Charcot, opposite p. 370.

‡ "The Geographical Journal," June 1911, end of volume; and "Über die Fortsetzung des Antarktischen Festlandes," &c., the Scottish Oceanographical Laboratory, Edinburgh, 1910.

American Andes,* we have hesitated in the matter of adopting the convenient name for these ranges as a whole already applied to them in the American Sector by Arctowski, "The Antarctandes," and have decided to call them "The Antarctic Horst." The general distribution of the Antarctic volcanoes, in relation to this great Horst, is discussed in the concluding chapter of this memoir.

A very interesting physiographic feature of Antarctica is that while the mountains of the Antarctic Horst are mostly considerably higher than the great plateau which lies behind them, they do not actually form the parting for the inland ice.† In the case of the plateau on which the South Magnetic Pole is situated our Expedition proved that there is a definite parting of the inland ice, as well as a parting of the dominant surface winds, at a point about 60 miles S.E. of the South Magnetic Pole area and about 180 miles inland from the coast.

Amundsen discovered a parting of the ice at the back of Queen Maud's Range on the meridian of 170° W., near 87° 40′ S. Shackleton in 1909 probably crossed a continuation of this ice parting before reaching his furthest south in 88° 23′.

Scott, in his important journey over the plateau to the west of the Ferrar Glacier, proved that that glacier is fed by a vast snowfield, the general surface of which is no less than 5000 feet lower than the mountains of the Royal Society Range, but slightly above the level of the low-lying part of the great horst, which lies between the Ferrar Glacier on the south and Mount Nansen on the north. According to Scott's levels, for over 100 miles west of the upper end of the Ferrar Glacier the surface of the inland ice, though undulating, is practically level, its height varying from about 7200 feet to 7500 feet above sea-level. It will be an interesting point for future expeditions to determine the exact trend of this ice parting and the varying directions in which the ice moves away from it. The approximate trend is shown on the general map of Antarctica in this memoir.

The special area with which our Expedition was concerned was that adjacent to the western shores of Ross Sea, Ross Island, and the land stretching inland from the coast towards the South Pole and the South Magnetic Pole. We may now proceed to summarise some of the chief physiographic characteristics of this Ross Sea region.

Coast. The coast which forms the western boundary of Ross Sea and of the Ross Barrier is one of the most wonderful in the world, and is obviously situated on a zone of stupendous fractures, mostly trending north and south, and with a heavy downthrow to the east, amounting probably to at least 5000 or 6000 feet (1525–1829 metres). From Cape Adare on the north to beyond the Beardmore Glacier on the south, a distance of about 870 miles (1394 kilometres), Ross Sea and the Ross Barrier are bounded by majestic table-topped ranges supported by gigantic buttresses, groins, and arêtes of dark rock, so steep that they are mostly bare of snow. At intervals of

* For example, the rocks of the ranges of South Victoria Land are mostly of Atlantic type and not folded. Those of Graham Land and neighbouring areas are essentially of Pacific type and are folded.

† In this respect the physiography of Antarctica much resembles that of Western Greenland.

from about 20 to 60 miles these ranges are breached by mighty glaciers, from 5 to 15 miles wide, and about 100 miles in length. There can be no doubt whatever that, if all the ice in this region melted away, what are now the lower ends of the outlet glaciers would give place to deeply indented fiords, the sea water following up the glacier ice, in its recession, for a distance probably of from 10 to 50 miles back from the coast. In places the great plateau descends in almost vertical cliffs fully 1000 feet high (304 metres) into the depths of Ross Sea. Near the western end of the Ross Barrier the stately volcanic pile of Ross Island raises its dark rocks of kenyte lava, some 13,000 feet (3962 metres) above sea-level in Mt. Erebus, over whose summit floats, like a pennon, the great steam cloud—an ideal wind-vane in a region where such an index to the trend of the upper currents is of priceless value. East of Ross Island stretches the great white wall of the Ross Barrier across the *senkungsfeld* of Ross Sea to King Edward VII. Land. There low mountains bound the Barrier eastwards, probably formed, in part at all events, of old crystalline rocks, as far as can be judged from dredgings from their vicinity, as well as from the specimens of biotite-hornblende granite found there *in situ* in 1912 by Lieutenant Shiraze of the Japanese expedition.* North of King Edward VII. Land the region is so beset with dense pack-ice, that the nature of the geographical conditions there to the east of the pack are at present almost wholly unknown. To the south of King Edward VII. Land the Ross Barrier, occupying a large gulf, is bounded on the east partly by land completely buried under ice, partly by land emerging above the ice and attaining an altitude of about 4000 feet, like the Carmen Land recently discovered by Amundsen. In places the coast is terraced. The significance of this will be discussed in the chapter on Raised Beaches.

As regards age, in the physiographic sense, the Antarctic coast on the west side of Ross Sea appears to be neither very young nor yet distinctly mature. Projecting promontories like Cape Washington, Cape Adare, Cape Barne, &c., have been cut back by marine erosion into high cliffs, like those of Cape Washington shown in the accompanying plate.

Obviously some considerable time is needed for the cutting back of cliffs from 200 to nearly 1000 feet in height. The formation of the remarkable coastal plain, which extends from near the Koettlitz Glacier northwards as far as Cape Washington, and which consists in part of worn-down ancient crystalline rocks, in part of morainic material and alluvium from thaw water (the whole mostly adjacent to the coastal piedmont glacier ice), again suggests that considerable time was needed for its development. On the other hand, the great fault scarp of Mount Nansen, although

* Since the above was written the fine work by Amundsen, "The South Pole," has appeared. In vol. ii. p. 396, J. Schetalig, Secretary of the Mineralogical Institute of Christiania University, in provisional remarks on the rock specimens obtained by Lieutenant Prestrud at Scott's nunatak, King Edward VII. Land, records white granite, micaceous granite, grano-diorite, quartz-diorite, and quartz-diorite schists. We are much indebted to Lieut. Shiraze for kindly presenting us with specimens of the hornblende-biotite granite from King Edward VII. Land.

PLATE II

Fig. 1. CAPE WASHINGTON SEEN FROM THE SOUTH

Fig. 2. CAPE WASHINGTON
A lofty headland of Cainozoic volcanic rocks. View looking about north-west.

[To face p. 4

deeply trenched in places by corrie glaciers, is on the whole but little reduced by erosion. In this connection one must bear in mind the protective action of ice and snow, so ably advocated by Professor Garwood.* The effect of this protection is to prolong the youthful appearance of a landscape, which, tested by the time-unit of a temperate, as opposed to a polar climate, might be said to have arrived at maturity.

The classification of this coast-line is discussed in the last chapter of this memoir dealing with the relation of Antarctica to other parts of the world.

The Antarctic Horst. If we now return to the main coast-line on the west, the land next to the coast is seen to have the form of an immense elongated horst, from 50 to 100 miles (180 to 160 kilometres) in width, bounded eastwards by faults, having a throw of at least 6000 feet (1829 metres) and westwards by faults throwing probably about 2000 feet (610 m.). This horst forms a gigantic retaining wall, damming back and so causing a higher piling up of snows which fall upon the plateau to the west. At intervals the horst is breached by valleys, perhaps partly of tectonic origin (in the beginning either synclines or trough faults, but greatly modified by subsequent glacial erosion), which form outlets, "by-washes," or "spillways" for the surplus inland ice and snow. The great N. and S. fault, near Cape Adare, is marked by a volcanic zone extending southwards to Coulman Island, and striking thence, through perhaps Franklin and Beaufort Islands, on to Mount Bird in Ross Island. On this line is situated one of the most wonderful geysers in the world, which occasionally bursts into eruption in sympathy with Mount Erebus. Thence, the fault trends through Mount Erebus and the zone of craters near Hut Point, and on through Black Island. Parallel to this fault, to the east of it, is a second fault, which runs through Mount Terra Nova, White Island, and Minna Bluff. To the west of Mount Erebus, and on the west side of McMurdo Sound, another strong meridional fault is probably marked by the very steep-to coast. The discovery in the course of our geological investigations of included fragments of Beacon (?) sandstone in the lavas of Erebus is further proof of the existence of this fault, for whereas under Mount Erebus the Beacon Sandstone † is presumably far below sea level, its base is about 5000 feet above the sea in the mountains to the west of Erebus. Just south of Minna Bluff this fault is shifted westwards by a strong cross fault and trends thence, first in a S.S.E., then in a S.E. direction. Northwards from McMurdo Sound this meridional fault following the coast trends northerly past the base of Mount Nansen. The western shore of Lady Newnes Bay, and the straight coast to the south of it, probably mark another fault intermediate between the Cape Adare line and the Nansen line.

* "Geographical Journal," vol. 36, 1910, pp. 310–339.

† The term Beacon Sandstone, first used by H. T. Ferrar, geologist to the National Antarctic Expedition of 1901–04, is here applied to all those more or less horizontally bedded strata, mostly sandstones, which overlie in East Antarctica, the Pre-Cambrian crystalline complex as well as the Archæocyathinæ limestones. For reasons stated in the concluding chapters of this memoir, their age at the base may be as old as Devonian, and at the summit may be Jurassic or even Cretaceous.

The most clearly defined of all the cross faults, which mostly trend east and west, is that which runs eastward from Erebus through Mounts Terra Nova and Terror. Westward the same fault may pass a little to south of west through Cape Barne to the Ferrar Glacier Valley, or to Dry Valley immediately to the north. Minna Bluff and Mount Discovery are situated on an E.S.E. and W.N.W. fracture. Cape Washington and Mount Melbourne are also on an E.S.E. and W.N.W. line. The remarkable straight coast, bounding Lady Newnes Bay on the north, probably represents an E. and W. fracture.

It will thus be seen that the chief centres of recent volcanic eruption in the Ross Sea region and South Victoria Land are the nodes of the meshes of a network of faults.

The position and direction of throw of the chief faults is shown on the accompanying map.

The details of the Antarctic Horst from Mount Melbourne to Minna Bluff are given on Plate III.

It will be seen from the three sections across the main ranges (Fig. 67) that, both to the west of the Queen Alexandra Range, the Royal Society Range, and Mount Nansen, the inland névé fields do not rise to the level of the mountains of the Horst, falling short of it by about from 1000 to 2000 feet (305–610 metres).

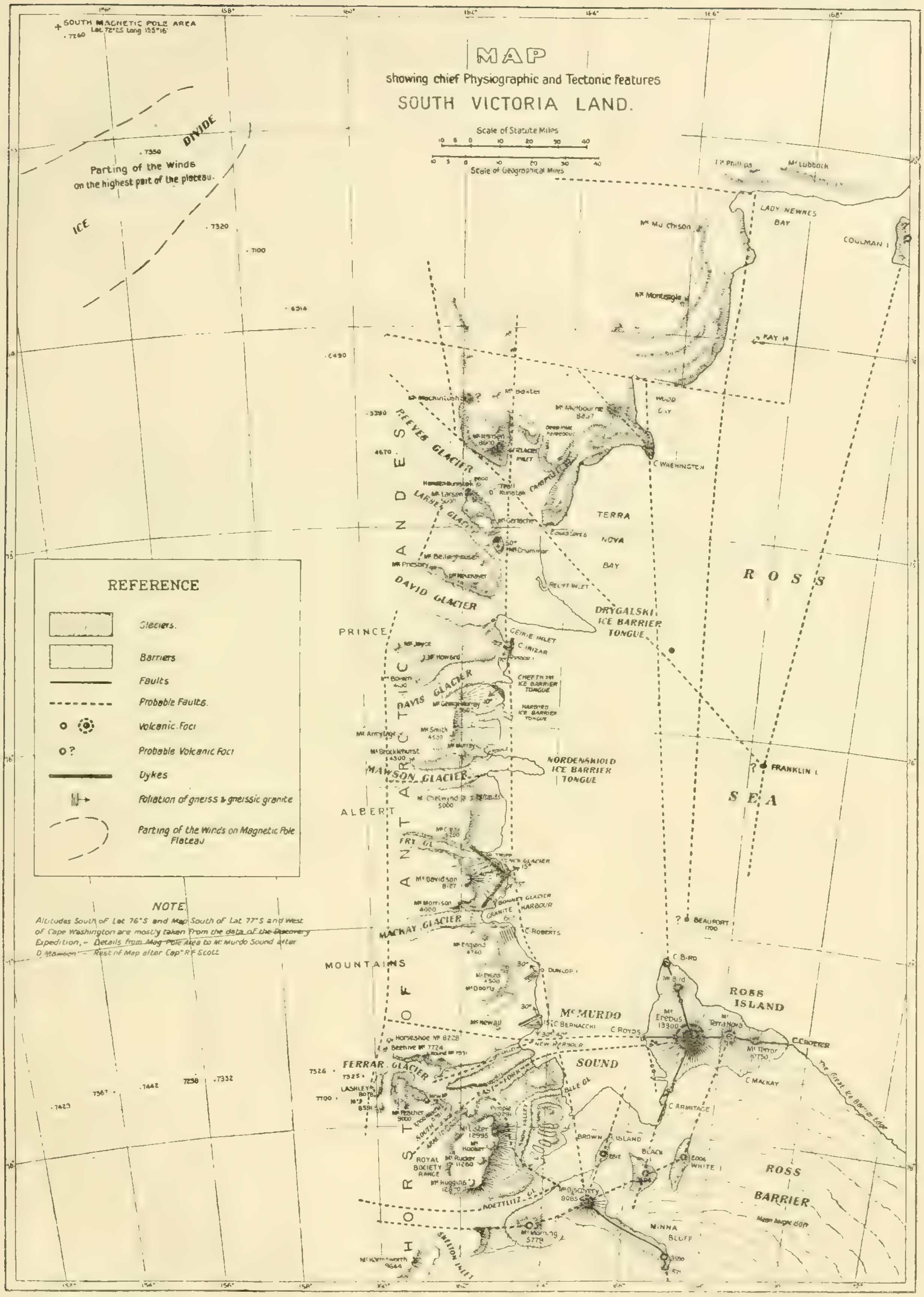
It may be added that the plateau character of the Western Mountains is preserved—as far as the southern party under Shackleton could see—for a considerable distance to the south-east of the Beardmore Glacier.* Northwards the plateau sandstones extend at least as far as Mount Nansen, a distance of about 800 miles (1299 kilometres). This plateau sandstone has been proved to be coal-bearing in places. Both it and the old peneplain, upon which it rests, are traversed by huge sills of quartz-dolerite or diabase analogous to the sills of the Karroo in South Africa, and to the gigantic quartz-dolerite sills of Tasmania.

Physiographically it is difficult to estimate the age of the Antarctic Horst with any approach to accuracy. The great horst, as a whole, has not been seriously reduced by erosion since its inception as the result of faulting. Provisionally it may be concluded that these ranges show signs of adolescence rather than of either youth or of maturity.†

Peneplains. There is strong evidence of the horizontally bedded plateau sandstone, the Beacon Sandstone, having been deposited upon an ancient peneplain of crystalline

* The photograph of Mount Fridtjof Nansen, 15,000 feet above the sea, published by Amundsen ("The South Pole," vol. ii., facing page 50) proves the plateau rocks to extend for at least 190 miles S.E. of the Beardmore Glacier.

† The fact must be emphasized that the great outlet valleys of the Antarctic have been cut down to depths of from 5000 feet to 8000 feet below the general original level of the plateau, that their width is from a mile up to about 15 miles, and their length from 30 to about 100 miles. Thus the Horst has been deeply dissected.



GENERAL MAP SHOWING THE CHIEF PHYSIOGRAPHIC AND TECTONIC FEATURES OF SOUTH VICTORIA LAND schists, gneiss, granite, slate, and altered limestone. A plateau of crystalline rock, extending eastwards from the eastern base of Mount Lister for a distance of about 10 to 12 miles (18–19 kilometres) in width, appears to be a very ancient peneplain. This may be a Pre-" Beacon Sandstone" peneplain, that is probably a Pre-Gondwana peneplain.* This has been "re-discovered" by erosion in Cainozoic time. Its height above sea level varies from about 4000 feet to 6000 feet. The figure below is a general panoramic view from our winter quarters at Cape Royds on Ross Island, looking westwards over 50 miles (80 kilometres) across McMurdo Sound to the Western Mountains.

Valleys. The Section, Plate V., shows the position and relative sizes of these transverse valleys, mostly of the "outlet" or Greenlandic type, which transect the Antarctic Horst.

The valleys may be divided, broadly, into (1) outlet valleys, where they cross the horst and form spillways for the inland ice reservoirs, and (2) alpine valleys, where they do not completely transect the horst, and thus merely discharge glacier ice formed within the drainage-area of the horst itself. These Alpine valleys have their "thalweg" mostly athwart the long axis of the horst, but some are parallel to this axis, like South Arm on the Ferrar Glacier, and the Mill, Keltie, and Hood Glaciers of the Beardmore Glacier. These longitudinal (subsequent) Alpine valleys may be in the first case of tectonic origin following fault planes parallel to the main lines of faulting which bound the Antarctic Horst. Both types of valleys, outlet as well as Alpine, have numerous hanging valleys emptying into them.

The main valleys, especially the outlet valleys, offer such impressive examples of ice-erosion as should convince even the most sceptical that glacier ice is able to carve rock on a grand scale. They are mostly very steep-walled and either spurless or with intensely faceted spurs. Details of these are given later in this report under the head of Glaciology, where the question is discussed as to how far the valleys are tectonic and how far glacial or fluviatile in origin. The interesting problem is also investigated as to how far the glacial ice streams have brought their channels to grade, the conclusion being that the channels are not by any means brought to grade on the inland side of the great horst. If Antarctica were bared of its snow and ice, extensive lakes would probably gather immediately to the west of the horst.

Plains. The steep coast of South Victoria Land is subtended for about 200 miles (319 kilometres) northwards from the head of McMurdo Sound by a remarkable plain. This is from 10 to 15 miles (16–24 kilometres) in width, and slopes up at a gentle angle to a height of from about 1000 feet to 1700 feet (305–518 metres) to

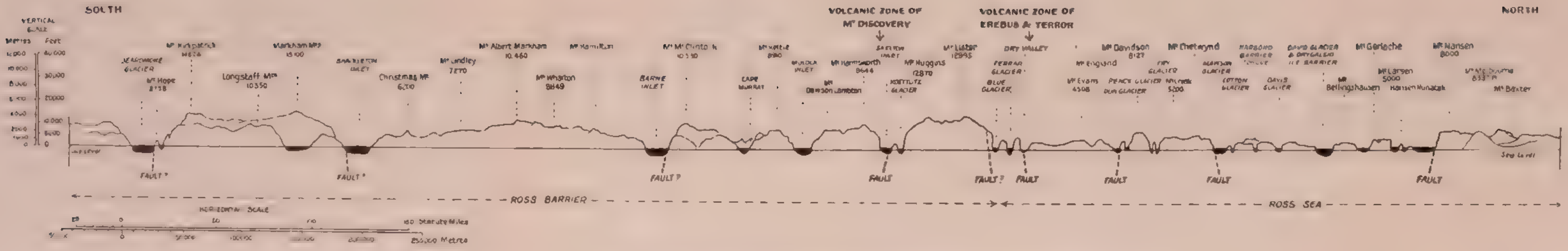
* In view of the resemblance of the lower portions of the Beacon Sandstone to the Devonian rocks of the Falkland Islands, as explained in the last chapter of this volume, and especially in view of the recent discovery by T. Griffith Taylor and F. Debenham, of the late Captain Scott's expedition, of bony plates, ascribed by Dr. A. S. Woodward to Devonian fish, this peneplain, in part at any rate, may be Pre-Devonian.

PLATE IV

THE ANTARCTIC HORST SEEN FROM CAPE ROYDS

[*To face p.* 8

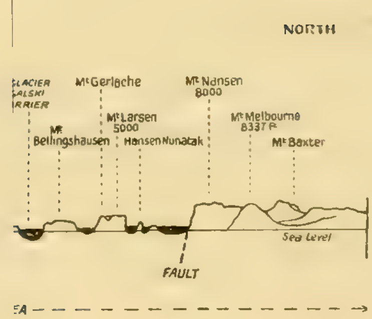
PLATE V



LONGITUDINAL SECTION ALONG ANTARCTIC HORST SHOWING GLACIERS AND FAULTS

[*To face p. 9*

PLATE V



[*To face p. 9*

the steep foothills of the plateau. As it is for the most part covered by the ice of the piedmont aground, one can do little more than guess at its structure. A study of its surface, where it outcrops from beneath the ice in the coastal cliffs, shows that for a considerable extent it is formed of an intensely glaciated surface of ancient crystalline rocks with the hollows filled with a thin covering of moraine material. The deepest hollows, being below the sea level, could not be examined. No true boulder clay (till) was observed. It has been suggested that this coastal plain represents a down-faulted segment, but, at present, evidence of such faulting is wanting. Mr. E. C. Andrews, of the Geological Survey of New South Wales, suggests that it is an old plain of marine erosion, and it may be so. It is also possible that it may represent an abrasion shelf notched back by the Ross Barrier at the time of maximum glaciation. To this last suggestion it may be objected that, during the maximum glaciation, the pressure of the local glaciers of the Western Mountains would suffice to repel, or shoulder away, encroachments on the coast by the Ross Barrier. The Barrier may, however, have shouldered them around northwards and commandeered them, so to speak, for the work of eroding the terrace. It seems a gigantic work for ice to have accomplished, but a mass of moving ice (and we know from the evidence of the erratics that it was certainly moving) 500 miles (805 kilometres) wide, and some 3000 to 4000 feet thick (914–1219 metres), represents a vast erosive force.

It might also be suggested that this coastal plain represents in part an old plain of aggradation, that is formed from deposition of continental waste, resting on an ancient plain of marine erosion, somewhat analogous to the coastal platform of the Malaspina Glacier.*

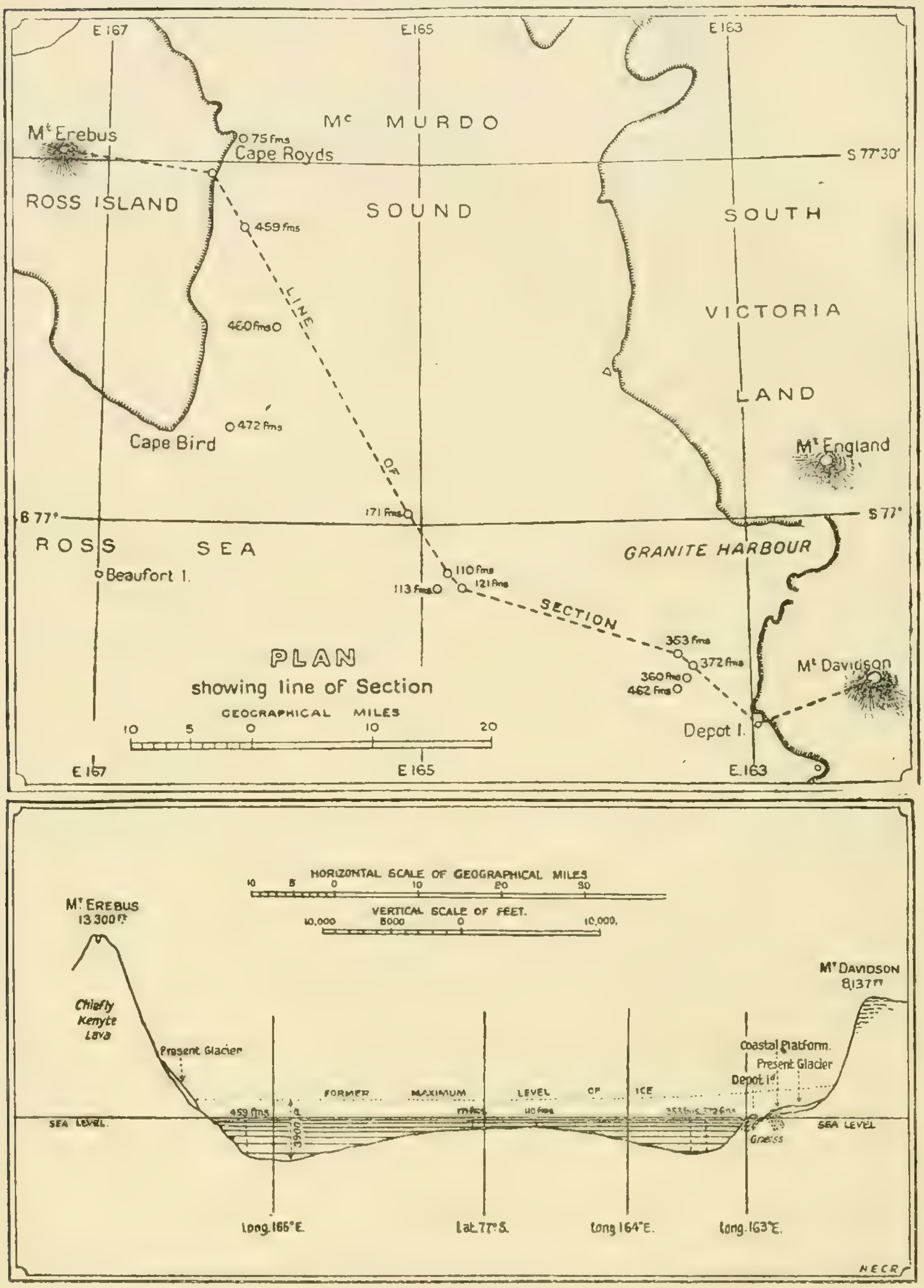
As far as our observations extend, there is no great thickness of alluvial material resting on the glaciated surface of crystalline rock.

Unfortunately we have only a few soundings, too few to admit of the construction of a continuous curve from where this plain ends at the coast down to the greater depths of Ross Sea. The few soundings that were taken indicate depths of from 350 to 450 fathoms within 12 miles of the coast, deepening to over 650 fathoms in the neighbourhood of a large glacier, like that which forms the Drygalski Ice Barrier Tongue. The following is a section across this coastal platform from Mount Davidson to Mount Erebus :

It will be noticed that after the soundings, taken from W. to E., deepen to 350 fathoms at 12 miles E. of the coast platform, they shoal to 110 fathoms in the middle of McMurdo Sound, then deepen again to 460 fathoms at only three miles off the west coast of Ross Island.

This shallowing towards the centre of the Sound is probably due to the vast amount of morainic material carried northward by the former Great Ice Barrier, when at its maximum, from the neighbourhood of Mount Discovery, or possibly it may be due to a submerged chain of small volcanoes. Probably the former is the correct explanation.

* I. C. Russell, 1899 ; R. S. Tarr, 1907 ; L. Martin, 1909.



Figs. 1 and 2. SECTION ACROSS McMURDO SOUND

Looking south, showing coastal platform on right, and rapid descent of sea floor to depth of 360 fathoms.

A third possible explanation of the shallowing of McMurdo Sound towards the centre is that it is the result not of addition of morainic or volcanic material, but of differential erosion. In this case it may be suggested that deeper hollows have been scooped inshore, where the thrust and consequent erosive power of the former great glaciers of the Western Mountains of South Victoria Land and of Erebus were perhaps greater than that of the central part of the great glacier which once moved down McMurdo Sound.

Ross Sea and *McMurdo Sound.* The boundaries of Ross Sea have already been given. Apart from the large number of valuable soundings recently taken by the British Antarctic Expedition of 1910–13 on the *Terra Nova*, and those of the *Discovery* Expedition of 1901–4, soundings hitherto have been few and far between. Captain F. P. Evans, R.N.R., and Lieutenant J. K. Davis of our Expedition took soundings wherever practicable, but the opportunities were few, about twenty only being recorded.

Some of our soundings across McMurdo Sound have already been given, and these added to the important series taken by Captain R. F. Scott, on the *Discovery*, from Ross Island to King Edward VII. Land give some indication of the shape of this part of the Ross Sea basin.

The Ross Sea is about 650 miles in width from west to east at its entrance, but the eastern side is so beset with pack ice that the actual land boundary there is not known. In the latitude of Ross Island the width of Ross Sea including that of McMurdo Sound is at least 550 miles. Practically the whole of the Ross Barrier is but a southerly prolongation of Ross Sea. Ross Sea from its southernmost point, at the junction with it of the Devil's Glacier, northwards to where it meets the Southern Ocean measures about 500 miles. Its depth near the latitude of Ross Island varies from about 200 to 460 fathoms.

As one approaches the edge of the Barrier, within 100 miles or so, the water becomes noticeably green in colour, owing probably to the otherwise blue water being stippled with the innumerable yellow flecks furnished by countless hosts of living diatoms.

Of special geological interest, from the point of view of glaciology, are the horizontal and vertical distribution of temperature in Ross Sea, and the directions of the prevalent tidal and other currents. Unfortunately as yet details are meagre, ut such as are available are of distinct interest.

First in regard to currents, some interesting notes on these have been published by our colleague, James Murray.* The vane of our tide-gauge off Cape Royds was not affected by tidal currents, at all events not appreciably so, as its depth below the surface was 16 feet (4.87 m.). The vane usually pointed nearly due N.W., but oscillated between N. 10° W., and W. 20° N.

The fact that all through the winter of 1911 Amundsen observed open water only about 8 miles (13 kil.) N. of Framheim, in the Bay of Whales, in spite of the intense cold of the neighbourhood of Framheim, demands the advection of warm currents from the north. It may be added that it is not only in the case of the S.E. corner of Ross Sea, near the Bay of Whales, that the sea remains open for the whole

* "The Heart of the Antarctic," vol. ii. pp. 372–375.

year. It is doubtful whether even in the coldest month (July), McMurdo Sound was completely frozen over, even when the mean temperature was $-17°$ F. ($-27°$ C.). Usually there was a long dark streak of open water about 15 to 20 miles off the land, as shown in the drawing by Mr. K. Craigie from an inferior photograph, showing the Western Mountains. To the north of Black Sand Beach, about one mile north of Cape Royds, there was open sea most of the winter.

Murray (*op. cit.* p. 373) quotes good evidence to show that at times there was a southerly current coming down from the direction of Cape Royds as far as Black Sand Beach, about a mile north of Cape Royds. Thence the current turned westwards across McMurdo Sound, and thence northwards towards Granite Harbour and the Nordenskjöld Ice Barrier Tongue.

The large number of stranded bergs along the west coast of Ross Sea renders it probable that the current, on the whole, has a northerly set from McMurdo Sound along its western shores.

Strong off-shore winds from the Western Mountains, often immediately preceded by southerly and south-easterly blizzards, would tend to give the water of Ross Sea a clockwise rotation, which would be further accelerated by the easterly winds of King Edward VII. Land. It seems very possible that the water of Ross Sea moves as a gigantic eddy, the southern edge of which passes under the Ross Barrier proper, while its south-western portion passes under the Barrier to the south of Ross Island and flows northerly up McMurdo Sound.*

Temperature. We have no sufficient data on the subject of the horizontal distribution of temperature over Ross Sea, so the following suggestions are very tentative.

In reference to the vertical distribution of temperature we may quote the following important observation by Sir J. C. Ross, quoted by Commander Hepworth : †

"On January 6, 1841, at noon, they (the *Erebus* and *Terror*) were in latitude 68° 17′ S., longitude 175° 21′ E., and found that they had been set twenty-six miles to the S.E. by the current during the previous two days. Here the temperature of the water at 600 fathoms was found to be 39·8° F. ; at 450 fathoms, 39·2° ; at 300 fathoms, 38·2° ; at 150 fathoms, 37·5° ; and at the surface 28° F."

Ross's thermometers were not protected against pressure by being sealed up in a strong outer glass tube as are modern thermometers. Nevertheless, this inversion of temperature with depth cannot all be ascribed to increase of pressure on the bulb of the thermometer. It may be mentioned that at a depth of over 620 fathoms, at the Drygalski Glacier, J. K. Davis on the *Nimrod* registered a temperature of about 40° F. This was so high that we discredited it at the time (February 5–6, 1909),

* Dr. W. S. Bruce and R. C. Mossman of the Scottish National Antarctic Expedition, 1902–4, hold that a similar eddy exists in Weddell Sea. Lieutenant Filchner in the *Deutschland* experienced a similar current circulation, as proved by the direction of drift of his ship.

† "National Antarctic Expedition," 1901–4. "Meteorology," part i. p. 420.

but while we do not claim that these temperatures are absolutely accurate, we are of opinion that the following considerations suggest that there is a slight inversion of temperature in much of the water of Ross Sea. Firstly, there can be no doubt that the sea ice of a preceding winter season is melted from below as summer approaches, so that 7 feet (2·13 metres) of sea ice towards the end of the summer may be less than 5 feet (1·5 metres) in thickness. In other words, half a metre may be lost annually to the sea ice near the latitude of Mount Erebus as the result of melting from below.* Secondly it was noticed that there was a tendency for open pools of water to form and keep open even during the winter at any point in Ross Sea where there was any obstacle, such as a submerged ridge or moraine which tended to deflect currents upwards. The pool of sea water which remained unfrozen until late in May to the north of the Cape Barne Glacier, the pool off the submerged moraine to west of Cape Armytage, and possibly the large strip of open water on the north side of the Drygalski Glacier,† may be due to the upward deflection of warmer but more saline water, so that locally it rises above the surface colder but fresher water.

This explanation of these pools seems more reasonable than the hypothesis that they may be due to the local warming effect of hot springs situated along lines of faulting. In a region of such modern volcanic activity such springs are almost sure to exist, but their heating effect on the vast body of water in Ross Sea would probably be negligible.

* Unfortunately we have only approximate data on this subject. The above statement is based on the fact that whereas we found that the sea ice acquired a thickness at Cape Royds, in 1908, of 7 feet (2·13 m.) during autumn, winter, and spring, in January its thickness had been reduced to about 5 feet (1·5 m.) with numerous intervening corrosion hollows where the thickness was less than 1 foot (·3 m.).

† That these open pools are connected with upward deflected currents seems highly probable. What is now needed is a series of accurate vertical temperatures at type localities. These will no doubt in part be supplied by the future reports of the recent British Expedition under Captain R. F. Scott.

CHAPTER II

DYNAMIC GEOLOGY

PART I. METEOROLOGICAL NOTES, WITH SPECIAL REFERENCE TO TEMPERATURE, SNOWFALL, AND ABLATION

Temperature. The close coincidence of the Temperature Pole with the Geographic Pole in Antarctica obviously constitutes ideal conditions for an immense permanent anticyclone if the land had been of low altitude, but, as Dr. W. N. Shaw has recently pointed out to us, the problem is much complicated by the rock and ice dome of the Antarctic taking the place of so much of what otherwise would have been the lower part of this anticyclone. The steep grade in temperature between land and water, often as much as 30° or 40° Fahr. within a mile back from the coast, combined with the vast amount of open sea in which the continent is placed, and the comparatively steep downgrade from the centre of the land to the coast, contribute to make the Antarctic the home of winds of a violence and persistence without precedent in any other part of the world. A continent of the shape, relief, and situation of Antarctica must always dominate local weather conditions. For example, it can scarcely be possible for weather conditions on the coast of one side of such a continent to travel across its altitude of upwards of 10,000 feet and descend on the other side. Such a movement would probably be possible only where the continent is very narrow, as at the "stalk of the pear" in the American sector of Antarctica. Since the discovery by Amundsen of the remarkably low temperature area south of the Bay of Whales, on the Ross Barrier, where the mean temperature in August 1911 was $-44{\cdot}5°$ C. ($-48{\cdot}1°$ F.), the suggestion by him that there may be at least two temperature poles (Cold-Poles) in Antarctica seems very plausible. In the Northern Hemisphere there are two such poles, one almost identical with the North Pole, the other near Verkhoyansk in Siberia. Amundsen's Cold-Pole on the Ross Barrier is obviously to be correlated with the calm state of the atmosphere in that region, a fact in turn dependent on the absence of high mountain ranges in the eastern region adjacent to Ross Sea. The Antarctic Horst, 10,000 to 15,000 feet high, is a powerful disturbing factor on the west side of Ross Sea. The high winds generated largely by it lead to a rapid interchange of air between the South Pole and warmer latitudes, and so tend to raise temperatures.

The table of temperatures given below is for our winter quarters at Cape Royds, for the *Discovery* winter quarters at Hut Point, and Borchgrevink's winter quarters at Cape Adare. Cape Royds was badly situated for obtaining accurate records of Antarctic temperatures on account of its close proximity to open water. For some reason which we were unable to determine there was a strip of open water in the middle of McMurdo Sound late into the winter, and it persisted through September and October into the summer. At times, especially after blizzards, this open water would extend close up to Cape Royds, and would, of course, raise the temperatures at those seasons of the year, as the surface temperature of the water was, of course, not below 28° Fahr., and therefore far above that of the adjacent coast, which was below zero from April to September inclusive. The same cause no doubt contributed to make the snowfall at Cape Royds abnormally high for that latitude.

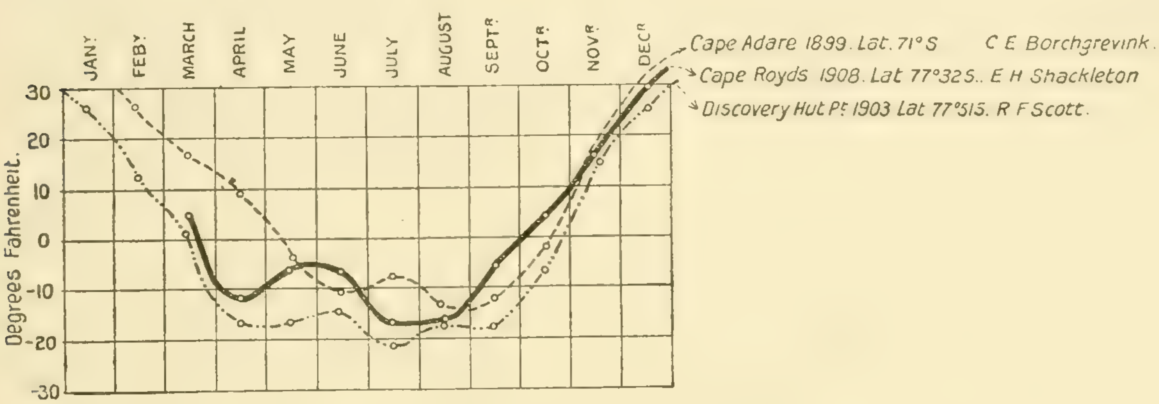


FIG. 3. · TEMPERATURE CURVES

These curves have been constructed from the figures given by Dr. H. R. Mill in his article on the Polar Regions in the "Encyclopædia Britannica," vol. 21.

These Tables, shown as curves, suggest the following interesting results :

Hut Point, although only about 24 miles southerly from Cape Royds, is much colder than the latter in early winter, when the former is some 25 miles distant from open water, whereas the latter is seldom more than about 10 miles from it, and frequently after blizzards within a mile of it. In August it will be seen that the curves for Hut Point and Cape Royds nearly touch one another. By this time, and for some little time previous, the whole of McMurdo Sound, with the exception perhaps of a very narrow strip near the centre, appeared to be frozen over. In September the ice began to break away from McMurdo Sound, exposing a relatively warm sea surface to within a mile of our winter quarters ; and it will be noticed that the temperatures at Cape Royds at once rose considerably above those of Hut Point. By November and early December, at which time a large proportion of McMurdo Sound is ice-free, the temperatures again approached one another nearly. The fact must be borne in mind that these figures are for different years, the *Discovery* for

1903, and the Cape Royds for 1908; but the figures for the *Discovery* observations at Hut Point for 1902 show similar features.

The lowest temperature we recorded was − 59° F. on the Great Ice Barrier late in September 1908. On August 15 of the same year on the Barrier, at a point about 10 miles S. of Cape Armytage, the thermometer registered − 57° F.

Vertical Distribution of Atmospheric Temperature. Of great interest geologically and meteorologically from the point of view of the origin of snow in the Antarctic, is the distribution of temperature vertically and horizontally. This matter is discussed in some detail in the meteorological report of the Expedition, so a brief summary will suffice here.

As regards vertical distribution, we obtained three pieces of evidence. Temperatures taken (1) on the ascent of Mount Erebus, (2) on the journey furthest south, (3) on the journey to the Magnetic Pole area. All three journeys, especially the two

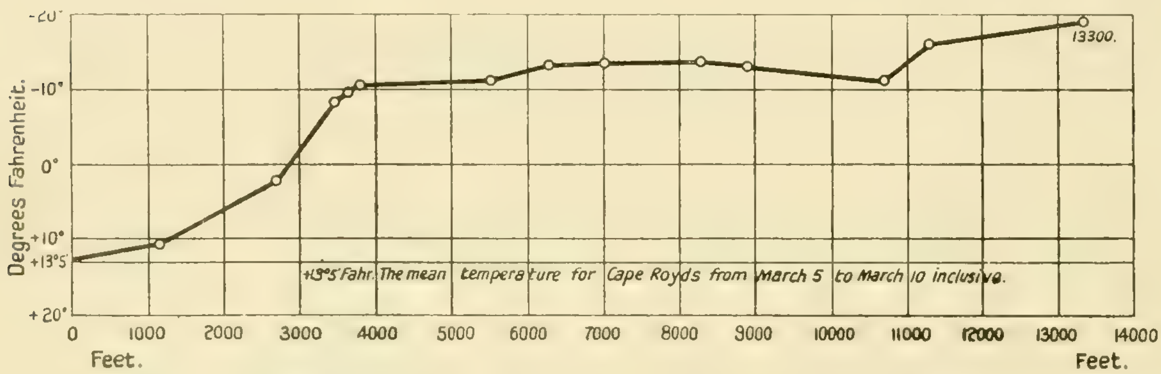


Fig. 4. TEMPERATURE CURVE ON ASCENT OF MOUNT EREBUS
March 5 to March 10, 1908.

last, give some information as to the horizontal distribution of temperature. For vertical distribution the Erebus observations are obviously the most important, for Erebus, rising steeply as a huge isolated cone to over 13,000 feet above sea level, probably does not seriously disturb the circulation of the upper atmosphere by the upward deflection that is occasioned by the edge of a high continent or the mass of a large mountain range.

The curve shown in the figure is, as stated, only a rough approximation. There may be an error in places of as much as 3° or 4° F., but the main fact is brought out conspicuously that there is a very steep gradient of temperature showing a fall of about 1° F. per 150 feet, from sea level up to about 3500 feet, and from that altitude up to 13,300 feet the fall is only about 1° F. per 1000 feet. The extra steep fall from 3500 feet to sea level is no doubt due in part to the proximity of the relatively warm water of McMurdo Sound, for the Sound was only just beginning to freeze over when we ascended Erebus; partly it may be due to the settling down of the cold air from the upper part of the great cone of Erebus to its base at about 7000 feet above sea level, and spreading thence downwards over the snow-covered lava sheets to a level of about 3500 feet. Such tendencies to inversion of temperature as one ascends mountains are of course common at the beginning of and during winter, serving to emphasize the fact that during winter the earth's atmosphere cools from the base upwards, and not from above downwards. These conditions obviously tended to unduly raise the snowfall near Cape Royds, where the warm air from off the sea met the cold air descending from Erebus. The average fall of atmospheric temperature from sea level to the top of Erebus is about 1° F. per 400 feet, which is not very different from the gradient in temperate latitudes, though of course the grade is less steep. It is suggested that the lessening in the rate of fall of temperature may have been due in part to the strong N.W. air current which swings, during a blizzard, into a N. and S. direction. This must have been blowing for some time over the top of Erebus during the furious blizzard of March 8, the day before we reached the crater. Such a high-level wind blowing from northern latitudes would of course be warmer than the normal W.S.W. wind which sweeps from off the continental plateau over Erebus. As regards the evidence of vertical distribution of temperature obtained on the journey of the Northern party to the Magnetic Pole area data are wanting for accurate comparison, on account of our distance from the base at Cape Royds, where the check temperatures were taken (about 400 miles at the maximum limit). Thus we can form only a rough idea from the temperatures at our base at Cape Royds what the temperatures at sea level on our route were likely to have been.*

In considering the distribution of temperature on the Magnetic Pole Plateau one must remember, that in advancing from the coast inland one has first to cross the block mountains of the coastal horst, and in these mountains, in summer time, a considerable amount of dark rock is exposed to the sun and absorbs its heat rays. At the back of this horst the plateau rises in a distance of about 180 miles to about 7350 feet above sea level. On account of the difference in specific heat between land and water, together with the absence of convection currents in the rock material of the land,† there is a considerable difference, in summer time, between the temperature of the sea water, and that of the rocks of the adjacent horst. Hence the air over the horst, by day especially, becomes warmer than the air over Ross Sea. The difference in specific heat between ice and water would have the same effect.

* The temperature obtained by Bernacchi for Cape Adare, at sea level, at 330 miles N.N.E. of Mount Nansen, are for another year (1903–4), but give one some idea as to what increase of temperature to adopt on our base temperatures at Cape Royds. We also have our own observations on the sea ice for over 200 miles N. of Cape Royds, 1908–9, as a check, as well as the temperatures taken by the *Nimrod* on her second outward voyage through Ross Sea. During part of this time she was locked in the ice-pack at the time that we were ascending the Magnetic Pole Plateau.

† The *specific* heat of water at 15° C. being taken as 1·000, the specific heat of granite, of which most of the exposed rocks of the plateau are composed, may be taken as ·192 at 12 – 100° C. ("Smithsonian Physical Tables," pp. 229–231.)

The specific heat of sea water having a sp. gr. of 1·0043 at 175° C. being taken as ·980, that of ice may be taken as follows:

− 18°	to	− 78° C.	·463
− 78°	,,	− 188° C.	·285
− 188°	,,	− 252° C.	·146 *

This appears to be an extremely important point in connexion with the wind circulation on the Magnetic Pole Plateau, and one which has not yet been properly emphasized in glaciological works. In other words, ice would heat up under the sun's rays, at the prevalent Antarctic temperatures, at about twice the rate of sea water, and in the greater cold of winter, so long as it was exposed to the sun, at a considerably increased rate. This would, of course, tend to raise air temperatures by day over the plateau, and so check the plateau wind which springs up so regularly during the night. As soon as the increasing heat of the sun towards noon had sufficiently warmed the snow to make the temperature of the air in contact with it approximate to that of the air over the water of Ross Sea, the plateau wind ceased.

At night the snow of the plateau parted readily with its heat, and the air above it became chilled and heavy, and commenced to flow seawards as the plateau wind. Hence the much greater daily range of temperature on the plateau than alongside of the open waters of Ross Sea.

At Cape Royds in December the daily range in temperature was about 5° Fahr. At the Drygalski Ice Barrier close to the open water at Relief Inlet the temperature was even more constant between night and day when neither the plateau wind nor the blizzard winds were blowing. On the plateau, the daily range of temperature during the end of December and January was of the order of about 20° Fahr.†

The specific heat of basalt at 12° − 100° C. is ·1996, as compared with that of ice at − 18° to − 78° C. of ·463. It is possible that, to a less extent of course, a similar phenomenon takes place with snow crystals on the plateau. Ice does not readily thaw in the sun's rays when the temperature of the air is below freezing-point on account of the relatively rapid conduction of ice, cold from the lower layers of ice being quickly transferred to its upper surface when slow convection currents are set

* "Smithsonian Physical Tables," p. 230.

† We had no minimum thermometer with us on our journey over the Magnetic Plateau. The small spirit minimum thermometer did not work satisfactorily. Hence there are no records of the temperatures between 11 P.M. and about 5 A.M., so the above figure is only approximate. At the same time the figures are the average of a considerable number of daily readings with a sling thermometer, and so are fairly reliable. This comparatively low specific heat of ice also suggests a reason for the rapid sublimation of the snow, and possibly for even a slight thawing below its surface, in the direct rays of the sun on the plateau, at a time when the general air temperature was far below thaw point. On the slopes of Erebus at about 9000 feet above sea level, on March 10, 1908, when the shade temperature was about 0° Fahr., the black rocks were quite warm to the touch, and the snow around them was melting rapidly.

up by a warming of the ice surface by the sun's rays. Snow crystals, however, are separated by non-conducting air gaps from the cold snow crystals below, and thus the heat rays of the sun are free to deal with each snow-flake, as a separate unit, and may melt it, and allow it to re-crystallise in the form which Dr. Mawson likened to anthracene. On January 6, 1909, the surface of the snow seemed softened as we sledged over it on the plateau at an altitude of over 7000 feet, when the temperature at its highest was only about 5° Fahr. On January 14, 1909, when the sun's rays made themselves strongly felt, the snow surface was carpeted with a dazzling sheet, about half an inch in thickness, of these "anthracene" ice crystals. They were each about half an inch in width, and about $\frac{1}{16}$ of an inch in thickness.*

In the ablation of the snow surface of the plateau the snow may thus disappear partly as water vapour, partly as ice vapour, if, as seems possible, the snow surface for the depth of half an inch or so can actually thaw while the shade temperature of the air, except where actually in contact with the snow, is below freezing-point.

Another interesting result from the difference in specific heat between rock and ice is that blocks of rock in the Antarctic, where the amount of insolation, during the months of the midnight sun, is very great, have a much more marked tendency to countersink themselves into the glacier ice than is the case with morainic blocks on the glaciers of the Swiss Alps. In fact, soon after leaving the last source of rock supply, these Antarctic moraines have so far sunk themselves below the surface of the glacier that they completely disappear, becoming englacial moraine.

Very low temperatures were experienced by Shackleton's party on the King Edward VII. Plateau, during a great blizzard which commenced on January 6, 1909. The wind at first was S.S.W., the temperature at noon being − 25° F. at latitude 88° 7′ S., longitude 162° E., altitude about 9837 feet. The next day the wind was blowing very hard from the S.S.E., with squalls of terrific force. The temperature at noon was − 33° F. On January 8, the wind hauled to the S.E., and blew harder than ever, with hurricane force. The noon temperature was − 40° F. This blizzard gradually slackened in the early morning of January 9.

It is interesting to note that in the case of this blizzard there was no Föhn effect. In fact the temperature fell a good deal below what appears to have been normal at that time of year for that locality, the normal temperature at noon being assumed to be about − 20° F. (− 28·8° C.).

In regard to rise of temperature with blizzard winds we experienced rises of temperature towards the end of a blizzard of as much as, in extreme cases, 42° to

* That snow may melt when the general air temperature is probably considerably below thaw point is suggested by Amundsen's observation of icicles at Christmas 1911, hanging from his snow beacons at The Butchery "Dog Depot," at an altitude of 10,000 feet above the sea and near lat. 86° S. It is highly improbable in view of the temperatures registered there by Amundsen, that there is ever a true thaw due to air temperature rising above freezing-point. An alternative explanation of the anthracene-like ice crystals, so common on the plateau after days of strong sunlight, is that they were formed during the succeeding night as the result of the condensation of ice vapour due to sublimation.

45° F. (23·3° C. to 25° C.) the temperature in one case rising, at Cape Royds from − 30° F. to 15° F. (− 34° C. to − 8° C.). While there are obvious reasons for believing that some of this rise of temperature is due to Föhn effect, and caused by the compression of air diving from a height on to the South Pole Plateau, and thence diving again on to the Ross Barrier, we consider that the Föhn effect is not by any means responsible for it all, but that the rise of temperature, as Commander Hepworth has suggested,* is due in a great measure to the rapid transfer of warm air at a high level in the Antarctic cyclone to replace the air that is lost during a blizzard originating near the Temperature Pole.

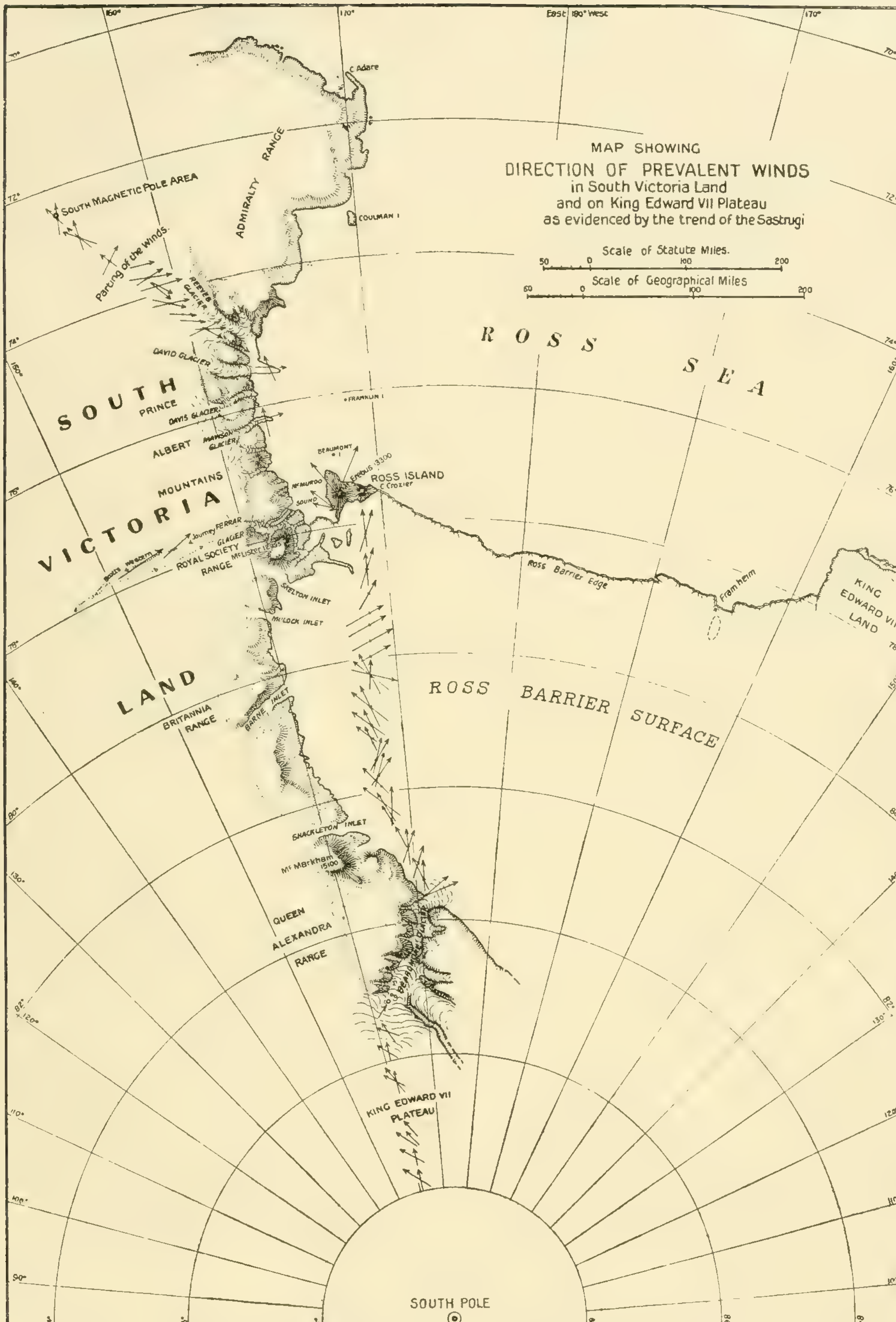
Finally in regard to the temperature of the Antarctic Regions as compared with the Arctic, the following explanations of well-known facts, though obvious, have not, as far as we are aware, found their way into text-books, so that we may venture to quote them here.

Antarctica differs from the Arctic chiefly in the lowness of the Antarctic summer temperature, and the lesser cold of Antarctica as compared with the Arctic in their respective winters. According to Hann's figures the mean winter temperature at the North Pole in January is − 41·8° F., whereas in the corresponding winter month, July, in the Southern Hemisphere the mean temperature is about − 28° F.† This greater winter cold in the Arctic as compared with the Antarctic is surely due chiefly to the geographical differences between the North and South Poles respectively. In winter not only is the whole of the Arctic Ocean frozen over, but the isotherm of freezing is down to a mean position in January of about 48° N. lat. In the month of July in the Southern Hemisphere the mean isotherm of freezing is situated in about 55° S. lat. This gives an area below freezing in the month of January in the Northern Hemisphere half as much again as that at a similar temperature during the winter of the Southern Hemisphere. Thus there is a mass action tending to increase cold in the Northern as compared with the Southern Hemisphere winter. The cold is further increased in the Northern Hemisphere by the surface relief, which is the very opposite in the two hemispheres. In the Southern Hemisphere the normal curve of the earth spheroid is bulged outwards into a huge dome which acts at once as a gigantic starter of convection currents, and so leads to a rapid interchange of air between the Temperature Pole and warmer regions; on the other hand, the Arctic Ocean is encircled by land much of which being fairly high acts as a wall of circumvallation to retain the cold air at the North Pole during winter, and by keeping it from moving checks convection currents, and stops access of warmer air from the south. On the other hand, in Antarctica, even in the depth of winter, no part of the continent is more than 1000 miles distant from

* "National Antarctic Expedition," 1901–4. "Meteorology," part i. p. 449.

† We have now the information that Amundsen found the mean temperature, for August 1911, at the edge of the Ross Barrier, in the Bay of Whales, at Framheim no less than − 48·1° F. (− 44·5° C.). This may modify the above argument in so far as relates to winter temperatures in Antarctica.

PLATE VI



MAP SHOWING
DIRECTION OF PREVALENT WINDS
in South Victoria Land
and on King Edward VII Plateau
as evidenced by the trend of the Sastrugi
Scale of Statute Miles.
Scale of Geographical Miles
ROSS SEA
SOUTH VICTORIA LAND
SOUTH MAGNETIC POLE AREA
Parting of the Winds
ADMIRALTY RANGE
C. Adare
COULMAN I.
DAVID GLACIER
PRINCE ALBERT MOUNTAINS
DAVIS GLACIER
MAWSON GLACIER
FRANKLIN I.
BEAUMONT I.
ROSS ISLAND
C. Crozier
McMURDO SOUND
FERRAR GLACIER
ROYAL SOCIETY RANGE
SKELTON INLET
MULOCK INLET
BRITANNIA RANGE
BARNE INLET
Ross Barrier Edge
Framheim
KING EDWARD VII LAND
ROSS BARRIER SURFACE
SHACKLETON INLET
Mt. Markham 15100
QUEEN ALEXANDRA RANGE
KING EDWARD VII PLATEAU
SOUTH POLE

the nearest open sea, the temperature of which cannot be below 28° F. The steep isotherm grade in Antarctica, combined with the quaquaversal slope of the land seawards from the Southern Temperature Pole all tend to further accelerate convection currents, and so promote advection of relatively warm air in winter, except in flat areas like Framheim and the Ross Barrier to the south, remote from mountains or plateaux. In summer the ice of the Arctic Ocean breaks up, and wide lanes of open water penetrate to the North Pole itself, and this open water breathes warmth into the surrounding air. Moreover the permanent surface cyclone of summer is constantly carrying in warmth to the North Pole at that season. On the other hand during the Antarctic summer the high gently domed land-mass, capped by a permanent anticyclone, blows cold air outwards spiralling seawards, and keeping down the temperature along its coasts to near freezing-point, and according to Meinardus and Hann, making the temperature at the South Pole, reduced to sea level, about 21·2° F. (− 6·5° C.) for the month of January.*

Such geographical differences appear to offer a partial, if not a complete, explanation of the existence of such different temperatures on the same parallels of latitude, as have been recorded from the Arctic and the Antarctic respectively. The matter is thus referred to by Dr. H. R. Mill: †

"Even in the South Orkneys, in latitude 60°, in the three warmest months, the air scarcely rises above the freezing-point as an average, while in Shetland (60° N.) the temperature of the summer months averages 54° F. But, on the other hand, the warmest month of the year even in 77° S. has had a mean temperature as high as 30°."

Prevalent Winds. The accompanying map (Plate VI.) shows the direction of all the principal sastrugi—hard snow ridges separated from one another by furrows torn out of the hard snow by the fury of the blizzards.

From the south end of Ross Island as far as 88° S., the information was obtained by Lieutenant Adams; while those from Mount Erebus, to the South Magnetic Pole Area, were obtained by our Northern party. The sastrugi directions on the plateau west of the Royal Society Range are taken from the description in Captain R. F. Scott's "Voyage of the *Discovery*." The importance, in control of surface wind directions, of distribution of land and water, and the relief of the land is at once apparent from this map.

The sastrugi from 88° S. on the King Edward VII. Plateau, northwards as far as 80° 30′, come from between S. and S.E., modified by the presence of the outlet glaciers, such as Beardmore Glacier, and the glaciers of Shackleton Inlet. Again from south of Minna Bluff, northwards to the Drygalski Ice Barrier Tongue, the general trend of the sastrugi is on the whole northerly.

* It seems doubtful in view of the temperatures obtained by Shackleton near the South Pole, and Amundsen at the South Pole itself, whether 21·2° F. is not too high a figure for the mean temperature, reduced to sea level, of the South Pole in January. Possibly about 12° F. is a closer approximation.

† The "Encyclopædia Britannica," 11th edition, vol. xxi. p. 970.

So far the winds follow the direction which they might be expected to take on the theory of streams of heavy cold air blowing spirally outwards down the slope of the inland ice from the summit of the main "ice divide."

The normal direction for such winds should, theoretically, in the latitude and neighbourhood of Ross Sea be from S.E. to N.W. or E.S.E. to W.N.W. There are four notable exceptions:

First, the easterly winds at Framheim. A disturbing factor in the simple anticyclonic circulation is the warm gulf of Ross Sea, in considerable areas of which water is open throughout the year.

This gulf encourages the further westerly deflection of the northerly moving air masses coming from off the land to the east of Ross Sea, and bends them around into easterly winds.*

The next departure from the prevalent direction is in the case of the winds which blow out of Barne Inlet and Mulock Inlet on the west side of the Ross Barrier. These winds have a general W.S.W. to E.N.E. direction.

They owe their direction probably to three factors:

(1) A sag in the horst before it reaches that "horst within a horst" the Royal Society Range. This allows the cold air of the plateau near the Britannia Range, dammed against the high bluffs and bastions of Mount Huggins, to spill over this sill in the horst, and stream into the low-pressure area of Ross Sea. This sag is further accentuated by deep inlets, the Barne and Mulock Inlets.

(2) The steep isobaric as well as isothermal grade towards Ross Sea.

(3) The general northerly movement of the Antarctic surface air from the Temperature Pole of the inland plateau.

The next exception to the general rule is that of the plateau winds west of the Royal Society Range. These blow to E. by N., or E.N.E. into Ross Sea. Apparently they are in part responsible for the deflection of the steam column of Mount Erebus, which usually spreads away in an E. by N. to E.N.E. direction. The cold air from this plateau appears to flow down into Ross Sea, following the steepest grade which is also the shortest route to base level. Along the coast, from McMurdo Sound to the Reeves Glacier near Mount Nansen, the blizzard winds have a S. to N. direction, blowing parallel to the steep western fault scarps of the great meridional horst.

These blizzard sastrugi are crossed, opposite each of the outlet glaciers, by strong sastrugi trending nearly W. to E. and marking the direction of the plateau wind when it sweeps, often with hurricane force, through the portals of the glaciers of the western mountains down on to Ross Sea.

The fourth exception, and a very remarkable one, is that of the winds between the coast near the Drygalski Barrier and the parting of the winds on the Magnetic Pole Plateau.

* Amundsen gives the following percentage of his total number of wind observations: N. 1·9; N.E. 7·8; E. 31·9; S.E. 6·9; S. 12·3; S.W. 14·3; W. 2·6; N.W. 1·1; Calm, 21·3.

These blow usually from about W.N.W. to E.S.E. Again, as in the case of the winds on the Barrier near Barne Inlet and Mulock Inlet, they owe their origin to the stemming action of the high portion of the Antarctic Horst known as the Admiralty Range. As shown on Plate V., the horst, as one passes from Mount Larsen (5000 feet), across the Reeves Glacier to Mount Nansen, jumps up suddenly in level from 5000 to over 8000 feet. Cold air flowing down the southerly slopes of this range overlooking the Reeves Glacier deflects the eastward-moving air masses flowing down to Ross Sea. These plateau winds in winter time must be of hurricane force, as they have torn out immense sastrugi in the hard snow of the Drygalski Barrier.

Along the belt of inland firnfeld marked "parting of the winds" on Plate VI. we found loose powdery snow devoid of sastrugi. This was the highest point on the

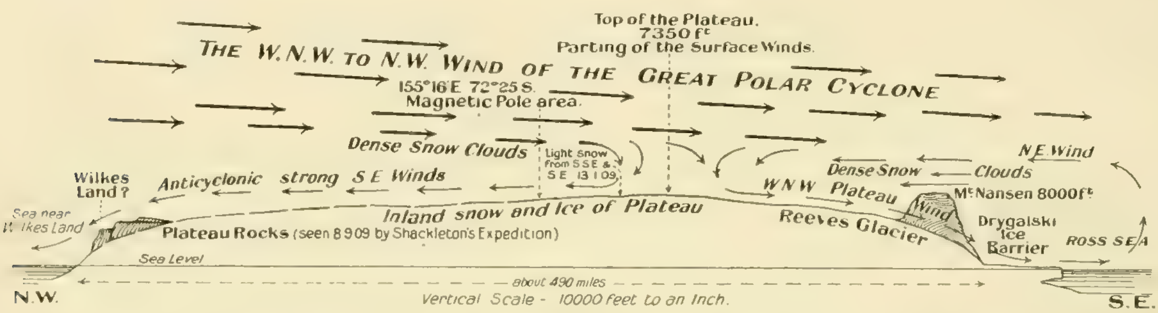


FIG. 5. SECTION ACROSS THE SOUTH MAGNETIC POLE PLATEAU

Showing the parting of the surface winds on the plateau, and the probable nature of the atmospheric circulation and snow supply

plateau on our line of traverse. It was 7350 feet above sea level. From thence, for 80 miles, to our furthest point N.W. the winds completely changed in direction, and blew chiefly in two directions forming two very definite and distinct types of sastrugi.

The wind blowing from S. by E., or S.S.E., was evidently the normal anticyclonic blizzard wind blowing with great violence and ripping up the surface of the hard snow into sharp-edged sastrugi, three to four feet high. These were crossed by what we call ramp* sastrugi, as, being flat-topped, they formed miniature inclined planes, placed at an oblique angle to the other sastrugi, and so enabling us to sledge over what would otherwise have proved to be almost impassable snow ridges and furrows.†

The foregoing figure (5) illustrates our view of the winds of the Magnetic Pole Plateau and the part they play in supplying snow to the plateau.

* Ramp in a fort is defined as a road cut obliquely into, or added to, the interior slope of the rampart.

† These ramp sastrugi seemed to us to be formed by the blizzard winds, as they slackened off, always hauling around to the east. As it swung around it gradually built these ramp sastrugi, which became flat-topped owing to the progressive swing of the wind direction from south to south-east.

There are perhaps at least three possible sources of snow supply to the Ross Sea region of Antarctica.

(1) Surface northerly to north-easterly or north-westerly winds sucked inland by the differential heating of the rocks of the Antarctic Horst and the adjacent snow-fields on the one hand as compared with the water of Ross Sea on the other. These may possibly be local extensions southwards of large cyclonic disturbances having their centres perhaps north of Ross Sea.

(2) Local "endless belts" of air travelling seawards at night as a land breeze, and returning as a high-level (sometimes as a low-level) sea breeze during the day. These are illustrated on Fig. 5.

(3) The great Antarctic high-level cylone overlying the permanent anticyclone. Some have doubted the existence of this cyclone, but from the fact that whenever there was an extra powerful eruption of Erebus, so that its steam cloud was carried to an altitude of about 20,000 feet, we invariably noticed that it was caught by a powerful W.N.W. or N.W. current, we are inclined to believe that this huge permanent cyclone really exists. It is to this source that the eminent Austrian meteorologist Dr. Julius Hann would refer most of the snow that falls far inland in Antarctica, following in this respect the German meteorologist Meinardus, whose fine memoir has shed so much light on atmospheric circulation in Antarctica. Hann quotes Meinardus * to this general effect:

"These considerations will also do away with the difficulty of explaining the ice masses radiating away from the Antarctic Continent, for the centre of a great fixed anticyclone is not only poor in snowfall, but is rather a place of increased evaporation; it is a region for starvation, not for alimentation of ice and glaciers.

"But if cyclonic westerly winds extend into the higher altitudes of the Antarctic Continent, provision is made for the conveyance of vapour and for precipitation. Thus precipitation will not be wanting even in the interior of Antarctica."

Professor Hobbs in his "Characteristics of Existing Glaciers" has followed Hann's views.

We know very little about snowfall on the inland ice of Antarctica during the winter, but know something about the supply in summer.

Snowfall. We may commence with the Magnetic Pole Plateau. As regards source of snow supply to this plateau, it is obvious that the prevalent winds depend, in part, for their direction upon the slope of the ground. The summit of the plateau has been termed on the map "the parting of the winds," and possibly it has actually in part been formed by the action of the winds. If the western winds perform more erosive work than the south-eastern upon equal quantities of annual snowfall, the divide will migrate westwards. If the reverse is the case, the divide will migrate south-eastwards. There can be no doubt that the original fall of the rocky plateau divided the position of the parting of movement of the inland snow and

* "Handbuch der Klimatologie," von Prof. Dr. J. Hann. Vol. iii. p. 689.

ice-fields in the first case, but after that the position of the surface divide would depend in part on the relative waste and supply effected by the prevalent winds.

Near the Magnetic Polar area the great size of the sastrugi indicate winds of great violence. These probably blow most strongly in the winter time, or in late autumn and early spring, when the atmospheric gradient between the extra cold land and the still open sea would be steepest.

Reference has already been made to the prevalence of the plateau wind, which is a land breeze on a large scale at night-time. When marching along the coast in October, November, and December of 1908, we found that the plateau wind reached the coast between about 8 P.M. and 10 P.M. and would go on blowing until about between 9 A.M. and 10 A.M. the following morning. It would usually freshen a little after midnight. Its usual speed appeared to be 12 to 15 miles an hour, scarcely sufficient to raise any drift snow, but with just sufficient speed to "sweep the carpet," that is, drive the snow before it in a thin moving layer an inch or two deep over the surface of the sea ice. The immense sastrugi at the Drygalski Glacier show that towards winter the winds must blow from off the plateau with great fury, as already stated.

It would seem as though the Ross Sea was the chief centre of low pressure. This would be due, of course, to its relatively warm water surface which is lightening the air above it, partly by warming, partly by supplying aqueous vapour to it. The cold airs to the south of Ross Sea rush into it from the south or south-east. The cold airs of the plateau stream into it from the west. It will thus be seen that the surface winds on the Magnetic Pole Plateau tend to blow radially outwards from the highest part of the plateau towards the sea, and at first sight do not seem likely to be bringers of snow.

Whence then come the snows which feed the plateau? On December 27, from our position on the inland side of Mount Larsen, cumulus and alto-cumulus could be seen drifting inland from N.N.E. off the Ross Sea towards the S.S.W., and at a still higher level the clouds were drifting inland from the N.E.

Later on the same day, great rolls of alto-stratus could be seen drifting N.W. to about S.E. The rolls were strongly bent with their convexities directed towards the S.E. to E.S.E., as though they were being pushed over in this direction by a strong N.W. upper current. At Erebus, the normal downward limit of this current, which appeared very steady and constant there, was about 15,000 feet above sea level.

Some additional light may be thrown on the snow supply of the Magnetic Pole Plateau, if we consider the conditions on the plateau west of the Ferrar Glacier. Here most of the snow which fell in November, according to Scott, came from a general S.W. by W. direction. On December 9, 1903, on the same plateau Scott records that there was evidence of a recent snowfall earlier that December, and that this December snowfall is far heavier on the edge than in the interior of the continent. He also states that the wind there in its most southerly direction brought a desirable increase of temperature, and on some days they had a fair imitation of the mild southerly blizzards which were such a conspicuous feature at the ship (*i.e.* at Hut Point, S. end of Ross Island.—AUTHORS).

These observations suggest two possible sources of snow supply for the plateau W. of the Ferrar Glacier :

(1) Moisture-laden air which has worked inland at a high level off the Ross Sea.

The chilling of the air on the high plateau from below upwards makes the layers of air next the plateau surface denser than before, but in so doing necessarily withdraws material from the air above, and, consequently, sooner or later a height will be arrived at in the atmosphere overlying the plateau where the pressure is lower than it is for air at a corresponding altitude over the Ross Sea. Thus, while a surface air current, "the plateau wind," blows down towards the sea and sweeps over Erebus in a current about 9000 to 10,000 feet deep between altitudes of 6000 feet and 15,000 feet, at a still higher altitude air will flow in to fill up the low pressure at high levels above the plateau. The air to replenish the cold masses which are continually gliding off the plateau can only be derived from the sea, and thus moisture, in other words, snow, is conveyed inland by what may be termed a high-level sea breeze. This movement of the atmosphere, of such importance for considering snow supply in the Antarctic, is illustrated in Plate VI.

The main source of supply of the moisture to the "high-level" sea breeze in the Antarctic is, of course, the Southern Ocean lying north of the main boundary of the continent.

The main high-level sea breeze probably flows towards the "Temperature Pole" (near the South Geographic Pole) in a grand high-level cyclone overlying the cold air masses which spiral out fitfully from the "Temperature Pole." But Ross Sea, when open, sets up a secondary high-level anticyclonic area with its "low" situated over the plateau. Air flowing in from over Ross Sea towards the Magnetic Pole Plateau would have the trend of its current governed by the nearest areas of lower pressure in this upper atmosphere, and the lowest pressure at *high* atmospheric levels lies over the coldest land. On the Magnetic Pole Plateau the land is colder the further one proceeds south towards the "Temperature Pole." Hence in this part of the Antarctic, near the west shore of Ross Sea, where the local high-level secondary cyclone perhaps dominates the main cyclone, one would expect the trend of the landward inflowing high-level air currents to assume a general N.E. to S.W. direction. This was the observed direction of the inflowing high-level air currents near the coast side of the Magnetic Pole Plateau on December 27.*

* On December 28, 1908, the weather was calm but very thick. At the surface of the plateau, later the same day, it was observed that a breeze from off the Ross Sea covered the top of Mount Nansen with cloud, but further inland this high-level breeze off the sea was deflected by the high-level N.W. air currents blowing from the South Ocean. Snow seemed to be falling heavily this day over the great horst to our east. We were at the time 20 miles west of the western side of the horst, and 50 miles distant from

We may return to the subject of the winds of the Magnetic Pole Plateau and the snow supply. It would appear that little snow falls on the centre of the plateau in summer time. During the five weeks that we were on the plateau, from December 25 to January 30, probably not more than one quarter of an inch of snow fell. The winds and their relation to snow supply on the Antarctic Plateau of the South Magnetic Pole Region may be summed up, very tentatively, as follows:

1. Anticyclonic winds, surface winds, mostly dry and cold, of two types:
   (*a*) The local surface plateau wind which parts at the summit of the Magnetic Pole Plateau into two air currents:
      (i) The W. by N. current blowing into Ross Sea. This is mostly a cold dry wind which does not produce snow on the plateau, but acts as a condenser and snow producer along the coast, where it meets the relatively warm, moist air over Ross Sea.
      (ii) The S. to S.E. plateau wind blowing from off the summit of the plateau towards the Southern Ocean in the direction of Adélie Land. This brought a little snow with it, and probably represented the high-level N.W. cyclonic current which had dived as it became chilled inland, and then, after reaching the surface, became reversed.
   (*b*) The blizzard wind which forms part of a larger intermittent atmospheric circulation blowing spirally outwards from the "Temperature Pole," or poles. Whereas on the west coast of Ross Sea the direction of the blizzard is nearly N. and S., on the edge of the plateau nearest the great horst it is about W. 30 S. This, it may be pointed out, agrees with Scott's observation as to the direction of the blizzard wind on the plateau at the back of the Ferrar Glacier, viz. that it had more southing in it than the normal plateau wind. Although we experienced a plateau wind of the violence of a mild blizzard (about 25 miles an hour) on January 8, 1909, we did not encounter any violent blizzards at all on the Magnetic Pole Plateau on our journey between Dec. 24, 1908, and Jan. 30, 1909.
2. Cyclonic winds:
   (*a*) The local high level N.E. air current from off Ross Sea. This carries

open water. Later the same day immense cloud pillars covered the top of Mount Larsen. On January 4, 1909, rolled cumulus spread fast over the Magnetic Pole Plateau coming from the N.W. towards the S.E., that is from the direction of the Southern Ocean near Adélie Land. This was over 100 miles inland from the Ross Sea.

On January 5, 110 miles inland, the sky except to the S. and S.E., was thickly overcast with snow-clouds. The air at the surface was calm. These dense snow-clouds had evidently come in from the N.W., but, as this day was comparatively warm, they may have been added to by vapour derived from the sublimation of the snow surface of the plateau. On January 8 we experienced a blizzard with much low drift. It was of a mild order, and slackened towards evening. We have no record of fresh snow falling on this occasion—apparently the drift snow was all old snow, but this is not certain. This was 140 miles inland.

snow-clouds in December and January for some distance inland. Probably when this system is accelerated, as it would be in autumn and winter, it may bring a great deal of snow to the eastern part of this plateau.

(*b*) Cyclonic surface winds, portions of large cyclones N. of Ross Sea.

(*c*) The N.W. high-level wind. This is part of a vast circulation. As already stated, we observed it frequently rolling in great masses of snow-cloud as alto-cumulus, alto-stratus, and on one occasion apparently cumulus, from the N.W. This great air current is the one which supplies the "Temperature Pole" with air to replenish the supplies which have flowed away from it down-hill as blizzard winds, modified in places by local conditions of the physiographic relief of the plateau.

There can be no doubt that when accelerated during spring or autumn, when the surface of the plateau is colder than on the occasion of our visit, it must bring quantities of snow with it to feed the inland Magnetic Pole Plateau, and even to take with it, as delicate ice needles, to the "Temperature Pole."

Thus the activity of great glaciers like the Reeves, Larsen, and David is probably due to this efficient double snowfall, the snow being partly derived from the northern part of Ross Sea, partly from the Southern Ocean, near Adélie Land.

We may now glance briefly at the snow supplies of the King Edward VII. Plateau and the region near the South Pole itself. Scott and Amundsen have recorded that at the South Pole itself the snow is soft to a great depth, so that a tent pole could be thrust six feet into it, and in doing this no evidence whatever of any stratification was detected. Evidently, therefore, there is no very considerable sublimation and no thawing taking place at the South Pole, and on the whole the area cannot be much disturbed by winds. It appears to be the eye of the great anticyclone. Thin hazes, described as "a light fine vaporous curtain," kept coming and going while Amundsen was at the South Pole from December 14–17.*

Possibly these mists or hazes of ice crystals were derived from vapour sublimed from the surrounding snowfields, though, of course, it is equally possible that it may have been transported by the high-level cyclone all the way from the Southern Ocean.

It is of great interest to note that from 80° S. to 88° S. Amundsen met with new falling snow *derived from surface winds.*

On November 27, 1911, just S. of 86° S. he encountered mist and snowfall, followed by dense fog and fine falling snow on November 28, the fog being described as "as thick as gruel." From November 29 to December 3, a strong S.E. blizzard brought new-falling snow in lat. 86° 47′ S.

* "The South Pole," vol. ii. p. 117. "Often—very often indeed—on this part of the plateau, to the south of 88° 25′, we had difficulty in getting snow good enough—that is solid enough—for cutting blocks. The snow up here seemed to have fallen very quietly, in light breezes or calms. We could thrust the tent pole, which was 6 feet long, right down without meeting resistance, which showed that there was no hard layer of snow. The surface was perfectly level; there was not a sign of sastrugi in any direction."

This remarkable blizzard reached King Edward VII. Land on December 1. The blizzard, with new-falling snow, continued to rage there until the morning of December 7. The same blizzard was experienced by Scott at the foot of the Beardmore Glacier, where it left 2 feet of new-fallen snow, as well as by Taylor and Debenham's party at Granite Harbour to the north of McMurdo Sound; but Day, on the west side of the Barrier near 82° S., escaped this snowfall altogether. Nevertheless, practically the whole of the Ross Sea region was on this occasion visited by the heavy snowfall. At Granite Harbour it was about 3 feet deep.

One cannot but think that this remarkable snowfall, preceded by two days of winds blowing in sharp gusts from the north with dense fogs, was derived from moisture which had travelled inland, from the Ross Sea and the Southern Ocean beyond, as a surface wind, part of some large surface cyclone system, rather than that it was derived from the downward-diving air of the Antarctic high-level cyclone. Doubtless the fierce insolation to which the rocks and snowfields of the Antarctic Horst are subjected, as summer develops, was responsible for some of the vapour in the air. Amundsen relates (*op. cit.* vol. ii. p. 141) that on Christmas Eve, just north of 88° S., the surface of the snow, as the result of having been exposed to powerful sunshine was quite polished, and that near "Dog Depôt" in 86° S., as seen on January 3, 1911, some of the snow beacons were found to be quite bent over, through the effect of the sun's heat, and that "great icicles told us clearly enough how powerful the sunshine had been." This interesting observation shows that snow can actually thaw, as already suggested, when exposed to long severe insolation, even when the shade temperature of the air in general, as distinct from the thin film next the snow, probably at no time rises to thaw point. "Dog Depôt" is 10,060 feet above sea level, so that the shade temperature at that latitude would probably not rise at all to thaw point.

Close to the latitude of 84° S. cumulus was observed travelling from N. to S. and at times from N.N.W. to S.S.E., but this drift from the north was quite exceptional.

Fresh-falling snow was recorded at 84° 35′ S. on the Beardmore Glacier, on December 14. For the whole of the previous day the surface wind had been N.E., and the cumulus had been drifting from E.N.E.

This suggests that the moisture which formed this snow was derived from the Ross Sea or the Southern Ocean beyond it.

S.W. or S.S.W. winds always brought with them clear skies.

If a great cyclonic wind were to dive at the Temperature Pole, it would surely retain some of its easterly component of movement and be a W.S.W., S.W., or S.S.W. wind.

J. B. Adams, of Shackleton's expedition, describes the surface at latitude 88° 23′ S., longitude 162° E., as being formed of hard snow and hard sandy crystal drift.

Summary. The question of snow supply to Antarctica is of course an extremely complex question which can only be dealt with satisfactorily by able meteorologists.* Our impression at present is:

(1) That if a great permanent high-level cyclone exists it does not carry any very appreciable quantity of snow far inland, for if it did there would be far more fresh-falling snow than has actually been observed towards the middle and end of blizzards.

(2) That the so-called permanent anticyclone of Antarctica is represented by a thin mass of cold stagnant air more or less concentric to the main Temperature Pole, in winter resting partly on the second Cold-Pole, discovered by Amundsen to the S. of "Framheim." That this cold air mass does not radiate outwards continually and systematically, but is spasmodic and local in its outrushes, breaking away often a bit at a time, each unit rolling down separately to sea level as an independent air avalanche.

(3) That such outrushes of cold air are partly replaced by a surface inflow, partly by an inflow at a high level, constituting for the time being a high-level polar cyclone. Probably, like the Polar cyclone, the high-level Polar cyclone is compound rather than simple.

(4) That it is these surface currents moving Pole-wards that are responsible for the heaviest snowfall, at all events in summer. In winter when atmospheric circulation in general is accelerated in Antarctica the high-level air current, like that which passes over the Magnetic Pole Plateau, may contribute to the snowfall to a greater extent than it does in the summer.

(5) Sea breezes in the Ross Sea, set up largely by the differential heating of the exposed rock masses of the Antarctic Horst as compared with the water surface of the Ross Sea, are responsible for a good deal of snowfall along the Western Mountains.

(6) *The surface relief of the land and the distribution of land and water have in many cases a paramount influence on the direction of the prevalent winds and consequently on the snowfall of Antarctica.* This is a fact which seems to stand out more clearly than any other in the meteorology of this region.

Amount of Snowfall. Observations at Cape Royds showed that the snowfall of the year 1908 was approximately equal to about 9 inches (230 mm.) of rain. This estimate is approximately correct, but allowance must be made for the fact that it was extremely difficult to distinguish between old drift snow which found its way into the rain-gauge and new-falling snow. The result is intended to be an approximation of the amount of actual snowfall during the year.

On the Great Ice Barrier in the latitude of Minna Bluff, 78° 45′ S., the amount of snowfall is not known, but it was found that over 8 feet (2·4 m.) of snow had

* Much fresh light will be thrown upon this problem when Dr. G. C. Simpson, the meteorologist to Captain Scott's expedition of 1910–13, collates and publishes his unique records obtained in the Ross Sea region.

accumulated above Captain Scott's Depôt A to the east of Minna Bluff, erected in 1902. This snow was found to be very hard and compact, and must have accumulated at the rate of about 13 inches (0·33 m.) per year. When thawed down it was found that these 13 inches were equal to $7\frac{1}{2}$ inches (188 mm.) of rain. The result, therefore, agrees fairly well with that obtained from the meteorological observations at Cape Royds. The snowfall at Cape Royds is somewhat heavier than that of the Great Ice Barrier, for the equivalent in snow of $7\frac{1}{2}$ inches of rain near Minna Bluff represents no doubt a great deal of drift snow as well as new-fallen snow. At the same time allowance must be made in the case of the Minna Bluff estimate for the removal of a certain amount of the snow by ablation.

Ablation. The term "Ablation" as used by Drygalski,* means the general lowering of the surface of ice, from whatever cause, except that of mechanical movement.

It may thus be due to (1) Generation of ice-vapour direct, without actually the thawing of the ice surface; (2) Generation of water-vapour from thaw water; (3) Mechanical abrasion of an ice-surface by drifting snow or by rock-dust impelled by blizzard-winds. W. H. Hobbs † uses the term as synonymous with surface melting; Chamberlin and Salisbury ‡ speak of the evaporation and of the melting of ice, but do not use the term "ablation." It will be used by us to denote a general lowering of the surface of the ice and snow from any of the three causes above specified; but as our experiments were conducted in the Antarctic, in autumn, winter, and spring, at a temperature far below freezing-point, the most important factor to be considered was, no doubt, in this case, ice evaporation. Hann§ emphasizes the fact that the pressures of ice-vapour over ice and of water-vapour over water are different at similar temperatures. His Table is given in the foot-note below. Hobbs has pointed out (*op. cit.* pp. 162 and 176) the great importance of rock débris in bringing about the ablation of snow.‖ In view of the fact that fine dust derived from rocks, mostly of dark colour, was widely distributed over the snow and ice at Cape Royds, where our experiments were carried out, what may be termed microscopic melting around minute dust-particles no doubt played an important part in the local ablation of ice and snow.

* "Grönland-Expedition," "Der Gesellschaft für Erdkunde, zu Berlin," 1891–1893, Berlin, 1897 (Band i. s. 541), where he renders Ablation, "Schwund der Eisoberflächen."

† "Characteristics of existing Glaciers," New York, 1911, p. 162.

‡ "Geology: Processes and their Results," London, 1908, p. 279.

§ "Lehrbuch der Meteorologie," Leipzig, 1906, s. 162. He there gives the following interesting Table:

Temperatur .	−0	−2	−4	−6	−8	−10	−12	−14	−16
Eis-dampf .	4·60	3·92	3·33	2·82	2·38	2·0	1·67	1·40	1·17
Wasserdampf .	4·60	3·99	3·45	2·97	2·56	2·20	1·88	1·61	1·38

‖ He states that "*for this purpose*" (clearing the snow during the construction of the Bergen Railway in Norway, completed in December 1909) "*covering the snow surface with fine dirt proved more effective than a corps of shovellers, the sun, in this case, performing the work.*"

Ablation at Cape Royds was measured by us in two ways. (1) By fixing bamboo poles into the lake ice, and marking on the pole the exact level of the ice-surface at the time the pole was fixed. Measurements, taken at intervals, showed that the surface was becoming progressively lowered. (2) Blocks of ice, approximately cubical, were cut from the ice of the lakes, and these were suspended in a position out of doors where sun and air had free access to them, and were weighed from time to time.

We fixed a bamboo pole in the ice of Coast Lake, near the centre of the lake, on April 3, 1908. At the time this bamboo was fixed in position in the ice it was noticed that in many parts of the lake the delicate tips of the freshwater algæ, so numerous in these lakes, projected about 2 inches above the surface of the ice. It is almost certain that the tips were about level with the surface of the water when the lake was first frozen over towards the end of summer. That is, from about the beginning of February to the beginning of April, about 2 inches of ice had been ablated. On June 13, 1908, it was found, when the measurements were made from the mark on the bamboo pole at Coast Lake to the surface of the lake-ice, that 1·35 inches of ice had been ablated. It was a matter of great surprise to us that such a large amount of ablation had taken place during such a cold period, when the thermometer was mostly below 0° Fahr. At Pony Lake, close to our winter quarters at Cape Royds, the ablation was even greater. Dr. Mawson fixed a bamboo pole in the ice on this lake on April 18, and, on measuring it on June 12, found the amount of ablation to be 1·5 inches. That is, in the case of Coast Lake, 1·35 inches of ablation had taken place in seventy days, and, in the case of Pony Lake, 1·50 inches of ablation in fifty-five days. The bamboo pole at Coast Lake was measured again on June 20, 1908, when it showed only a little over 1·3 of an inch total ablation. A straight-edge, in the form of a light board with parallel sides, was used on this occasion, in order to ensure greater accuracy, as there seemed a slight tendency for the ice immediately around the base of the bamboo to be slightly lowered below the level of the surrounding ice. This reading is therefore perhaps more reliable than the one taken on June 13. It is hardly likely that the surface of the lake ice would have gained in height in the interval. On July 13 we fixed up another ablation-pole, this time in the ice of Blue Lake. On July 16 we fixed a second ablation-stick in Blue Lake. On July 22 we fixed another ablation-stake at Blue Lake, and also one at Clear Lake and one at Green Lake.

On August 5 we measured the ablation-pole at Coast Lake, and the amount of ablation since April 3 was 1·9 inches. On October 2 we re-measured the bamboo pole at Coast Lake, and made out the total ablation to be about 1·63 inches, that is from April 3 until October 2. This seems inconsistent with the measurement, taken on August 5, of a total ablation already at that date of 1·9 inches, but it must be remembered that, in the intervals between the measurements, a good deal of snow had fallen and covered this lake, temporarily at any rate; and, in the second place, the surface of the lake was intersected with a network of cracks (see Fig. 54) and the fragments of ice between the cracks became slightly convex and tilted at various angles from the horizontal.

Fortunately, this ablation can be checked by the observations made at the same time on the other stakes.

Measurements on October 2 showed that, at Blue Lake, the ablation since July 16 had been about ·42 of an inch, at Green Lake ·25 of an inch, and at Clear Lake ·33 of an inch. It may be mentioned that the ice of Blue Lake and of Clear Lake was practically fresh, while that of Green Lake was saline.

Blue Lake, as being a large expanse, and having, at the point where the stake was fixed, a smooth and but slightly cracked surface, may be taken as giving a reliable figure for the ablation between July 16 and October 2; that is about ·0054 of an inch per day—or ·42 inches for seventy-eight days. Had the ablation at Coast Lake continued at 1·9 inches (the amount measured on August 5) from June 20 to October 2, 113 days, the rate of ablation would, practically, have been the same as for Blue Lake, viz. ·0053 inches per day.

We may conclude that the ablation due chiefly to evaporation of ice-vapour and water-vapour, was, in 1908, at Cape Royds, equal to about 2 inches from April 3 to October 2—a period of 150 days.

This evaporation was probably, for the most part, due to generation of ice-vapour, possibly in part to the formation of water-vapour from microscopic thawing around dust-particles, at a time when the general temperature was still far below freezing-point.

This amount of ablation due to evaporation alone is truly surprising, especially when one reflects that from April 23 until August 22 the sun was continually below the horizon. Thus one can easily credit the evidence of ablation, already alluded to, afforded by the distance to which the tips of the freshwater algæ were found to project above the surface of the lake-ice on April 3, viz. that about 2 inches of ablation, due chiefly to evaporation, had taken place already between the beginning of February and April 3.* This would make the total amount of ice-ablation about 4 inches from February to October. It remains to be seen what amount of ablation due to evaporation takes place during October and November, December and January. If another 3 inches disappears, then this will make the total evaporation 7 inches, which will about account for nearly all the precipitation in that part of the Antarctic. The annual precipitation at Cape Royds, in 1908, was probably equal to about 9½ inches of rain. The precipitation was entirely in the form of snow. It must also be remembered that, in December and January, the ice and snow suffer a considerable amount of ablation, not only through evaporation of ice and thaw water, but also through the running off of the thaw water.

* The alga being very flexible and flaccid during the summer thaw, its tips would not project above the general level of the thaw water of the lakes as long as the water remained unfrozen. Thus the tips would begin to be left in relief only after the date of the final freezing of the lake at the end of the summer.

These ablation results are not very different from the evaporation observations made by the *Discovery* Expedition.* In these experiments three shallow dishes were employed, giving areas respectively of 12, 12, and 24 square inches. These were filled with water, which was allowed to freeze, and then the dishes were placed on the meteorological screen. The dish and ice were weighed day by day, and the difference between two consecutive weights gave the loss by evaporation.

From March to October inclusive, in 1903, the total evaporation amounted to 2·910 inches, and the evaporation for November of the previous year amounted to 0·702 of an inch. If this be added to the previous amount the evaporation for the nine months from March to November would be 3·612 inches. The amount of evaporation for December, January, and February is wanting, but it appears to one of us (Professor David) that the amount would have been of the order of ·8 inch per month. In this case the total annual evaporation would have been about $2{\cdot}4 + 3{\cdot}612 =$ in round numbers about 6 inches.

It will be noted that in the case of our experiments we employed actual lake surfaces instead of dishes, and that occasionally the lake surfaces were temporarily snowed over. In most cases, however, the snow covering was quickly dusted off them by strong winds, except in the case of Clear Lake, where there was evidence of some irregular lumpy structure developing on the previous even surface of the ice some time subsequent to snowstorms.

Probably the estimate given of 7 inches as the total annual evaporation at Cape Royds (irrespective of the ice and snow that are lost by actual thawing through heat radiated from sun-warmed rocks) is not an over-estimate. This great amount of loss of ice by evaporation is, no doubt, due (1) to the extreme dryness of the air; (2) to the consequent intensity of solar radiation; (3) to the speed of the blizzard winds. This immense evaporation is obviously a fact of the first importance in studying the glaciology of Antarctica, especially when the additional point is borne in mind (and this point cannot be too strongly emphasized) that probably at least 95 per cent. of the surface of Antarctica is covered superficially not with ice but with snow. The great surface offered by snow spicules and flakes in proportion to their volume would greatly accelerate the rate of the evaporation and so increase its amount. For example, we noticed the tracks of sledges or footprints in the snow within a few weeks were left strongly in relief. This may have been in part a mechanical "survival of the fittest," that is, the compressed snow may have resisted the mechanical force of the blizzards better than the loose snow.

Spiracle Ice or *Moss Ice.* Another evidence of ice evaporation is to be found in what may be termed spiracle ice. Dr. Mackay first called attention to this on the journey to the South Magnetic Pole area, when the party was crossing the Drygalski Ice Barrier Tongue. This glacier was heavily crevassed, and here and there were to

* "National Antarctic Expedition," 1901–4. "Meteorology," pt. i. published by the Royal Society, London, 1908, pp. 11 and 473–475.

be seen low rounded clumps of pure white needle-like ice crystals of plano-convex shape, with the convexity uppermost. These masses were from a few inches to a foot or so in diameter, and from a few inches to about 6 inches thick. Their appearance was somewhat as follows:

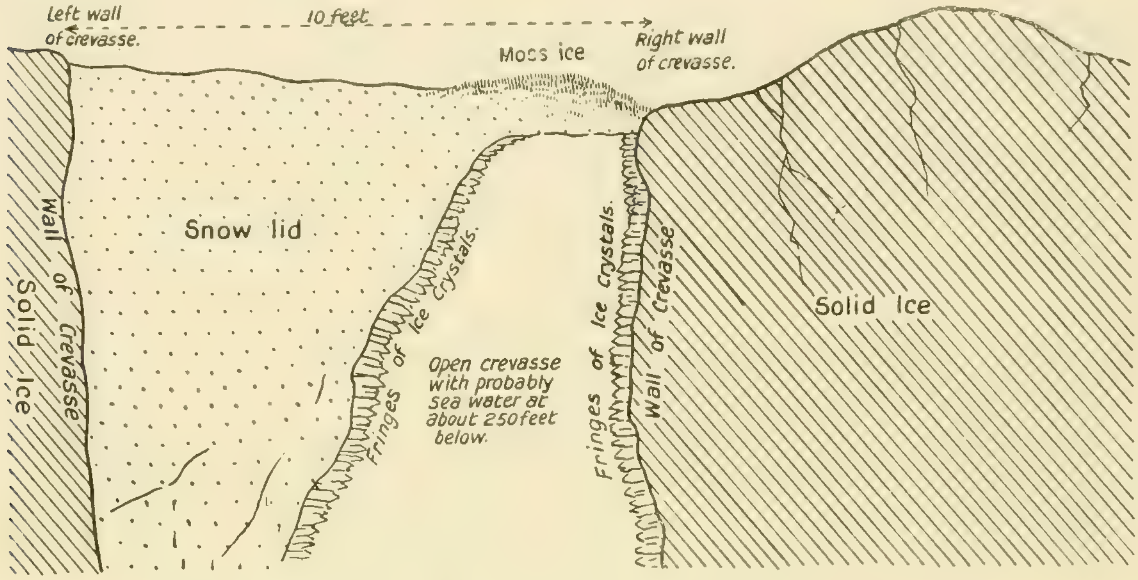


FIG. 6. MOSS ICE OR SPIRACLE ICE
Formed by crystallisation of vapour, from sea water at bottom of crevasse, transpired through snow lid of crevasse

We crossed the Drygalski Barrier early in December, and this spiracle ice was obviously of quite recent growth. The crystals evidently developed at spots where the lid of the crevasse was so thin as to be capable of being used as a respirator. Air would alternately filter into or filter out of the crevasses through these "respirators," beautiful vertical needles of ice growing upwards from the upper side and downwards from the lower sides of the respirator. The probable explanation of these tufts of moss ice is that on this part of the Drygalski Barrier the lower portion of the crevasse may reach down to sea-level, and even be filled with sea water, or, at all events, have a temperature near the freezing-point of sea water. Thus the relatively warm vapour would rise from below and be chilled higher up in the crevasse with deposition of ice needles on the walls and at respirators. At "Priestley Shaft" at the Blue Lake, Cape Royds, a similar phenomenon was observed. The vapour from next the bottom of the lake formed ice crystals on the walls of the upper part of the shaft.

In part this moss ice may be due to convection currents under the lid of the crevasse, due to differential solar heating; but the former hypothesis seems more probable.

That an appreciable amount of vapour is present in Antarctic crevasses is proved by the fact that in summer, at all events, from near Mount Nansen on the north to Beardmore Glacier on the south they are lined with delicate ice crystals.

Pie-crust Snow. Another phenomenon due to ablation is what may be termed Pie-crust Snow. The surface of the snow under the influence of the direct rays of the sun in a cloudless sky becomes alternately softened by microscopic thaw around dust particles, and again, as temperature falls towards midnight, it becomes hardened by re-freezing. Such pie-crust surfaces were met with notably on the sea ice on the journey from Cape Royds to the head of the Farrar Glacier, on the Great Ice Barrier, and on the Drygalski Glacier. They were distressing to sledgers, for one's feet would break through the tough crust at every step, and sink some 4 to 6 inches into loose powdery snow beneath, and each time one's foot was pulled out the toe of the ski boot or finnesko would tear away a piece of the crust with it.

This structure was perhaps best developed in the snow covering the sea ice. Different stages of its formation were specially studied by one of us (R. E. Priestley) on the western journey when travelling over the snow-drifted surface of the sea ice of McMurdo Sound. At first a fine glazed surface became developed on the northern end of the sastrugi, due to the heat of the sun on the drifts when the sun is to the north of them, as it is by day, and the freezing action when the sun's heat is lessened, towards midnight during the season of midnight sun in December. At the time these observations were made, between December 14 and January 6, no corresponding glazing took place on the southern side of the sastrugi, owing, of course, to the diminished intensity of solar radiation when the sun was in the south. On flat surfaces, however, this glazing process affected extensive areas. On January 26 the snow crust formed by the heat of the sun was strongly in evidence, and was evidently continuous over large areas. It was poised so delicately that when one set foot on the edge of such an area the whole patch, sometimes a hundred or more square yards in area, fell in with a long-drawn sibilant sound, which resembled nothing so much as the noise made by the falling of heavy hoar-frost from a tree when the branches are beaten by a stick. Below this surface crust the snow is loose and powdery, and often shows incipient traces of granulation. For example, the snow on the south side of the Nordenskjöld Ice Barrier Tongue, on November 11, 1908, showed the section (Fig. 7) on page 38.

Again, at the S.W. end of McMurdo Sound it was observed that adjacent to the "pinnacled ice" was sea ice three or four years old. Its surface was three or four feet above sea level, but less than two feet of the portion above sea level appears to be ice. It seems probable that the whole thickness is not more than 15 to 16 feet. It was covered with drift snow. The older drifts were not quite sufficiently hard to bear the weight of a man, and at every step one dropped eight or nine inches on to a firmer surface. The space between the two crusts was filled with a coarse-grained snow powder, due to a selective action of the thaw and evaporation, those ice crystals or ice grains which were left having increased in size at the expense of the grains which had been partly vaporised, partly absorbed, while thawing, to swell the volume of the larger granular crystals. Underneath this eight or nine

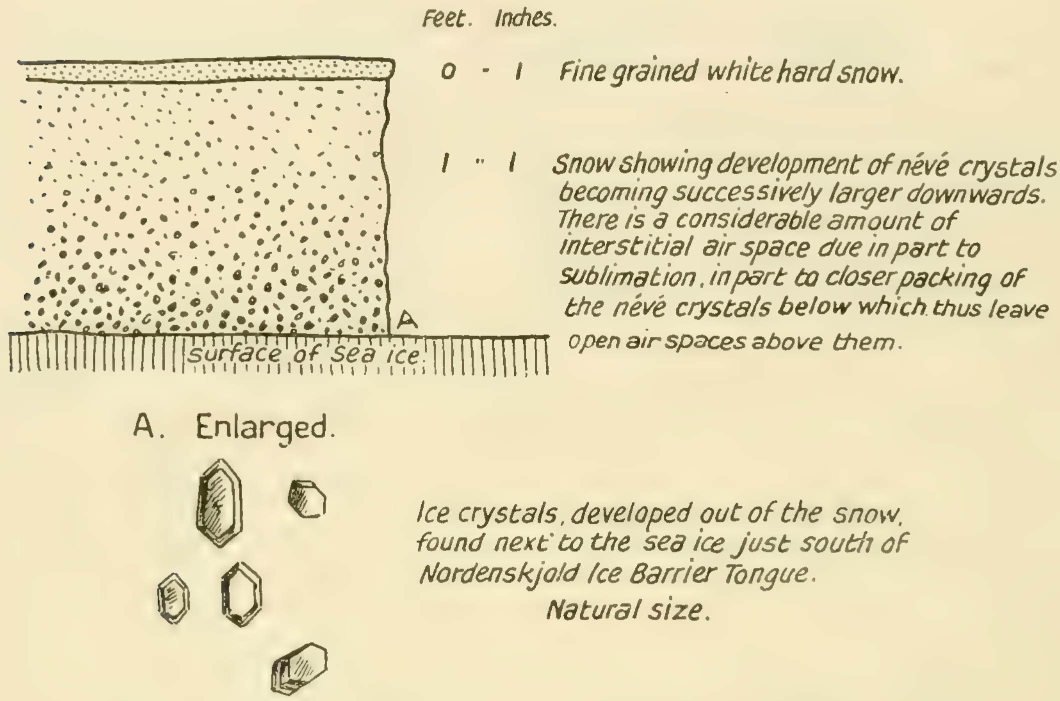


Fig. 7. SKETCH SHOWING EFFECT OF SUBLIMATION ON SNOW OVERLYING SEA ICE NEAR NORDENSKJÖLD ICE BARRIER

inches of crust snow and ice granules was an older surface of crust snow. The structure of the whole is illustrated in Fig. 8.

It seems probable that the formation of this crust snow is somewhat in this way :—The sun on bright clear days warms the air above the snow and even in the interstices between the snow grains for some little depth down.* Consequently evaporation during the warmer part of the day becomes very rapid, chiefly at the surface of the snow, but also penetrating to a depth of several inches. In cases where the snow seldom actually thaws, as on the vast névé fields of the high inland plateau, little but waste of the snow surface takes place during the warmer parts of the day ; but as the surface temperature falls at night the ice vapour still rising from the interstices between the snow crystals beneath the surface is deposited in a solid form on the snow crystals at or near the surface, and so tends

* That the sun's heat passes rapidly through a considerable thickness of ice, is abundantly shown by the temperatures taken by us in shafts sunk through the lake ice of Cape Royds, as explained elsewhere in this memoir. Its penetration through snow would no doubt be much slower. Unfortunately we did not onduct any experiments on this subject.

to cement them together. This carrying up of ice-vapour from below to enrich the surface in ice somewhat resembles the feature of the surface caking of garden soils, if left for some time undisturbed. In the latter case the caking is the result chiefly of

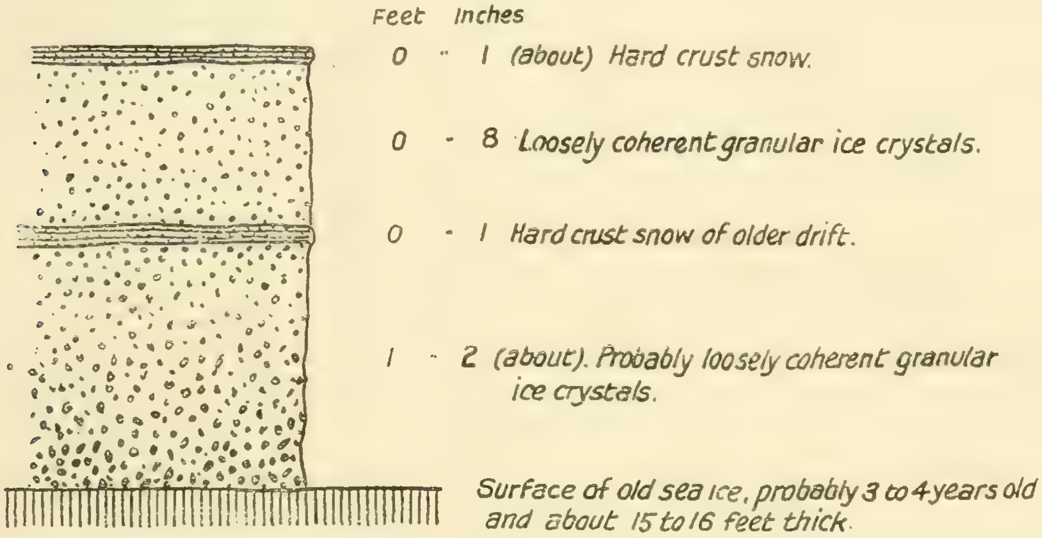


FIG. 8. SKETCH SHOWING EFFECT OF SUBLIMATION AND THAWING UPON SNOW NEAR "PINNACLED ICE" OF McMURDO SOUND

water, ascending by capillarity, and carrying mineral matter dissolved in it, depositing that mineral matter at the surface of the ground when the water evaporates. In the case of the Antarctic snowfields the crust is formed, not by capillarity, where there is no thaw, but by ascent of relatively warmer ice-vapour coming in contact with the cold air at night above the snow surface. Where snow crusts develop on snow-drifts near sea level the hardening of the surface is much facilitated by actual thawing, and it is even possible then that capillarity may assist in conveying thaw water up to the snow surface. On very hot days evaporation proceeds so rapidly that it completely removes the harder top crust, and sets free at the surface the granular ice crystals originally formed beneath the surface. Shackleton states in regard to the snow surface over which the Southern party travelled on the high plateau (from 7000 feet to over 10,000 feet above sea level) to the south of the Beardmore Glacier: "Still further south we kept breaking through a hard crust that underlay the soft surface snow, and we then sank in about 8 inches. This surface, which made the marching heavy, continued to the point at which we planted the flag." *

Again Shackleton describes the crust snow on the surface of the Great Ice Barrier (*op. cit.* 12): "After we had passed latitude 80° S., the snow got softer day by day, and the ponies would often break through the upper crust, and sink in right

* "Heart of the Antarctic," vol. ii. p. 18.

up to their bellies. When the sun was hot the travelling would be much better, for the surface snow got near the melting-point, and formed a slippery layer not easily broken. Then again a fall in the temperature would produce a thin crust through which one broke very easily." *

On consulting the thermometer readings of the Southern party, we find that the highest temperatures recorded for their journey over the Great Ice Barrier were 22° Fahr. at 8 A.M. on December 3, 1908, and 21° Fahr. at 1 P.M. on December 2. The shade temperature for noon on December 3 was not taken. On December 2 the shade temperature at 8 A.M. was 14° Fahr. There was a rise therefore on December 2 of 7° Fahr. between 8 A.M. and 1 P.M. If there was a similar rise in temperature on December 3, the shade temperature on that day may have been about 29° Fahr. at 1 P.M. December 3 was the last day of the Southern party's journey over the Great Ice Barrier. Previous to these two days the shade temperature had been considerably below freezing-point. It was probably the case that the softening of the snow surface, described by Shackleton as preceding the formation of the crust on the snow surface, was due to actual microscopic thawing partly caused by minute particles of rock dust, spread over the snow by the blizzards.

Granular Ice Crystals from Snow. On relatively warm bright days in summer it seemed as though crops of granular ice crystals were growing on the surface of the snow. On the Barrier near latitude 83° 16′ S., Shackleton states : * "The surface of the Barrier still sparkles with the million frozen crystals which stand apart from the ordinary surface snow." Again (*op. cit.* vol. ii. p. 12) he says, speaking of the surface of the barrier : "The snow generally was dry and powdery, but some of the crystals were large, and show in reflected light all the million colours of diamonds."

At an altitude of over 7000 feet on the plateau on which the South Magnetic Pole is situated, these crystals are much in evidence. These ice crystals on January 14, 1909, were found to be about half an inch in width and about one sixteenth of an inch in thickness. They form a layer about half an inch in thickness over the top of the névé. In the bright sunlight the snow surface covered with these sheets of bright reflecting ice crystals glitters like a sea of diamonds.

Probably these crystals were not being freshly developed each sunny day at the surface of the snow, but were crystals originally formed an inch or so below the snow surface and subsequently exposed through the removal of the former covering by evaporation. If this is so, their presence shows that there is considerable evaporation taking place on these high Antarctic plateaux.

The snow surface of this plateau was never up to thaw point, and almost certainly never is. The hottest temperature that the Northern party experienced on the part of the plateau near to the Magnetic Pole area, where the above observation was made, was about 15° Fahr.† on the noon of January 5, 1909, at an altitude of about 7000

* "The Heart of the Antarctic," vol. i. p. 303.

† Not corrected for instrumental error.

feet. The plateau here is also practically free from rock dust. It may therefore be questioned whether even near the summer solstice the temperature there rises to thaw point. There can be no doubt that these large ice crystals, where they are developed on the higher plateaux, are formed by a process of vaporisation and recrystallisation at a temperature considerably below freezing-point. Near sea level granulation below the snow surface is to be attributed to partial thaw in many instances as well as to vaporisation. As granulation is of course much more active in summer than in winter, the drift brought up by a blizzard in summer consists largely of finely granulated snow. This fact was specially experienced and noted by the Western party. They found that in summer the drift snow on the sea ice of McMurdo Sound was composed in its upper portion of loosely coherent granular snow, the individual grains being much larger than those accompanying the winter drifts. It was from such snow that the largest quantity of the low-flying drift was derived which accompanied the southerly gale of December 7, 8, 9 of 1908. It was a distinctive feature of the summer blizzards, experienced during the Western journey, as opposed to the winter ones experienced at Cape Royds, that the drift accompanying them was always low-flying and heavy, and if it did reach as high as the face—a most unusual thing—it felt like fine gravel. This is no doubt due to the thawing action of the sun on the freshly fallen snow lying on the sea ice and glacier surfaces.

On January 2 the Western party observed a curious type of hoar-frost precipitation from water-vapour or ice-vapour—which is described as follows in the diary of one of us (R. E. Priestley):

"On January 2 a new type of precipitation was observed, and one so unusual that we have noted it as follows:

"Yesterday and the day before, this part of the Sound was traversed by a layer of moisture-laden air moving slowly towards the north-west. To-day the snow and ice are covered by little snow-trees about an inch to an inch and a half high, and consisting of a central axis with six branches, three short ones to leeward separated from each other by a very acute angle, and these in turn separated by an obtuse angle from three long branches, similarly disposed, to windward. These branches were directed upwards at an angle of 30°, and as both they and the central axis increased in size as the height above the ground increased, the resulting structure looked decidedly top-heavy. Sometimes the trees were compound, having several other single main axes with their six branches of exactly similar appearance, except that the branches on those axes nearly at right angles to the stem were of equal length on either side.

"These peculiar 'trees' seem to be due to an accretionary growth of ice from the moisture in the air, but the most interesting point about them was undoubtedly their singularly symmetrical form."

Ice Flowers. Somewhat analogous in their origin are the ice flowers. The condition most favourable for their growth appeared to be a sudden fall of temperature during an interval of calm weather, just after a blizzard had stripped the ice off the sea.

The finest development of ice flowers, shown on Plate VII., Fig. 2, took place on March 20, 1908.

The ice under the ice flowers on March 20 was about 3 inches in thickness, and, though tough, bent very much under a man's weight. The meteorological conditions which led up to the development of these "ice flowers" were the following:—On March 8 there was a very violent blizzard which drove out practically all the ice which had formed on McMurdo Sound. On March 11 there was a light gale from S.E. threatening to develop into a blizzard and keeping the sea ice-free. The wind continued mostly from the S.E. The temperature was continually falling, and on March 16 the sea, which was now much warmer than the air (about 20° Fahr. as compared with 6·3° Fahr.), was covered with steam or frost smoke, as though it had been boiling (*see* Fig. 1, Plate VII.). On March 18, 19, and 20 the weather was calm, and, with a mean air temperature on March 19 of $-8{\cdot}9°$ Fahr., the sea surface froze over very rapidly, and a splendid crop of ice flowers developed (*see* Fig. 2, Plate VII.). On that afternoon about half an inch of snow fell. The following day the temperature fell further, then rose again on March 24, 25, and 26, reaching a few degrees above zero Fahr. On March 27, at a temperature of 1·50° Fahr., all that remained of the ice flowers were miniature domes of snow about $1\frac{1}{2}$ inches high and 2 inches wide. These were pierced by slits where the plates of the crystals had been dissolved out. Lying around the bases of these domes and pointing outwards radially, were the still frozen edges and tips of the plates, the petals, as it were, of the flower. These being formed of pure ice derived from the frost smoke had remained frozen, while the centre of the flower, formed of various cryo-hydrates, had melted away. Thus under the centre of each dome was a tiny pool of bitter saline water. Dr. Mawson has thus explained the origin of these ice flowers :

"During the formation of the surface ice some of the sea salts are squeezed upwards through capillary cracks to the surface, and there in the form of concentrated brine eventually freeze as cryo-hydrates and form nuclei for additions from atmospheric vapour. The net result is the production of little rosette-shaped aggregates of radiating crystal blades, which were met with up to 2 inches in height." *

We also observed ice flowers, as Murray has already recorded (*op. cit.* p. 341) on the freshwater ice of Clear Lake and Blue Lake near Cape Royds. "They were on the ice rapidly and tranquilly formed in the trenches sunk for the observation of temperature. They were much smaller than those on the sea ice, being only half an inch or less in diameter."

Bund Structure in Sea Ice. Another phenomenon due to freezing of vapour is the raising of the edges of ice-floes through the freezing of vapour rising from the sea

* "Heart of the Antarctic," vol. ii. p. 337.

PLATE VII

Fig. 1. FROST SMOKE RISING FROM THE SEA

After young sea ice has been broken up by blizzard, McMurdo Sound, March 16, 1908

[Photo by David

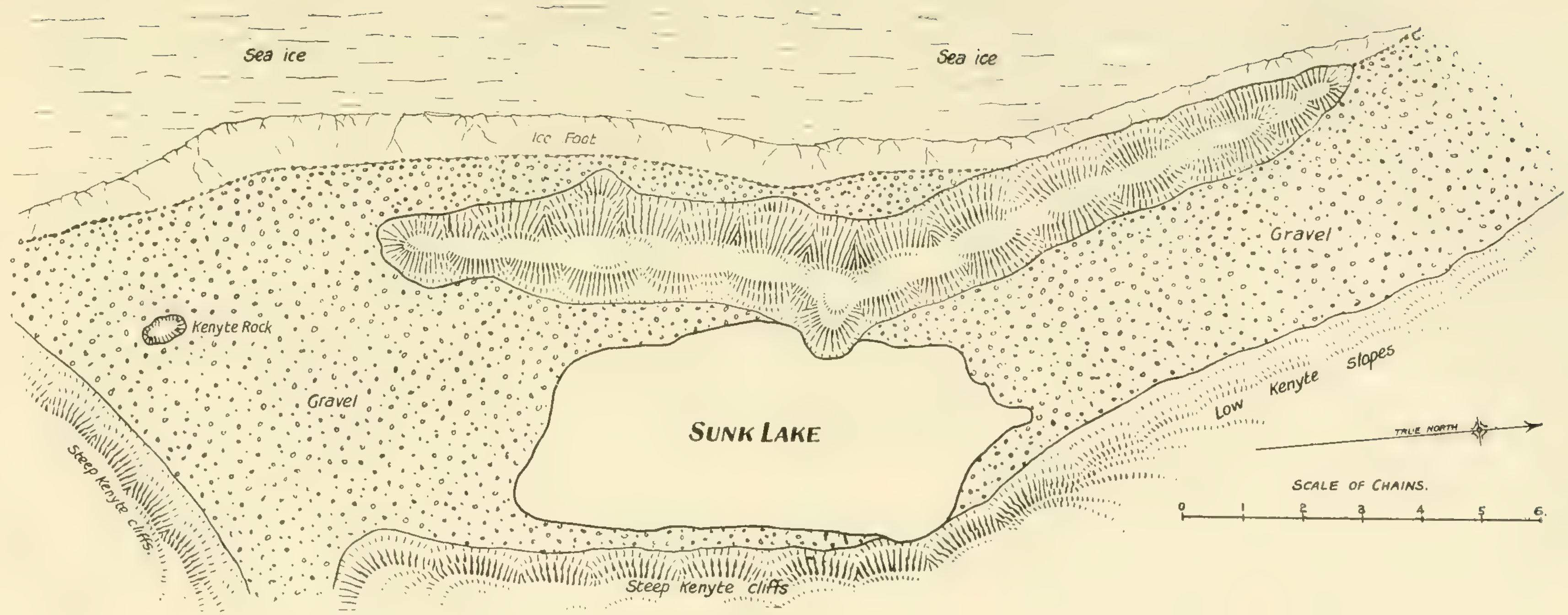
Fig. 2. ICE FLOWERS ON SEA ICE

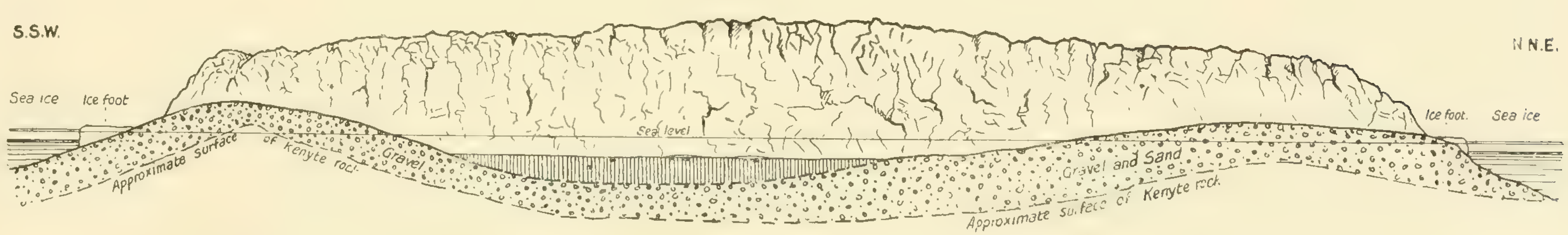
McMurdo Sound, March 28, 1908. The centres of the clusters are formed of the cryo-hydrates of sea water. The edges are formed of ice of the nature of hoar-frost.

[Photo by Shackleton

[*To face p.* 42

PLATE VIII





Section across Sunk Lake, ice surface 18 feet below Sea level, near Cape Barne.

Horizontal Scale. 0 1 2 3 4 5 6 Chains. / 0 10 20 40 60 80 100 120 Metres

Vertical Scale. 0 50 100 150 200 250 Feet. / 0 10 20 40 60 80 Metres

SECTION ACROSS SUNK LAKE (ICE SURFACE 18 FEET BELOW SEA LEVEL), NEAR CAPE BARNE beneath, on the walls of the ice-floes, raising them slightly at their edges, reminding one of the little mud walls or bunds raised by the agriculturists of India and Ceylon to impound water in their rice-fields. The sea ice there was repeatedly cracked by the heaving of the sea outside the bay during blizzards. Thus while the edges of the floes touched, the cracks between them were kept open, so that vapour was continually steaming up from below. These little walls of circumvallation, from 4 to 6 inches high, are not to be confounded with the upturned edges of thin ice floes, the upturning being due to constant collision while the ice at the edge of the floe was in actual process of growth.

In reference to the relation between precipitation in general, in the Ross region of Antarctica, and ablation,* what appears to us to be an exceedingly important piece of evidence is afforded by Sunk Lake near Cape Barne. In the case of very numerous small lakes, near Cape Royds, there is fair evidence of recent and still existing conditions of desiccation. These either still exist amongst the moraines or ice-scooped rock hollows on the western flanks of Erebus, some showing traces of old terraces now considerably above their present water level, or have dried up completely, leaving only old shore lines fringed with algal peat and diatomaceous mud to tell of their former presence. Nevertheless, as much of this morainic material at a depth rests on ice, and this ice is from time to time thawing and so causing the morainic material above it to slowly subside, it might be argued that some, at any rate, of these lake hollows have become dry through a process of draining rather than through evaporation exceeding precipitation.†

No such explanation, however, will apply to Sunk Lake, which is shown on Plate VIII. Its ice surface is 18 feet below sea level in spite of the fact that it is only about 70 yards from the sea to the nearest point of the lake.

The lake is certainly wind-swept, so that very little snow lies upon it; at the same time it is well supplied with snow-drifts, which during the season of thaw contribute a good deal of thaw water to the lake.

On the whole this lake may be regarded as a large rain-gauge, and the fact that its ice surface is so far below sea level appears to us to bear most important testimony to the fact that at present in this part of Antarctica ablation, in this case due chiefly to evaporation, exceeds precipitation.

* Ablation is here used in the widest sense, to comprise all the natural processes which lead to the removal of a surface of snow or ice, whether upper or under surface, and includes the processes of sublimation, surface thawing and melting at the base, removal of snow by wind as well as loss by wind abrasion, and also loss through the breaking away of bergs.

† The ice under these old moraines is probably fossil ice left by the former Ross Barrier when at its maximum extension.

CHAPTER III

DYNAMIC GEOLOGY (*continued*)

PART II. GLACIOLOGY

Dr. Mawson, Mineralogist, Chemist, and Physicist to our Expedition, proposes to deal with the subject of Antarctic ice as a mineral, with special reference to granulation, crystallisation, &c. We propose to divide this subject into land ice and sea ice. In the matter of land ice we adopt H. T. Ferrar's classification,* who in turn has followed Drygalski,† Heim, ‡ H. Rink, § Arçtowski, || and Gourdon.¶ We divide the different type developments of land ice as follows:—

1. Inland Ice.
2. Ice Caps (*Calottes*, *Hochlandeis*).
3. Piedmont Glaciers (*Glaciers plats* and *Glaciers côtières*).
    (*a*) Piedmonts on land.
    (*b*) Piedmonts aground.
    (*c*) Piedmonts afloat.
4. Glaciers of Greenland type, usually termed by us Outlet Glaciers or Spillway Glaciers.
5. Glaciers of Norwegian type, flowing down defined valleys from large firnfeld.
6. Glaciers of Alpine type (*Glaciers encaissés*). These drain small basins only.
7. Cliff Glaciers. Reconstructed (recemented) Glaciers.
8. Hanging Glaciers.
9. Corrie Glaciers, Cwm Glaciers, Cirques (*Kare*).
10. Ice-slabs. These remarkable stagnant masses of glacier ice, without visible means of subsistence except to a limited extent from drift snows, are considered by Ferrar to be peculiar to the Antarctic. They are either "beheaded" glaciers which have lost their firnfeld, or are dune glaciers formed in the lee of high mountains along the coastal strip.**
11. Icebergs.
12. Lake Ice.

* Nat. Ant. Ex., 1901–4. Geology, p. 63.

† "Grönland Expedition," 1897.

‡ Handbuch der Gletcherkunde.

§ Danish Greenland, 1877.

|| Expédition Antarctique Belge. Géologie—Les Glaciers, 1897–99.

¶ Expédition Antarctique Française, 1903–5. Charcot.—Glaciologie, Gourdon. Also "Le Pourquoi-Pas? dans l'Antarctique," 1908–9. Charcot.

** Similar glaciers are described from Alaska by S. K. Gilbert, Records of the Harriman Alaska Expedition, vol. iii., "Glaciers."

As Mr. Griffith Taylor, Senior Geologist to the late Captain R. F. Scott's Expedition, has made recently a special study of the Antarctic cirques, we omit more than passing reference to them in this Memoir. Icebergs will be described under sea ice, in which we include all fragments of floating ice, as well as fast ice.

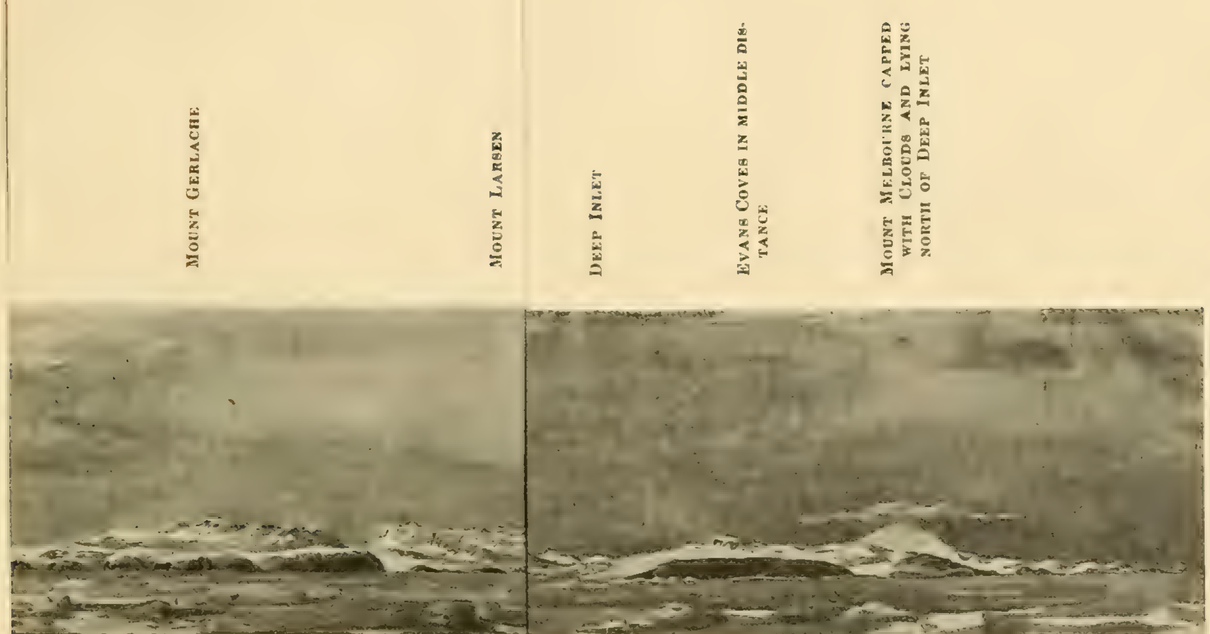
We may now pass on to consider the glaciers of the Antarctic Horst in detail, commencing with the northernmost group examined by us, the Drygalski-Reeves Piedmont.*

Reference to the map (Plate IX.) shows that each of these three glaciers is of the "outlet glacier" type, that is, they are ice canals draining vast inland ice-fields, and resemble the glaciers of the west coast of Greenland. The ice in excess of that which is held by frictional resistance moves under gravity and other causes through the channels of the Reeves, the Larsen, and Drygalski and other glaciers into Ross Sea. These glaciers preserve their individuality only where they cross the great horst. To its west they are united in the vast inland snow-fields and underlying ice-fields, while on the coast to the east the Larsen Glacier is united in the form of an "ice-apron," or piedmont afloat, to the Drygalski Tongue, which passes inland into the David Glacier. The united Drygalski and Larsen ice-aprons almost coalesce on the north side of the Larsen Piedmont with that of the Reeves Glacier. Formerly during the period of maximum glaciation all three must have not only been united together, but were also joined along the coast to the Davis Glacier, the Cheetham Ice Tongue, the Harbord Ice Tongue, the Mawson Glacier with the Cotton Glacier, the Nordenskjöld Tongue, the Fry Glacier, the Penck Glacier, the Mackay Glacier, and the Ferrar Glacier. As the last mentioned glacier was formerly united to the ice of the great Ice Barrier—it was probably so united in Sir James C. Ross' time in 1840–42—we may conclude that that gigantic piedmont afloat was formerly continuous to at least as far north as Evans Coves, if not to the north side of Terra Nova Bay near Cape Washington.

All trace of the great continuous piedmont ceases just before Cape Washington is reached. The high steep-to character of the coast at Cape Washington, with absence of the usual coast platform, is shown in Figs. 1 and 2 of the Physiographic Chapter. There can be little doubt that, during the maximum glaciation, the whole coast and south-west part of Ross Sea, from Cape Bird on the south to Cape Washington on the north, was filled with ice. This would give the Ross Barrier an extension of about 220 miles northwards of its present northerly limit, so that during the maximum glaciation the Ross Barrier had a total length of perhaps 700 miles.

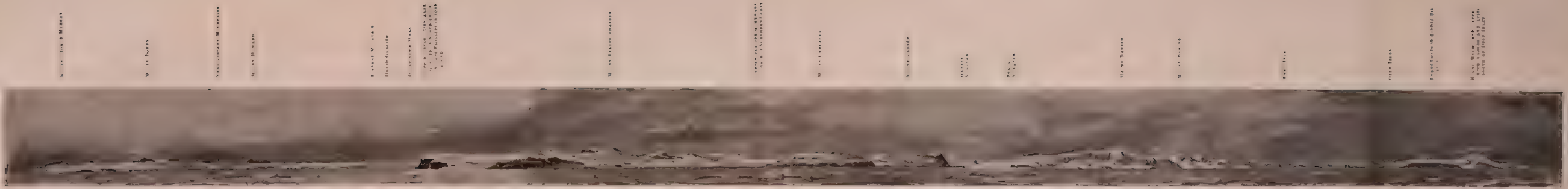
In some sense then, in dealing with the Reeves, Larsen, and David Glaciers, we are dealing with the now shrunken former tributaries of the Ross Barrier. By

* The following descriptions of the glaciers of this region are based on the observations of the Magnetic Pole Party—Professor David, Mawson, and Mackay.



HOWING THE DRYGALSKI-LARSEN-RE
5 miles. Sketch by T. W. E. David, redrawn b

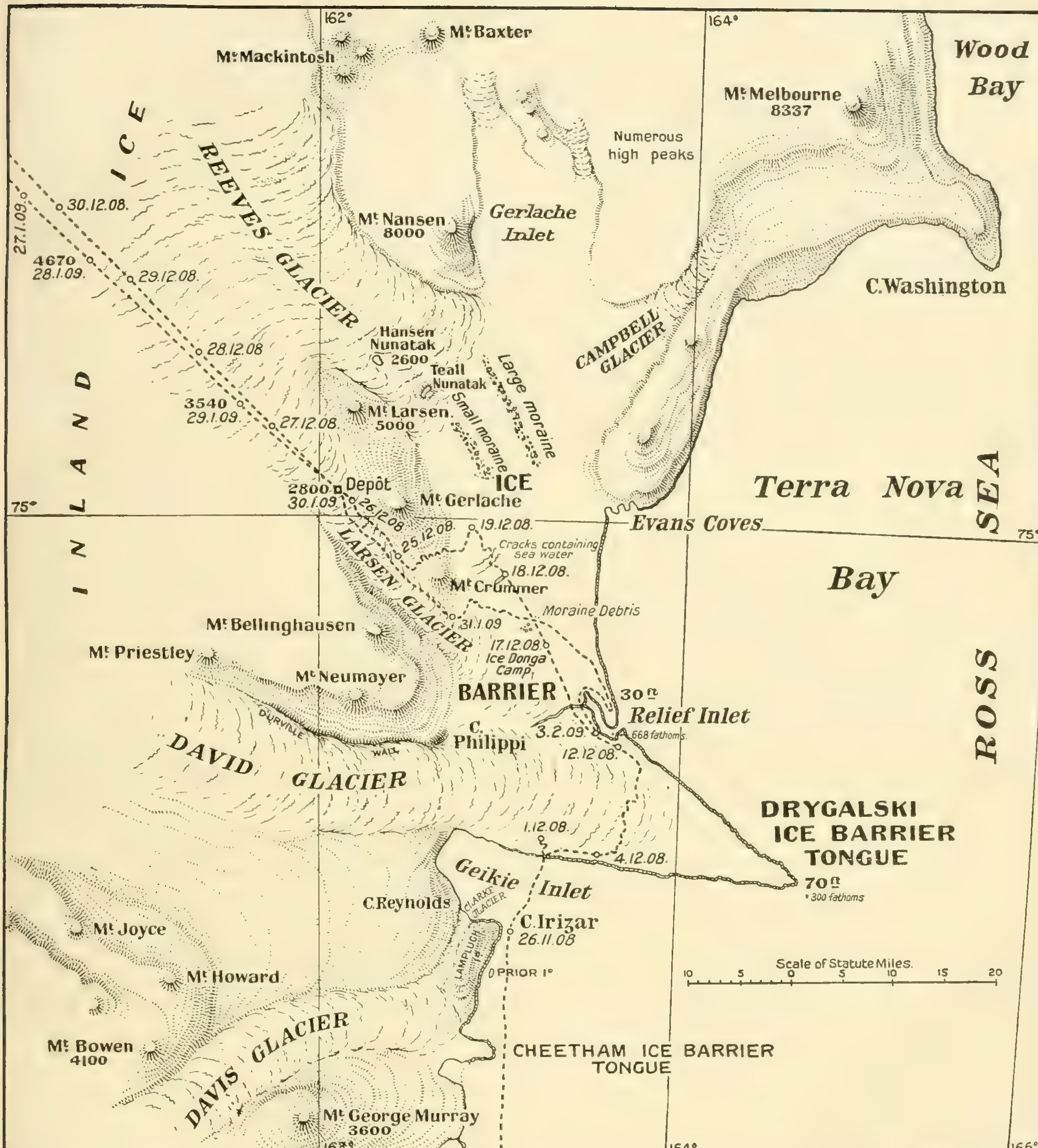
[To face p. 46



PANORAMA ILLUSTRATING NORTHERN PARTY'S JOURNEY AND SHOWING THE DRYGALSKI-LARSEN-REEVES PIEDMONT IN FOREGROUND

The distance from Evans Coves to D'Urville's Wall is 45 miles. Sketch by T. W. E. David, redrawn by George Marston

To face p. 46.



Map of Nansen-Drygalski area of South Victoria Land
showing Coast, Horst, outlet Glaciers, & Inland Ice.
Chiefly after Survey by Dr. Mawson.

a process of betrunking, such as rivers suffer through coastal submergence, but which is due in this case to deglaciation, the old ice drainage has become disintegrated and all these glaciers have become dismembered, with the exception perhaps of the three with which we are now dealing,* and even of these three the Reeves Glacier is all but, if not quite, dismembered from the Larsen-Drygalski Piedmont.

The doubt in regard to this question of the exact line of demarcation, if any, between the Reeves Piedmont and the Larsen Piedmont, is due to the fact that at their margins each apron seems to pass gradually into old sea ice laden with the snowfalls of many years. It is hard to say where glacier ice ends and sea ice begins. There does appear to be a narrow strip of sea ice between the two piedmonts.

The general aspect of the coast-line is shown on Fig. 8; Evans Coves are immediately to the right. In line with Mount Melbourne is a very deep inlet, which is shown from a slightly different point of view. On Fig. 8 this is termed the Campbell Glacier. Farther to the west is another deep inlet (called by the Scott Expedition "Corner Glacier"). West again of this lies another deep inlet (called by them Priestley Glacier), apparently occupied by a large glacier. Farther still to the left is Mount Baxter, apparently of the order of about 8000 feet in height; and then to the left of this rises the majestic table-topped mountain, Mount Nansen, 8000 feet high according to Mawson's survey, 8788 feet according to the *Discovery* observations. This is capped with Beacon Sandstone, with apparently limestone below the above formation, the whole resting on a massive foundation of gneissic granite. Farther to the left is the wide, deep valley of the Reeves Glacier, with Teall Nunatak to the right front and Hansen Nunatak near the centre. The massifs of Mounts Larsen, Gerlache, and Crummer, also mostly of granite and entirely formed of crystalline rock, separate the Reeves from the Larsen Glacier on the left. Next the massifs of Mounts Bellinghausen, Gerlache, and Priestley separate the Larsen Glacier from the David Glacier.

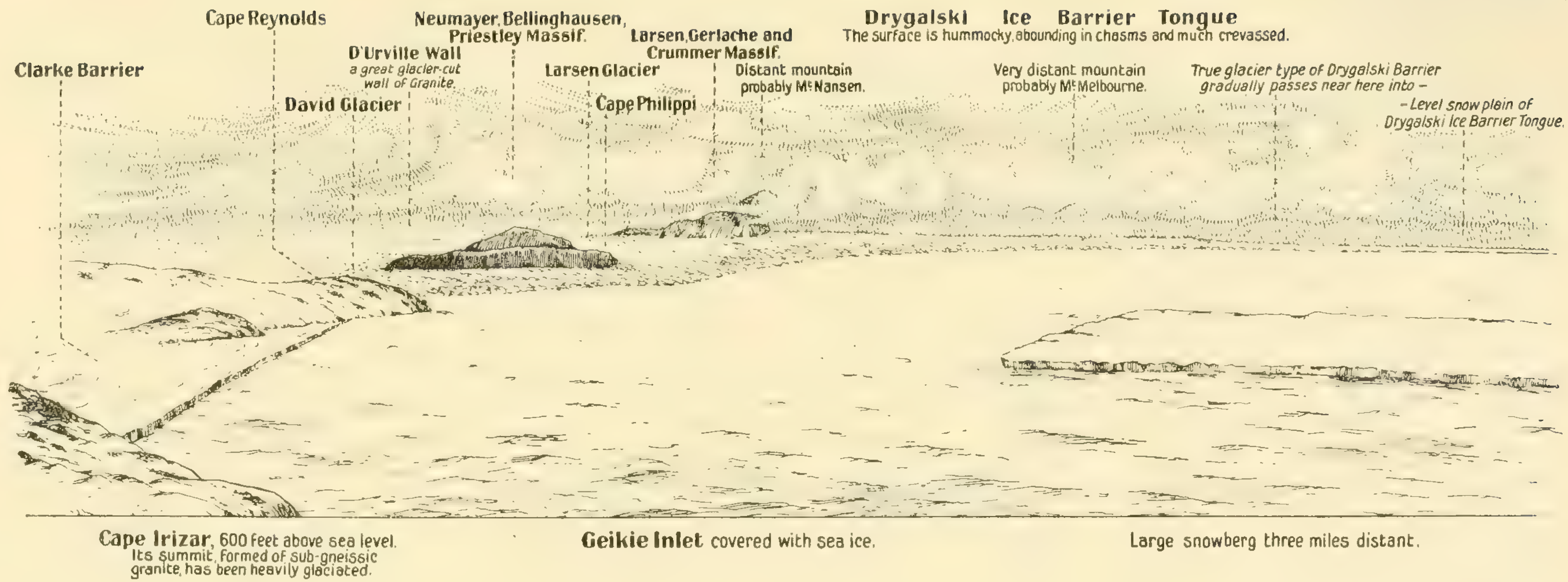
Time did not permit of an examination of the Campbell Glacier in 1908–9. It seemed formed of very gently-sloping glacier ice for a great distance inland. Corner Glacier probably contributes ice to the Nansen Piedmont, as does the Priestley Glacier.

The description of the ice formations between Terra Nova Bay and Geikie Inlet may commence with the Drygalski Barrier, and thence we will proceed inland up the glaciers. The Drygalski Ice Tongue is about 38 miles in length from the shore to its seaward end. At 10 miles west of its extreme point it is 7 miles in width, at 20 miles west it is 13 miles in width, and along the shore about 25 miles.

Its general appearance, as seen from Cape Irizar, is shown on the following sketch.

* Lieutenant Campbell's party of Scott's recent Antarctic Expedition discovered and explored several new glaciers contributing to this piedmont. They will shortly be described by Priestley.

PLATE X


Clarke Barrier
Cape Reynolds
David Glacier
D'Urville Wall
a great glacier-cut wall of Granite.
Neumayer, Bellinghausen, Priestley Massif.
Larsen Glacier
Cape Philippi
Larsen, Gerlache and Crummer Massif.
Distant mountain probably Mt Nansen.
Drygalski Ice Barrier Tongue
The surface is hummocky, abounding in chasms and much crevassed.
Very distant mountain probably Mt Melbourne.
True glacier type of Drygalski Barrier gradually passes near here into –
– Level snow plain of Drygalski Ice Barrier Tongue.
Cape Irizar, 600 feet above sea level.
Its summit, formed of sub-gneissic granite, has been heavily glaciated.
Geikie Inlet covered with sea ice.
Large snowberg three miles distant.

This sketch shows in the foreground on the left Cape Irizar, which at the point where the sketch was made is 600 feet above sea-level. The granite surface of this cape is strewn with erratics of intensely glaciated small pebbles of diabase, gabbros, hornblende-lamprophyres, sphene-granites and pink felsites, &c. The rock surface not only exhibits numerous *roches mountonnées*, but is powerfully grooved in a general W.N.W. and E.S.E. direction. This is a point of special interest, as a glance at the map will show at once that this is the trend of the David Glacier, the principal feeder of the Drygalski Ice Barrier. It is obvious that this intense glaciation of the summit of Irizar is due to an ancestor of the above glacier, at a time when it was confluent with the Davis Glacier. There must have been a considerable thickness of ice over the top of Cape Irizar to have produced this intense glaciation. At this time the David Glacier before reaching the coast must have been at least 20 miles in width instead of from 6 to 7 miles as at present. The contour of the hills grouped around Mount Neumayer is clearly indicative that they have been heavily glaciated close up to, if not right over, their summits. If this inference is correct—and there seems little reason to doubt it—the David Glacier at its present outlet near Cape Philippi * was formerly at least 2000 feet higher than at present.

On the north side of Geikie Inlet, and on the north side of the Drygalski Glacier, is a magnificent glacier-cut cliff, approximately 8 to 10 miles in length and some 1000 feet or so in height. It ends eastwards in Cape Philippi. At the back of this magnificent wall is the Mount Neumayer, Bellinghausen, and Priestley Massif. To the right, on the far side of the Drygalski Ice Barrier, rises the massif of Larsen and Gerlache, with the Larsen Glacier between. Dimly seen through the clouds on the day the sketch was made, behind Larsen is Mount Nansen, 70 miles distant, and still farther to the right is probably Mount Melbourne, 90 miles distant. It will be noticed that the surface of the Drygalski Ice Barrier is bristling with hummocks, ridges, and occasional seracs.

On approaching the glacier from the south side we found that the sea ice by degrees developed a more and more undulating surface. We heard the roar of a crack opening in the ice near by, and as it was at the time a calm day, this cracking was probably due to the pressure of the ice of the active Drygalski Barrier.† There were here two sets of sastrugi, one directed N. and S., the true blizzard sastrugi, the other directed about E. 35° S. and W. 35° N., produced by wind coming from that direction from off the plateau. The latter sastrugi are made by the land breezes or plateau wind, the great "consequent" air stream which blows from off the cold plateau at night on to the relatively warmer surface of Ross Sea. This

* Named after the distinguished geologist, the late Dr. Philippi, the associate of Drygalski on the Gauss-Antarctic Expedition.

† Some of these cracks, newly opened in the sea ice by the forward pressure of the Drygalski Glacier Ice, were about 10 feet in width.

wind started, at the end of November, between 8.30 P.M. and midnight, and blew at the rate of about 12 to 15 miles an hour until sometimes as late as about 9.30 A.M. the following morning, though usually it dropped earlier. Evidently in winter this plateau wind blows with intense violence, ripping out the old hard snow into deep chasms.

The effect of the twofold directions of these strong winds added to the undulations caused by the pressure which impels the ice forwards, and probably the etching effect of the sun on the ice and snow, combine to make the surface of the Drygalski Barrier in summer very difficult for sledging. As we advanced, the undulating old sea ice raised rounded ridges to bar our progress. The crests of the waves rose first to heights of 8 to 10 feet above their troughs; then to 20 feet; gradually, without any visible trace of a tidal crack, the sea ice rose to the blue or pale green ice of the glacier. The glacier surface here resembled that of a storm-tossed sea suddenly frozen. Long embankments of hard snow trending about E. 30° S. and W. 30° N., parallel to the plateau wind, joined billow to billow. The north-easterly faces of these embankments were precipitous and often overhung with a snow cornice, producing a seemingly endless series of more or less impassable ravines. On following the embankment for a few hundred yards it would be found that the bottom of the chasm shallowed, and it was found possible to lower the sledge and get across it.

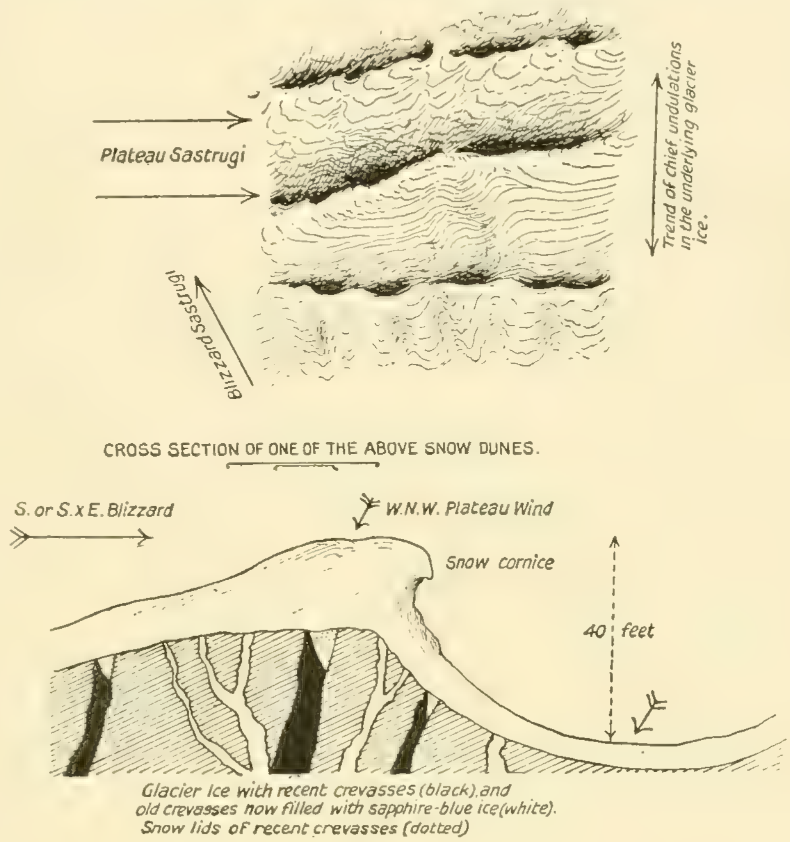


FIG. 9

The structure is illustrated diagrammatically in Fig. 9.

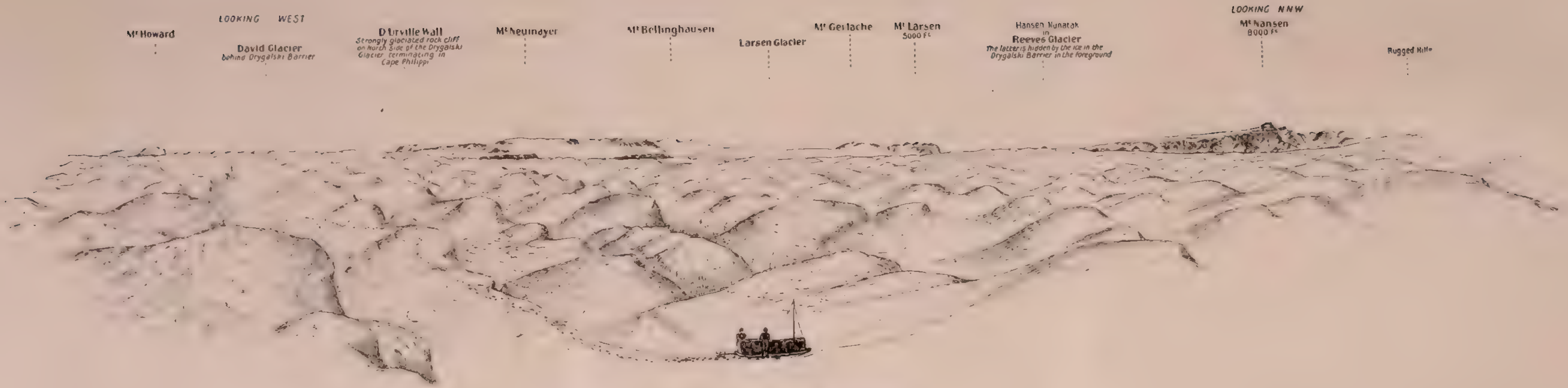
The extraordinary structure produced in the surface of this glacier as a result of a combination of pressure ridges, blizzard sastrugi, and plateau wind sastrugi, is shown on Plate XI. It presented a perfect labyrinth of high broken ridges, with gentle to steep slopes directed southwards, and vertical to overhanging cliffs with snow cornices directed northwards. These chasms were usually about 40 feet deep. According to aneroid levels, which cannot be considered very reliable, as the crossing of the Drygalski lasted for six days, the high portions of the Drygalski Barrier on the route where the northern party crossed it ranged from 130 feet to about a maximum of 200 feet above sea-level. At about a couple of miles south of its northern margin the Drygalski Glacier merged gradually into an undulating snow plain about 100 feet above sea-level. Where this terminates at Relief Inlet soundings were obtained by Davis, first officer on the *Nimrod*, in 624 fathoms. The bottom was a fine marine mud. If the density of the Drygalski Ice be taken as ·88, and the maximum height as 200 feet, the maximum thickness of the Barrier ice, on the line of section, would be about 1960 feet. Obviously, therefore, at Relief Inlet, where the thickness of the Barrier is only about 800 to 900 feet, the Barrier must be afloat; and even where the Barrier on our route of crossing was thickest, if the depth of sea water is still maintained southwards from Relief Inlet at over 3700 feet, the Barrier must be afloat there also. But the question is, Is the depth found at Relief Inlet maintained right under the Drygalski Barrier? As yet no soundings have been obtained in Geikie Inlet. Two miles E.S.E. of the end of the Barrier Captain R. F. Scott, in the *Discovery*, got a sounding of 300 fathoms, and at a spot 3 miles to the south-east of the Barrier end one of 368 fathoms. If this shallower depth of 1800 feet be maintained under the highest point of the Barrier on our route, viz. 200 feet, the ice there having a total thickness of 1960 feet, the ice there below sea-level would be about 1760 feet thick, so that it would just float in the 1800 feet of water. It therefore becomes a nice point as to whether the Drygalski Ice Barrier is for the greater part aground or afloat. Probably the centre is aground, the sides afloat. As already stated, no definite traces of a tidal crack were observed by us on the south side of the Drygalski, at the point where we first struck it, but at the point where we made our second (the successful) attempt to cross it there was a curious section of this kind (Fig. 10).

At Relief Inlet the crevasse into which Mawson fell probably marked one of many tidal cracks. The whole of the glacier is a perfect network of crevasses, and, on the assumption that many of them extend right down into sea water below the bottom of the Barrier, the Barrier must be capable of differential movements, so that it may be likened to a slab of flexible sandstone (itacolumite). The eastern extremity of the Barrier was determined by Scott to be 70 feet high. At a distance of 2 miles off it the water is 1800 feet deep, so that if this depth is maintained under the eastern end of the Barrier it must be afloat.

The curious growths of moss ice which were so conspicuous above the lids of the crevasses near our position, marked on map of Drygalski Ice Barrier 1.12.08, imply probably, as already suggested, that the crevasses for about 2 miles north of the

PLATE XI

[Between pp. 52 and 53



DRYGALSKI ICE BARRIER TONGUE

[*Between pp. 52 and 53*

southern margin of the Barrier at this point are filled with sea water. The convexly-shaped lids of the crevasses, met with on its northern side at about 2 miles back from the margin, suggest also that the fact of their being in relief is

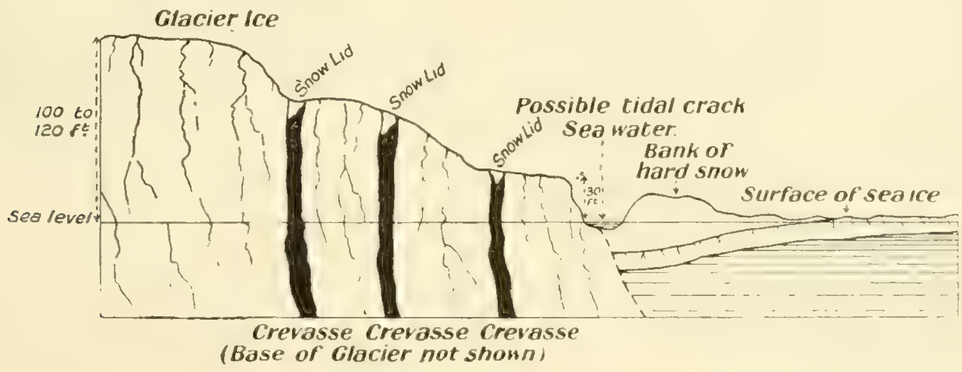


Fig. 10

due to sea water filling the crevasses at a depth, and constantly giving off vapour, which is built up in the form of arched girders across the tops of the crevasses. No trace of moss ice, nor of arched crevasse lids, was observed by us in the central part of the Drygalski Barrier. Diagrammatically the section appears to have been as follows :—

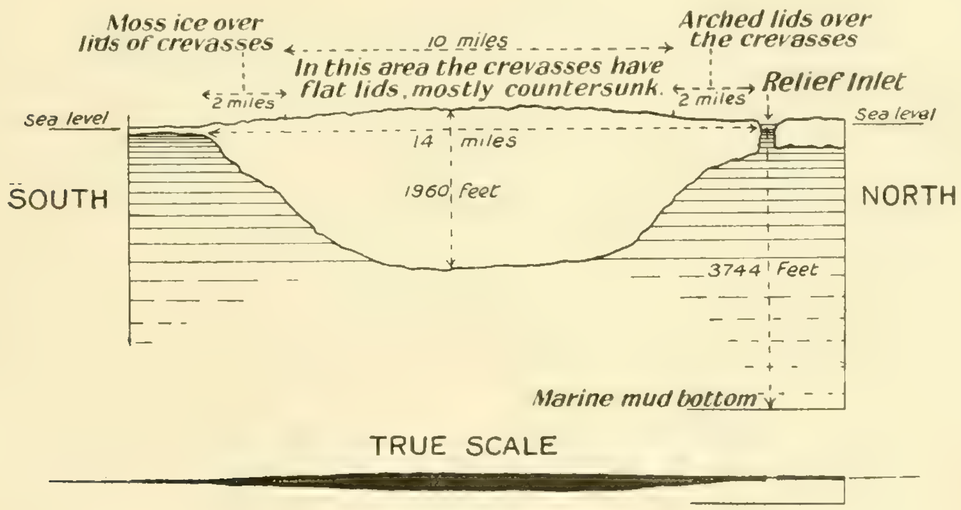


Fig. 11

It is, therefore, highly probable that there is actually sea water under the Drygalski Barrier on our line of march for 2 miles inwards from either margin. As far as the evidence of the structure of the lids of the crevasses go there is no evidence that there is sea water under the central 10 miles of the Drygalski Ice

Barrier, but this in itself is not evidence that the Barrier is aground. If we examine the evidence further on the north side of the Barrier as to whether or not there is a tidal crack the evidence is unsatisfactory, for all the sea ice had gone out at the time of our visit, and the Barrier ice was, as already stated, traversed by a network of cracks and crevasses, and was intersected with what we called ice barrancas and ice dongas. The origin of Relief Inlet (see Plate IX.), as well as of some of the ice barrancas and dongas, is almost certainly to be sought in shearing, the result of the forward movement of the Drygalski Barrier.

Relief Inlet has the form of a long, wide curving natural dock in the Barrier. Its general appearance is shown in Plate XII. Fig. 1.

The sea under the glacier near here is over 600 fathoms deep. The glacier is, therefore, there, probably a piedmont afloat.

In February 1909 there was open water at the bottom of the inlet for about 2 miles up from its mouth ; for the remaining 4 miles of the inlet, examined by us, it was floored across with sea ice, very much cracked, with sea water showing through the cracks and numerous seals lying on the ice. Its general appearance at the spot where we made our unsuccessful attempt to cross it on the return journey from the Magnetic Pole area is seen in Plate XII. Fig. 2.

This ice barranca, a continuation shorewards of Relief Inlet, is about 150 yards wide and 50 feet deep. It will be noticed that it curves to the left towards Cape Philippi, which is the northern boundary of the Drygalski Barrier on the coast.

At the point where we attempted to scale the cliff it was for its upper part wholly formed of snow, that is, for fully 20 feet. Perfect curtains formed of icicles concealed the middle part of the cliff from view, and its base was hidden by drift snow. It is difficult, therefore, to say whether this old snow was resting on old sea ice or on glacier ice. Relief Inlet, and the ice barranca in which it terminates inland, represent one of many shear planes which mark off the Drygalski Piedmont from the Nansen Piedmont.

In travelling from a point a short distance to the north of this barranca, on our outgoing journey to the Magnetic Pole Plateau, we passed a number of what we called "ice dongas." These had the appearance of small trough faults and step faults. Their appearance is shown in the following diagram (Fig. 12).

For some time before reaching the first ice donga Mawson and Mackay reported that sea water could be seen at the bottom of some of the cracks in the undulating surface of ice and snow over which we were sledging. The dongas, like the larger barrancas, are probably formed by shearing movements. Occasionally, but rarely, we passed by an ice knob some 10 feet above the general level of the plain, and they reported that they could see ice to a depth of 30 to 40 feet in the sides of a crevasse running through one of these knobs. After crossing this ice donga we traversed four pressure ridges, each of them with a small downthrow of 10

PLATE XII

Fig. 1. RELIEF INLET
A shear plane 200–300 yards wide in the Drygalski Ice Barrier, looking S.E.

Fig. 2. RELIEF INLET
A great shear plane in the Drygalski Piedmont

Fig. 3. POOL OF SEA WATER
Near pressure ridge of the Larsen-Drygalski Piedmont

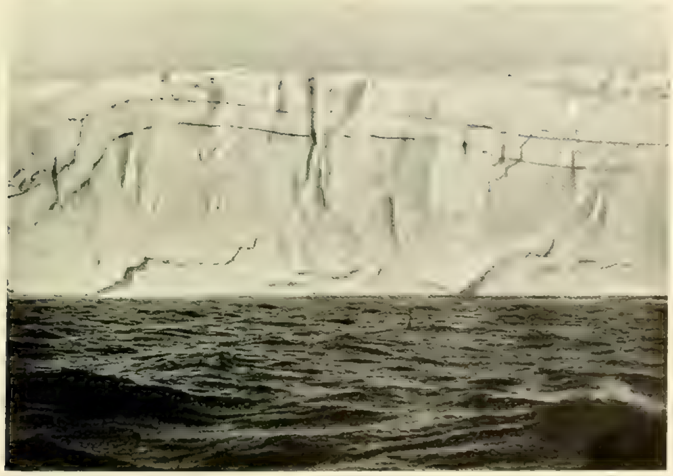


Fig. 4. ENGLACIAL MORAINE
In sea cliff of the Reeves Piedmont

Fig. 5. LOOKING TOWARDS THE REEVES GLACIER
With the Hansen Nunatak showing just over the sledge

[*To face p.* 54

to 15 feet in the direction of the Reeves Glacier. We were, consequently, still in the region of pressure of the Drygalski Barrier. Farther to the north-east was a large moraine bank with blocks of granite up to 7 feet in diameter. This was a reddish porphyritic granite, with pink orthoclase crystals up to 2 inches in diameter. It was associated with sphene-diorites, aplites, and fine-grained dolerite. This large moraine must either have been resting on the sea bottom, or was partly embedded in the surface of some old glacier ice. Sedimentary rocks were not noticed in this moraine. Farther to the north-west, after passing over a little more ice that looked like glacier ice, we passed, at the bottom of a gentle undulation, cracks in the ice with open water in the cracks. We tasted this, and found it to be very salt. There can be no doubt that it was sea water. Beyond, to the north-west, glacier ice belonging to the Reeves Glacier rose against us in great rolls from 50 to 80 feet in height, and traversed by a perfect labyrinth of crevasses.

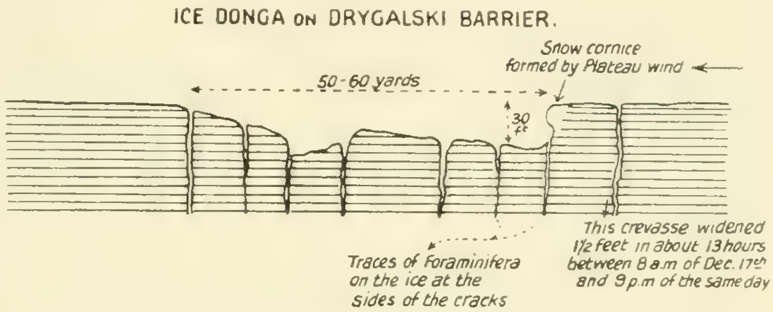


Fig. 12. ICE DONGA ON DRYGALSKI BARRIER

This "donga" is a shear plane or shear zone in the Drygalski Barrier, due to differential movement. The central parts of the donga are probably old sea ice

The line of demarcation between the Nansen Piedmont and the Drygalski Piedmont may, therefore, be drawn provisionally at these cracks in the sea ice. In retreating from the all but impassable ice waves of the Reeves Glacier towards Backstairs Passage (see Plate IX.) we reached another extensive moraine.

In addition to numerous large boulders of granite, we found here fragments of sandstone and limestone with small pieces of grey clay shale showing faint impression of rootlets (?). This was, no doubt, derived from the Beacon Sandstone. Each boulder was surrounded by a thin crust of ice, through which, when sledging, we continually broke, falling into the thaw-water below. Between this moraine and the rocky coast at Backstairs Passage, a distance of about 1 mile, was a stretch of what certainly appeared to be sea ice, with an occasional open pool like that shown in Plate XII. Fig. 3.

At the back of the pool is a pressure ridge in the glacier ice or old sea ice. This pressure appeared to come from the Drygalski part of the Barrier. Still farther inland were marine muds, forming conical mounds resting on a foundation of ice. The muds were 20 to 30 feet above sea-level, and washed in among the boulders. This ice tasted slightly saline, but not as salt as typical sea ice. Probably it was old glacier ice; its salinity was due to its having been over-ridden by upthrust marine sediments. In one place on this same moraine we observed a very large and delicate compound siliceous sponge firmly attached by growth to a granite boulder. (See figure in Chapter on Raised Beaches.)

These muds, which are probably of the nature of upthrust marine muds, are described in detail in the Chapter on Raised Beaches. The structure of the piedmont between the Drygalski-Larsen and the Reeves Glaciers has been described in detail, as it is of great import in the glaciology of this interesting region, and is the key to the mystery of the Ross Barrier, as will appear later.* When ascending Backstairs Passage we observed two considerable moraines sweeping out from the shore

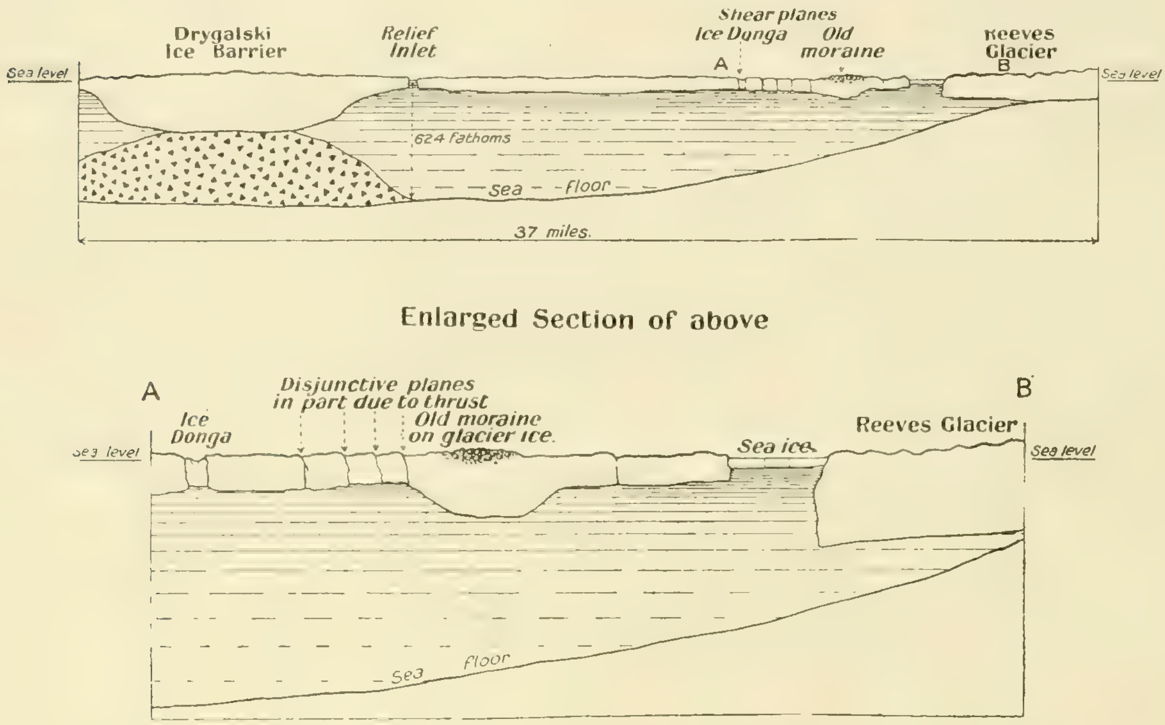


Fig. 13. SECTION ACROSS THE DRYGALSKI PIEDMONT, AFLOAT FOR A GREAT PART

at the foot of the Reeves Glacier seawards. In travelling from the Drygalski Glacier around the ice cliff of Terra Nova Bay to Evans Coves, one of our colleagues on the *Nimrod* took a photograph of the ice cliff with dirt bands embedded in it (Plate XII. Fig. 4).

While much still remains in doubt, a section may be drawn provisionally from the farthest point of our route up the Reeves Glacier to the Drygalski Barrier at Relief Inlet, and thence to the point where we first reached the southern side of the Barrier (Fig. 13).

* A summary of the Drygalski and Reeves Piedmont will be given when the rest of the evidence supplied by its feeding glaciers has been stated.

Reeves Glacier. Viewed from the Drygalski-Reeves Piedmont, the Reeves Glacier is a magnificent spectacle, some slight idea of which may be gained from the photograph, Plate XII. Fig. 5.

Mount Nansen is here seen from a distance of about 35 miles, and Mount Larsen from a distance of about 20 miles. Hansen Nunatak, near the centre of the glacier, rises to a height of about 2800 feet. It is a most impressive and majestic monolith. The most striking glacial feature in this landscape is the stupendous granite cliff of Mount Larsen, which towers some 3000 feet above the glacier ice at its base. There can be no doubt that during the maximum glaciation the ice of the Reeves Glacier pressed high up against the giant cliff of Mount Larsen, and must have almost, if not altogether, overtopped it. The general outline of its summit is very suggestive of its having been completely glaciated. The Reeves Glacier is an immense outlet glacier, about 12 miles in width, and about 25 miles in length measured up to the area on the west side of the great horst, where it merges gradually into the snow-field of the Magnetic Pole Plateau. Fig. 14 shows details of the Larsen-Gerlache-Crummer Massif, which separates the Reeves Glacier from the Larsen Glacier.

The Reeves Glacier falls about 4000 feet in its 25 miles of length. Two moraines derived from it are conspicuous, the northern and larger one derived from near Teall Nunatak, and the other from neighbourhood of Hansen Nunatak. As already stated, these sweep out to sea across the Nansen Piedmont. The surface of this glacier undulates strongly, and is very heavily crevassed.*

Backstairs Passage is a shallow and narrow breach in the rocky massif which divides the Reeves Glacier from the Larsen Glacier. It may be described as a small spillway and branch of the Larsen Glacier. It is about a quarter to a third of a mile in width, and about 2 miles in length. In this distance it ascends about 1500 feet. Though somewhat steep it is only slightly crevassed, and on the whole offers a good surface for sledging.

The next glacier to the south is the Larsen. It is from 2 to 3 miles in width, and, like the Reeves Glacier, is about 25 miles in length. In this distance it falls over 3000 feet, its slope being very steep just before it reaches the coast. It descends there in a turmoil of great pressure ridges, heavily crevassed, to join the Drygalski Piedmont. North-westwards from its junction with Backstairs Passage right on to the plateau the Larsen Glacier is not very seriously crevassed, and affords a good road on to the plateau for sledging parties. The Larsen Glacier shows every evidence of having at one time overridden Mount Crummer, which now rises approximately 1500 feet above its surface.

* When attempting to force a passage up it our sledge was on several occasions all but engulfed from the collapse of the snow lids, and dragging a sledge up the rolls of slippery ice is extremely laborious. The glacier might, nevertheless, be traversed by a party who could afford an abundance of time for the purpose. By far the best track so far found for any one desirous of mounting the plateau in this vicinity is Backstairs Passage.

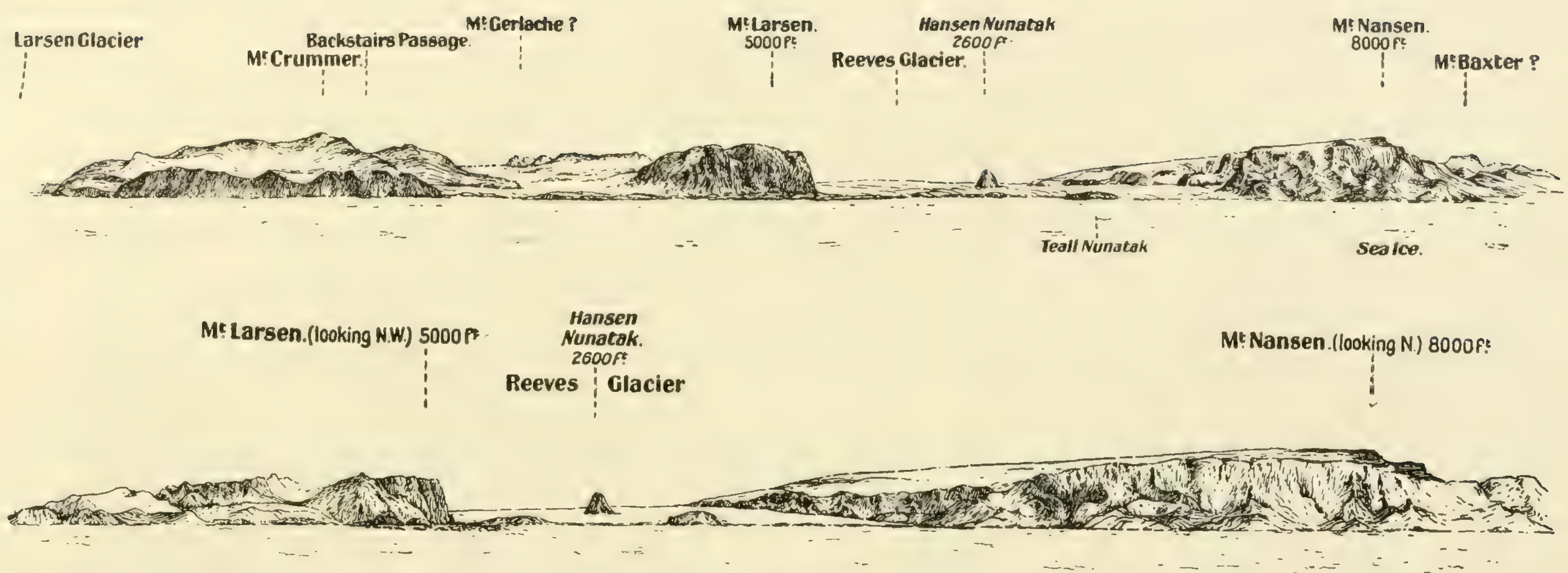


Fig. 14. SKETCH SHOWING ANTARCTIC COAST, ROSS SEA, BETWEEN LARSEN GLACIER AND MOUNT NANSEN

Fig. 1. BACKSTAIRS PASSAGE GLACIER
Looking north to Mount Melbourne

Fig. 2. LOOKING S.E. DOWN BACKSTAIRS GLACIER
With Mount Crummer to right

Fig. 3. MAGNETIC POLE PLATEAU
Mount Larsen to left, Mount Bellinghausen to right

Fig. 4. MAGNETIC POLE PLATEAU
About 80 miles inland, looking north towards the distant plateau ranges. On right the snowfield falls toward the Reeves Glacier [Photo D. Mawson

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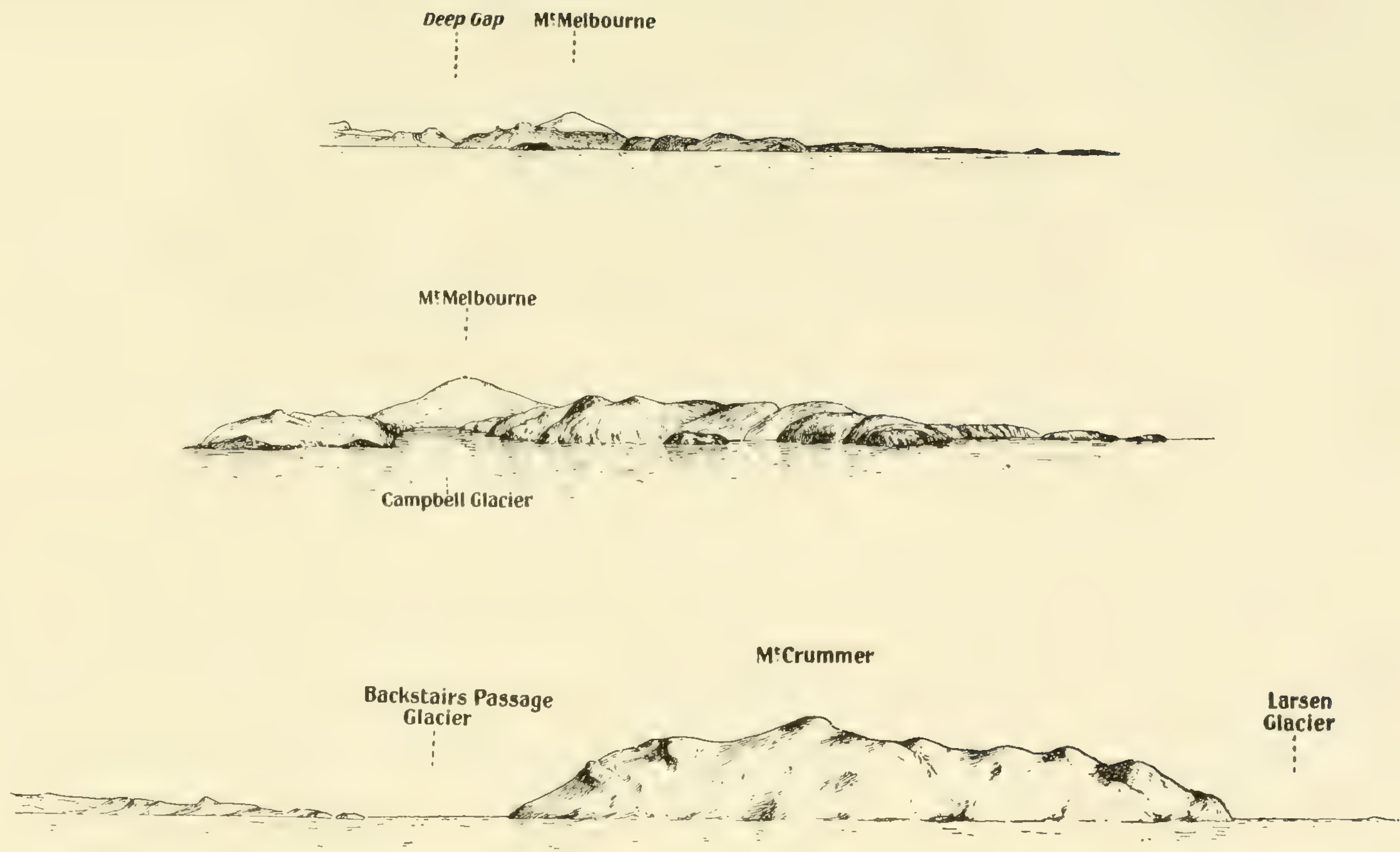


FIG. 15. SKETCHES LOOKING NORTH WHEN ASCENDING BACKSTAIRS PASSAGE GLACIER. THE LOWEST VIEW IS LOOKING SOUTH-EAST

The outline of Mount Crummer, and the outlook from the Backstairs Glacier, in the direction of Mount Melbourne, are shown on the sketches on Plate XIII.

The David Glacier. This glacier is another of the outlet or spillway type. At Cape Philippi it is about 8 miles in width. It also appears to be about 25 miles in length. Heavy ice-falls could be seen far inland up this glacier as viewed from the sea ice. Its surface is so rugged as to be almost impassable. It is evidently an important outlet for the snow-fields of the plateau. Its great pressure ridges, shearing planes, and numerous crevasses testify to its activity.

Snow-fields and Ice-fields of the Magnetic Pole Plateau. Plate XIII. Fig. 3 shows the general appearance of the snow-fields at the back of Mounts Larsen and Gerlache.

A study of this photograph makes it clear that the summits of Larsen and Nansen would be easily overridden by an ice sheet were the snow surface about 2000 feet higher than it is at present.

The surface of the plateau was found to undulate in broad billows about 40 to 50 feet deep, and many hundreds of yards from crest to crest. A crevasse was observed as far inland as 55 miles from the coast, and ice-falls, formed above of hard marbled snow, were observed at a total distance of 70 miles inland. The whole snow-field must, therefore, be in a state of slow movement, at least as far inland as this. Strong undulations in the snow surface, still about 50 feet deep from trough to crest, continued inland for fully 90 miles back from the shore, and 70 miles back from the inner edge of the plateau horst. From this last distance of 90 miles inland the undulations lessen, and could not be recognised near the summit of the plateau. This attains an altitude of 7350 feet at a distance from the coast at the Reeves Glacier of 180 miles. No trace of any material approaching to ice could be seen on the inland side of the ice-falls, the latter being situated 70 miles inland.

A sketch of the general outline of the ranges bounding the Reeves Glacier from Mount Nansen north-westwards through Mount Baxter and Mount Mackintosh is shown on Fig. 15 and on Fig. 4 of Plate XIII.

The plateau character of the inland ranges is very obvious in the sketches; some of the rocks—particularly those of Mount Mackintosh—appeared to be very black, which suggests that they may be formed of basic material. They are largely formed of Beacon Sandstone. It will be noticed from the section on Plate XIV. that the summit of the Magnetic Pole Plateau is very flat, not varying in height by more than 50 feet over a distance of 30 to 40 miles. In a distance of 35 miles a fall of about 90 feet was recorded by us in a general direction towards the north-west from the summit of the plateau to the farthest point reached north-west. Our direction of march at the time was about N. 30° W., and it was in this direction that the slight fall was recorded. It does not, of course, follow that this was the direction of greatest fall. That we actually passed over the summit of the plateau before reaching our farthest point north-west, is proved, apart from the levels, which in themselves are slender evidence, by the remarkable and complete change in the direction of the prevalent winds. As indicated by the trend of the sastrugi they blow to the east of the summit towards Ross Sea, to the west of the summit towards Adélie Land.*

Structure of Inland Snow. It is much to be regretted that, owing to lack of time and food, we were unable to sink a shaft, much as we wished to do so, in the inland snow-fields to discover their structure. The importance of this has been impressed by us upon the Australasian and British Expeditions in Antarctica in 1911–14. Sastrugi, 3 feet deep, failed to reveal anything more than tough snow. No distinct trace of granulation was noticed; in fact, no true *névé* seemed to form

Fig. 16

in this surface portion, on account, doubtless, of the extreme cold and dryness of the plateau. The granulation process may be said to be at a minimum on the high plateau.

SUMMARY AND PAST HISTORY

The whole length of the Reeves and Larsen outlet glaciers with their snow-fields and piedmonts is approximately 200 miles, made up as follows:—

	Miles.
Snow-field and underlying ice	155
Outlet glacier	25
Piedmont	20

In the case of the Larsen Glacier its piedmont merges in that of the Drygalski Glacier, and so has the length of 38 miles, as compared with 20 in the case of the Nansen Piedmont. In the case of the David Glacier, only the length of its piedmont, the Drygalski Ice Barrier, is known, and that is 38 miles.

* This fall of the plateau to the north-west is now quite confirmed by the recent observations of R. Bage, S. Webb, and C. F. Hurley of Dr. Mawson's Australasian Expedition. They found the plateau rose steadily from Adélie Land to 5900 feet, their farthest point reached, in lat. 70° 36′ S., long. 148° 12′ E.

These large active glaciers are the outlets for the inland snow- and ice-fields. They are nourished by snows, which probably fall mostly in spring, autumn, and winter. These snows are borne inland at a high level, partly by the widespread Antarctic cyclone, the high level constant W.N.W. to N.W. wind, partly by a local intermittent N.E. wind coming off Ross Sea. The indraught of the latter is due partly to the physiographic relief of the plateau giving a comparatively steep down grade towards Ross Sea, partly to the difference in the specific heats of ice and sea water, which leads to a much greater daily range of temperature on the plateau than at sea-level, the daily range on the plateau being about 20° Fahr., while that at sea-level is only about 6° Fahr. This big range of temperature encourages air currents. At night, in December–January (the time of our observations), the rapid chilling of the plateau surface starts air currents—the plateau wind, of the nature of a land breeze. By about 9 A.M. the following morning the sun, if the day is fine, has so warmed the plateau that the land breeze, or föhn, is entirely checked, and the withdrawal by night of cold air masses off the plateau having established a high level down gradient from Ross Sea towards the plateau, snow-bearing air currents stream in over the plateau from above the open water of Ross Sea from the north-east.

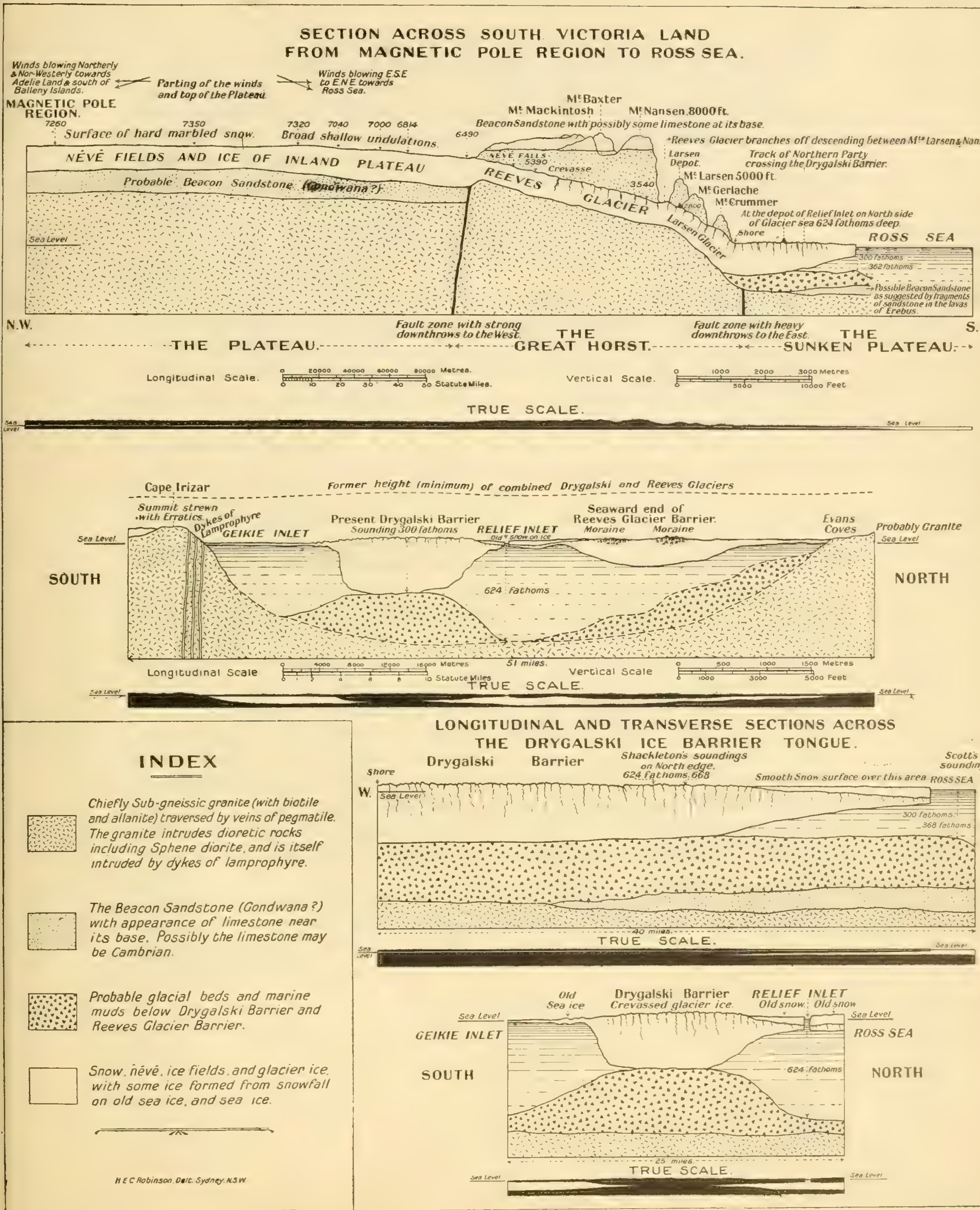
The Reeves Glacier fans out on reaching the sea coast to form the Nansen Piedmont, stretching seawards for 20 miles. This piedmont is joined by sea ice to the Drygalski Piedmont.

The Larsen and David Glaciers together form the Drygalski Piedmont, which extends seawards for 38 miles from the coast. At its sides, especially its northern side, where there is a great accumulation of drift snow from the southerly blizzards, and for a distance of about 10 miles west of its seaward end, the Drygalski Barrier is afloat. The central part of the Drygalski Barrier is probably aground on its own bottom moraine or submarine esker. This ice mass is still in forward movement, perhaps a yard a day in December, as proved by the great shear planes which have produced Relief Inlet and the ice barrancas and dongas. Further proof of this movement is afforded by the upthrust marine muds, as described in our Chapter on Raised Beaches.

The bottom moraine and fluviatile material of the Drygalski Barrier is probably of great thickness, perhaps of the order of 1500 to 1800 feet, as suggested by the only three soundings available. According to this view, the piedmont is riding on a species of railway embankment, which it has constructed as a support for itself when, as the result of its increasing buoyancy, as deglaciation succeeded the time of maximum glaciation, it tended to float up higher and higher above the rocky bed of the Terra Nova Bay.* That during the maximum glaciation it must have completely filled even the deepest hollows alongside of it, such as the 668 fathom

* That there are passages for ocean currents under the ice over the top of the embankment is rendered probable through the persistent pool of open water north of the Drygalksi Tongue.

PLATE XIV



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sounding at Relief Inlet, is abundantly proved by the positive evidence of the former height of the ice flood during the maximum glaciation. The most conservative estimate of the heights up to which the adjacent mountains have been glaciated places the former thickness of the ice here as at least 1000 feet, almost certainly 1500 feet, and in the case of the Reeves Glacier probably 3000 feet higher than it is at present. Therefore at Relief Inlet during the maximum glaciation the ice would have been 668 fathoms + 1000 feet = in round numbers 5000 feet thick.

Thus we have evidence of three kinds as to the extent of former glaciation :—

1. The height to which the rocks above sea-level are glaciated above the level of the adjacent glaciers.

2. The depth to which the rocks below sea-level have been scooped out by the old glaciers when they pressed hard on their rocky bed, as at Relief Inlet.

The sounding of 624 fathoms at Relief Inlet does not probably represent the full former thickness of the Drygalski ice below sea-level, as the driving tube on each of the three soundings made at this point always brought up with it fine marine mud. It may be noted that about 2 miles farther east we obtained a sounding of 668 fathoms.

3. The height to which the Drygalski Barrier has aggraded its own bottom moraine and submarine eskers as it gradually floated up higher and higher as the deglaciation progressed.

That the Drygalski Barrier is an outlier of the former Great Ice Barrier, which during the maximum glaciation was continuous with the Drygalski-Nansen Piedmont, will become clear when the glacial evidence along the coast between the Drygalski Barrier and the Ferrar Glacier is being discussed.

It is much to be hoped that many more soundings will be secured along the coast and in various parts of Ross Sea by the present British Antarctic Expedition. It would be of great interest to further develop by sounding the contour of the sea floor eastwards of the present termination of the Drygalski Barrier. It would obviously also be of importance to secure soundings in Geikie Inlet. Much light will be thrown on the structure of the Ross Barrier by a further study of the Drygalski-Reeves Barrier. Its structure, compounded, as it is, of a number of ice jetties united by strips of old bay ice reinforced with the granulated snowfall of many years, makes the Drygalski-Reeves Piedmont in many ways a key for the interpretation of much that is at present puzzling in the structure of the Ross Barrier.

Lastly, it may be added that the observer cannot but be impressed with the stupendous erosive power of the glaciers of this region during maximum glaciation. The D'Urville Wall and northern cliff face of Mount Larsen are eloquent tributes to the facetting power of glacier ice.

CHAPTER IV

GLACIOLOGY (*continued*)

CAPE IRIZAR TO DRY VALLEY

From Cape Irizar southwards to the Ferrar Glacier, a distance of over 150 miles, the coast belongs to a somewhat sunken region on the line of the Antarctic Horst. While Mount Nansen on the north rises to over 8000 feet above sea and the Royal Society Range on the south to nearly 13,000 feet above the sea, there are only a few of the coastal mountains within the area now being considered which exceed 5000 feet in altitude.* One exception to this rule is Mount Davidson, the height of which is given by Scott as 8127 feet. The plateau character of the rocks is obvious. An old peneplain of crystalline rocks is capped with Beacon Sandstone throughout the greater part of this coastal section. The sandstone itself is mostly capped by sheets of black rock, probably sills of diabase. It is possible that some of them may represent contemporaneous lavas. The horst in this region is breached by transverse valleys having a general east and west trend. Taken in order from north to south, these are :—

1. The Davis Glacier, with the Clarke Barrier to the north and the Cheetham Ice Tongue to the south.
2. The Harbord Ice Tongue.
3. The Nordenskjöld Ice Tongue, and Mawson Glacier with the Cotton Glacier.
4. The Fry Glacier.
5. The Penck Glacier.
6. The Mackay Glacier, with the Geikie Glacier.

Cape Irizar, a bold headland of pink granite with hornblende, biotite, and allanite, traversed by dykes of lamprophyre, forms possibly part of a long island, Lamplugh Island, trending north by east and south by west. To the south it is bounded by the Cheetham Ice Tongue. On the north it is bounded by Geikie Inlet, and on the west by the Clarke Barrier. The island, if it be an island,†

* Viewed from the top of Mount Erebus by Priestley and a sledge party of the Scott Expedition of 1910–13, mountains seen far inland at the back of Granite Harbour, &c., appeared to rise to heights of over 8000 feet.

† The uncertainty is due to the fact that inland it dips sharply under the low-lying ice sheets of the Clarke Glacier and Davis Glacier, and it is just possible that it may prove eventually to be a peninsula, but it is probably an island.

is about 10 miles in length by about 2 miles in width. The general appearance of Cape Irizar and the coast in its neighbourhood is shown on the sketch below (Fig. 17). The observer is looking about W.S.W. up the Clarke Glacier, with Mount Howard in the distance.

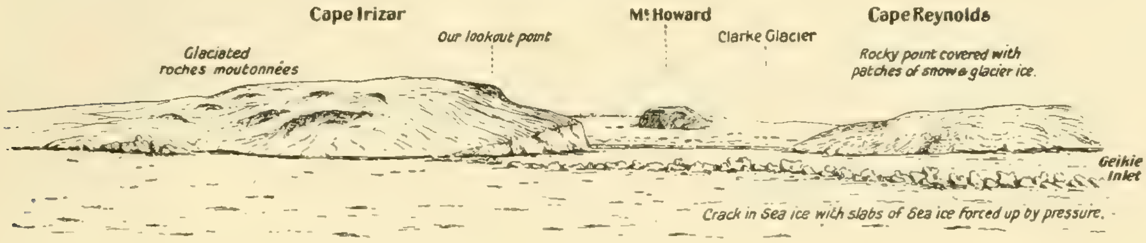


Fig. 17. View of coast looking to W.S.W. at point 8 miles south of Drygalski Ice Barrier Tongue

The next sketch (Fig. 18) shows Cape Irizar itself, about 600 feet high, formed of biotite allanite granite peeping out in places from under the ice calotte. The

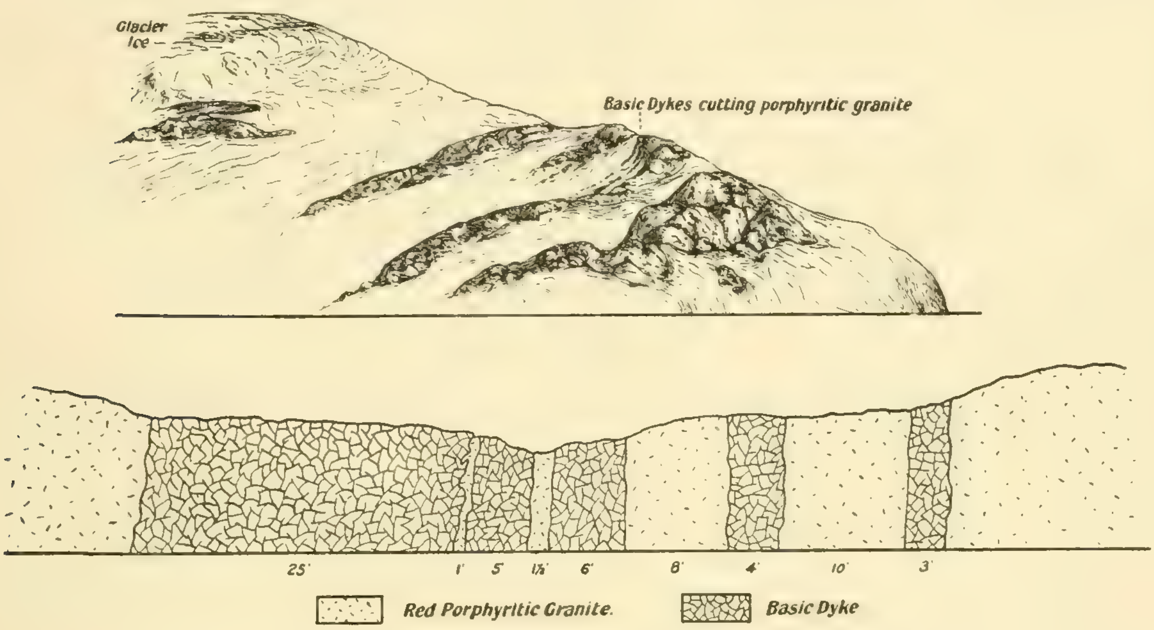


Fig. 18. DETAILS OF CAPE IRIZAR AND ITS ICE CALOTTE

The section below is taken across the basic dykes shown in the upper sketch

granite is intersected by an interesting group of kersantite dykes, described by Dr. Mawson in his chapter relating to the petrology of this area.

On either side of the dykes, for a distance of a few feet, the felspars of the granite were deeply reddened as the result of contact metamorphism. This granite was also traversed by acid dykes, apparently aplitic in character, and of earlier origin than the basic dykes. These acid dykes are lenticular in character.

The granite is traversed by small veins of a dark mineral which is probably biotite or schorl. The granite showed evidence of having been very heavily glaciated, showing that recently there was a great thickness of ice over its summit. On the summit were numerous erratics of gabbro, dolerite, hornblendic dyke rocks, sphene-granite, pinkish-grey felsites, &c. Between the Drygalski Ice Barrier and Cape Irizar we encountered several formidable cracks in the sea ice, evidently caused by the forward thrust of the Tongue. On November 28, 1908, we heard one of these cracks open with the peculiar noise of ice when being riven.

It will be seen from this sketch that Prior Island is isolated from the mainland rocks on the left by a low stretch of piedmont glacier ice, which appears to be confluent with the Davis Glacier. Its height as estimated is only very approximate. Its strongly glaciated outlines are proof of a considerable thickness of ice having at one time over-ridden it. The sketch shows that the ice at its base, to the right, is now only 20 feet or so above sea-level. On the next sketch, taken 2 miles

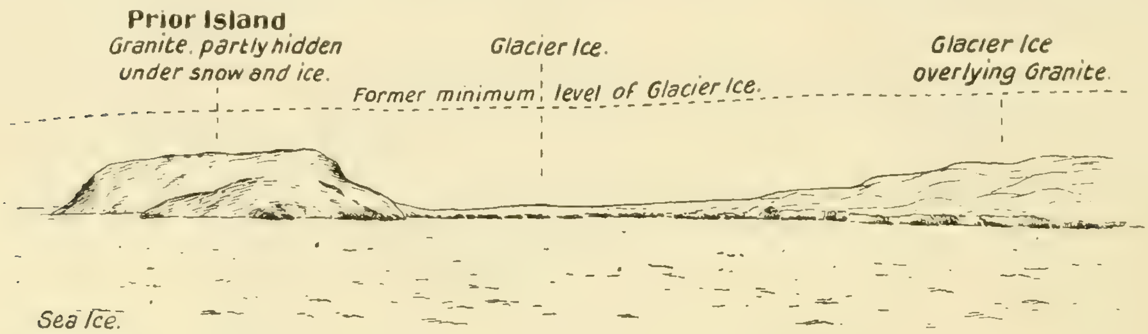


Fig. 19

farther south, it will be seen that the north-east end of Prior Island is somewhat rugged and unsmoothed, so that evidently this was the lee side during maximum glaciation.

The nature of the main coast-line immediately to the S.S.W. of Prior Island is shown on the lower sketch of Fig. 20.

The gneissic granite on this part of the mainland was here very heavily glaciated in a general north-east direction, and the exposed surfaces were remarkably fresh. As weathering, due to the great diurnal changes of temperature, is very rapid in these regions, the exposure of these rock surfaces through deglaciation must have been very recent.

The direction of the striæ pointing towards the end of the Drygalski Ice Barrier Tongue is interesting. The striæ on top of Cape Irizar trend towards E.S.E., and were evidently formed by an ancestor of the David Glacier; while those near Prior Island trend towards the north-east, and were no doubt produced by an ancestor of the Davis Glacier. It is clear that the whole of the island, of which Cape Irizar is the northern end, has been formerly over-ridden by an ice sheet, the top of which, at a minimum estimate, cannot have been less than 1000 feet above sea-level, where the surface of the piedmont glacier is now only from 20 to about 50 feet above sea-level.

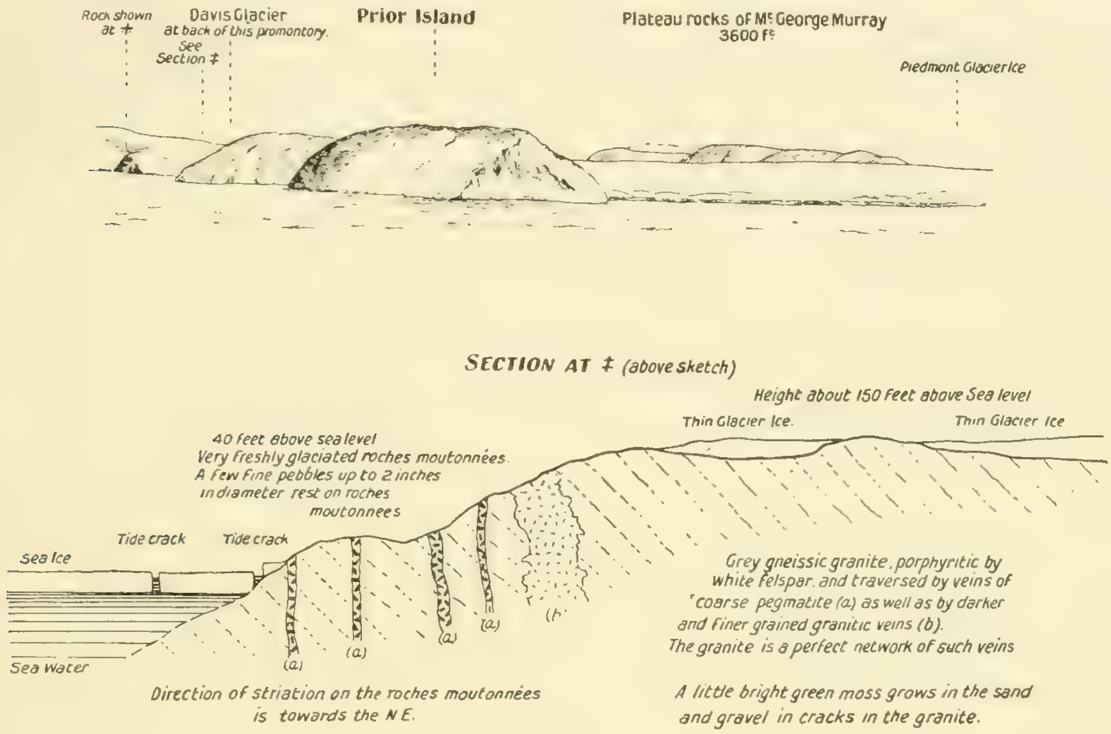


FIG. 20

The next outline sketch of the coast was taken at 16¼ miles south of the Drygalski Ice Barrier Tongue, and just north of the Cheetham Ice Tongue, looking westerly.

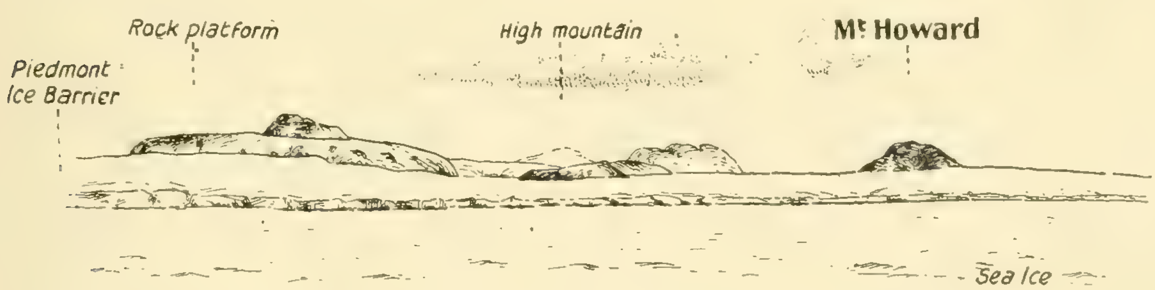


FIG. 21. West coast of Ross Sea, 16¼ miles south of Drygalski Ice Barrier Tongue, looking westerly

It shows an extensive coastal piedmont aground, with the plateau rocks in the background. Mount Howard has a very dark appearance, suggestive of dolerite or other basic rock.

The next object of interest southwards is the Cheetham Ice Tongue, 17 miles south of the southern side of the Drygalski Ice Barrier.

This small Tongue was about 40 feet in height, and seemed largely formed of snow. At the time it appeared doubtful whether it was a true ice tongue or merely a grounded or frozen in snow-berg. Mawson has shown it on his map as a tongue, and this view has been provisionally adopted. Mawson shows it as being attached to the Davis Glacier.

At 19 miles south of the Drygalski Barrier is the Davis Glacier proper. It is very heavily crevassed. Its general appearance at its seaward termination, seen at a distance of about 3 miles, is shown on the next sketch.

Fig. 22

Judged from the height of the rock at the left of the sketch, the terminal end of the Davis Glacier may range from 300 to 500 feet above sea-level, possibly more.

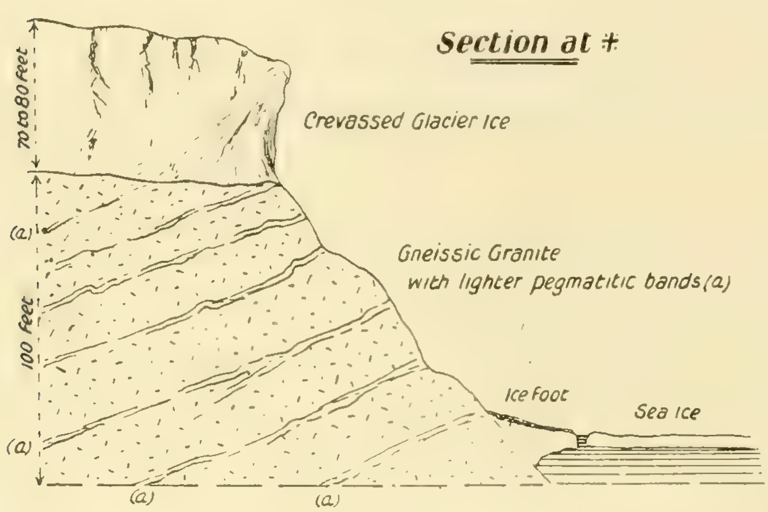


Fig. 23

It is improbable that the height of any point along the coast from the Davis Glacier to Cape Irizar, following the coastal piedmont, exceeds 1000 feet in altitude. Below is a section of the piedmont ice resting on a rocky point of gneissic grey granite with veins of pegmatite. It will be seen from this that the piedmont glacier ice at the cliff face here is only from 70 to 80 feet thick, and at the top of the cliff about 180 feet above sea-level. The ice at the back rises to a considerably greater height, but probably does not much, if at all, exceed 600 feet, the ascertained height of Cape Irizar.

Fig. 24 is a continuation of the preceding section, showing the coastal piedmont aground for a farther distance of about 10 to 12 miles southwards.

Mount George Murray is about 20 miles distant, and 17 miles back from the coast-line. The width of the coastal plain, on which the piedmont rests, is here about 15 miles. (See Fig. 26.)

The Harbord Ice Tongue is about 30 feet in height at its eastern end, about 1 mile wide, and 5 miles long. It will be noticed that there is a very wide breach

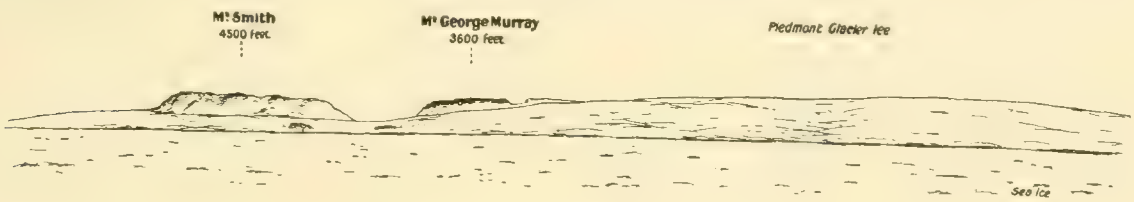


Fig. 24

in the plateau between Mount George Murray and Mount Howard, through which gap the ice from the inland plateau passes seawards.

The total aggregate length of coast seen in these two sketches is about 28 miles. The coastal piedmont is about 15 miles wide.

The outlines of the hills to the left of Mount Smith suggest that they have been intensely glaciated right over their summits. The next sketch of the part of the coast which follows immediately to the south shows its configuration near the Mawson Glacier. In the foreground, just back from the coast, is the glacier ice of the piedmont. This gradually passes on to an intensely glaciated rock terrace,

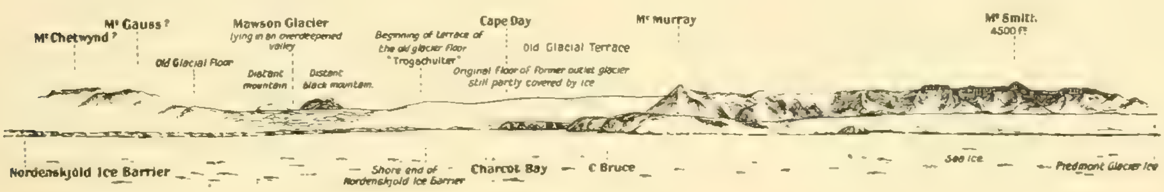


Fig. 25

seen at the centre of the sketch. This terrace is much overspread with large patches of morainic material (Fig. 25).

The sharp peak at the back of this terrace is Mount Murray; it is evidently formed of a granitic rock, and its outlines showed evidence of its having been glaciated over its summit. It is of the nature of a tind. The wide gap between Mount Smith and Mount Gauss, at the bottom of which lies the Mawson Glacier, shows clear evidence of former much more extensive glaciation. The shore end of Nordenskjöld Ice Tongue is shown just to the left of Charcot Bay.

This part of the coast appearing to be of special interest, several sketches were made of it.

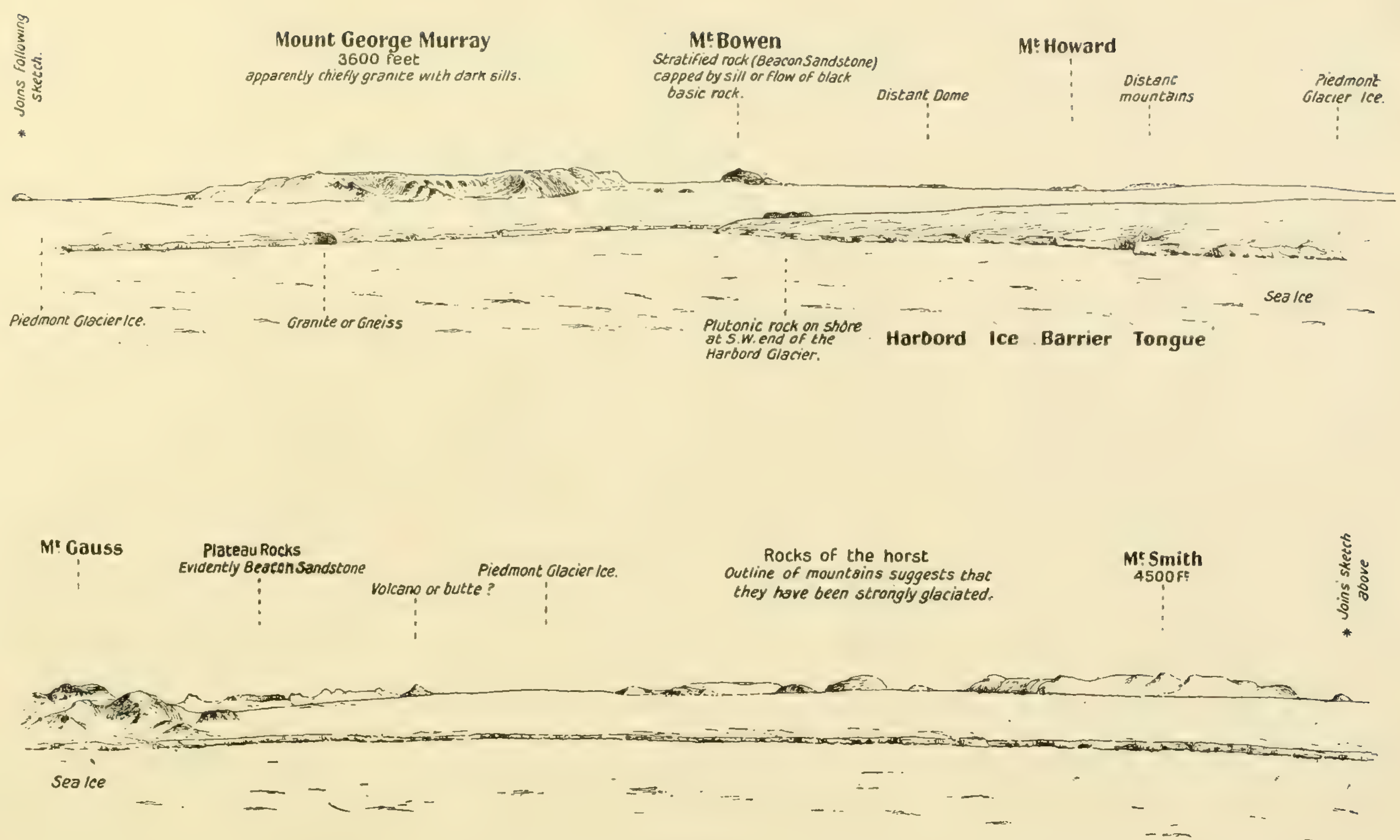

* Joins following sketch.
Mount George Murray
3600 feet
apparently chiefly granite with dark sills.
Mt Bowen
Stratified rock (Beacon Sandstone) capped by sill or flow of black basic rock.
Distant Dome
Mt Howard
Distant mountains
Piedmont Glacier Ice.
Piedmont Glacier Ice.
Granite or Gneiss
Plutonic rock on shore at S.W. end of the Harbord Glacier.
Harbord Ice Barrier Tongue
Sea Ice
Mt Gauss
Plateau Rocks
Evidently Beacon Sandstone
Volcano or butte ?
Piedmont Glacier Ice.
Rocks of the horst
Outline of mountains suggests that they have been strongly glaciated.
Mt Smith
4500 Ft
* Joins sketch above
Sea Ice

Fig. 26

Fig. 26 is a panorama taking in about 20 miles of coast from the Harbord Ice Barrier Tongue to Mount Gauss. The view is taken from the flat top of the Nordenskjöld Ice Tongue, looking north-west towards Mount George Murray, and west by south towards the Mawson Glacier.

The point of attachment of the Nordenskjöld Ice Tongue to the Mawson Glacier can be seen just at the point where that glacier comes down to sea-level. This attachment is much constricted by a long narrow gulf on the southern side of the Tongue, and by Charcot Bay on the north.

The erosive force of the sea, impelled by the fierce southerly blizzards, threatens soon to betrunk the piedmont, and separate it entirely from its parent glacier. There is a great contrast between the appearance of this glacier on this southern side as compared with that of its northern. The photograph shows the features of the northern edge of the Tongue.

Northwards this Tongue terminates in a precipice from about 50 to 70 feet in height. At the point where we crossed it, we discovered a very steep snow slope, shown in the photograph, down which we lowered the sledges. At the top of the cliff was a species of crevasse, separating the slope of hardened snow from the barrier edge. This crack was apparently due to a settlement of the snow drift, and in this settlement the snow cornice at the top of the cliff had been cracked across, thus :—

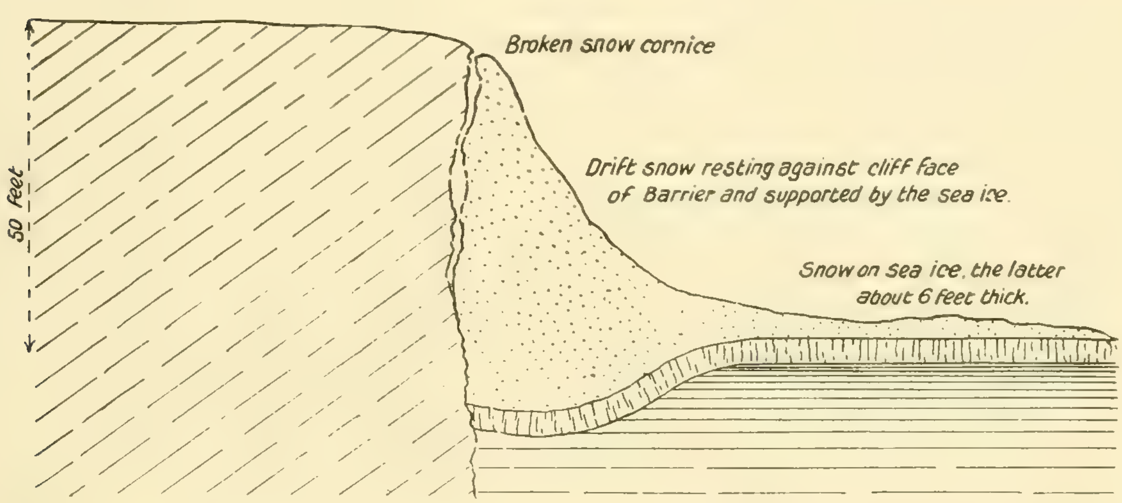


FIG. 27. Section across northern edge of the Nordenskjöld Ice Barrier Tongue

This aspect of the Tongue is in strong contrast to that presented in the following sketches, taken at its south side (Fig. 28).

Both these sketches exhibit the rounded, clean-swept bosses of true glacier ice characteristic of the southern side of the Tongue. They also show two deep indents, of which the western, next the coast, is several miles in length, trending from south

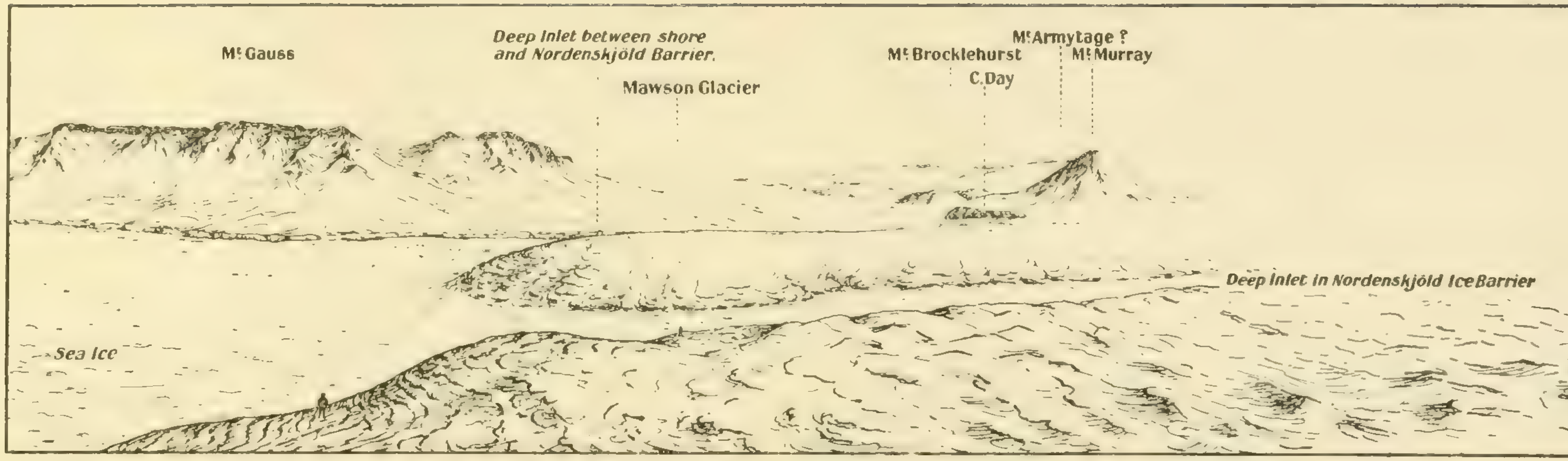


FIG. 28. VIEW FROM SOUTHERN SIDE OF THE NORDENSKJÖLD ICE BARRIER TONGUE

Showing two long inlets formed by the southerly blizzards. The slope where the figure in the foreground is standing is bare glacier ice. The barrier to the right is covered with hard snow, showing two sets of sastrugi made respectively by the blizzard and by the plateau winds

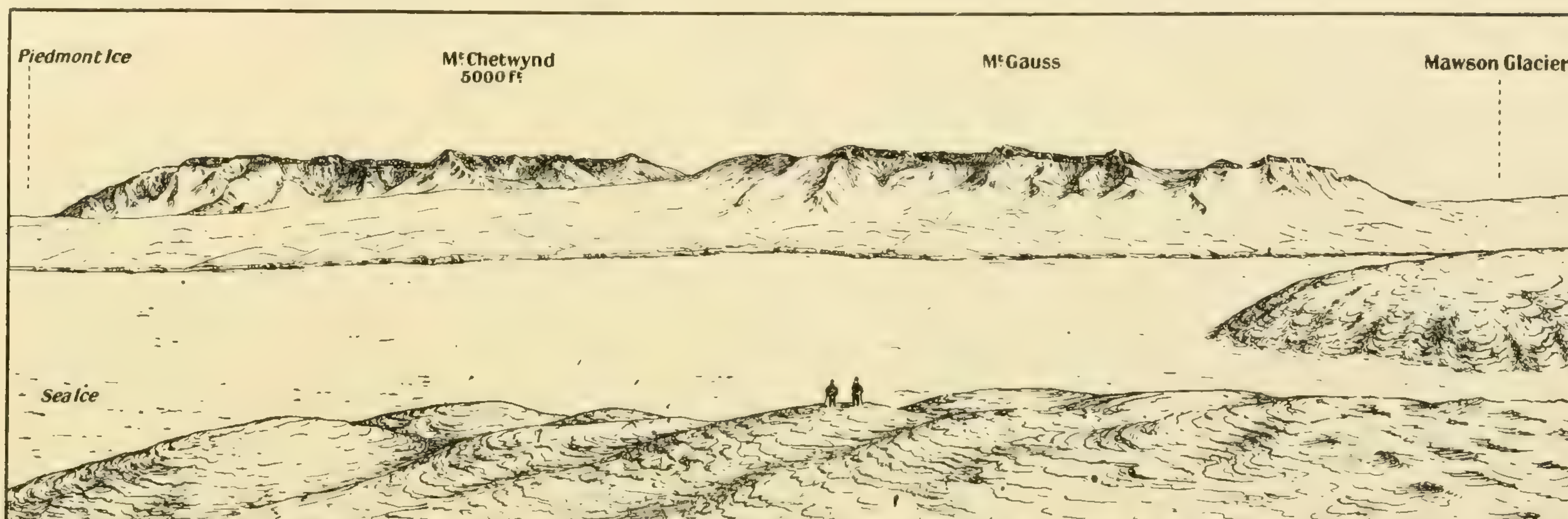


FIG. 29. VIEW LOOKING WEST ACROSS THE SEA ICE TO THE PIEDMONT ICE AND THE PLATEAU RANGES

As seen from the south side of the Nordenskjöld Ice Barrier Tongue, a large floating glacier 8 miles in length, being the seaward extension of the Mawson Glacier

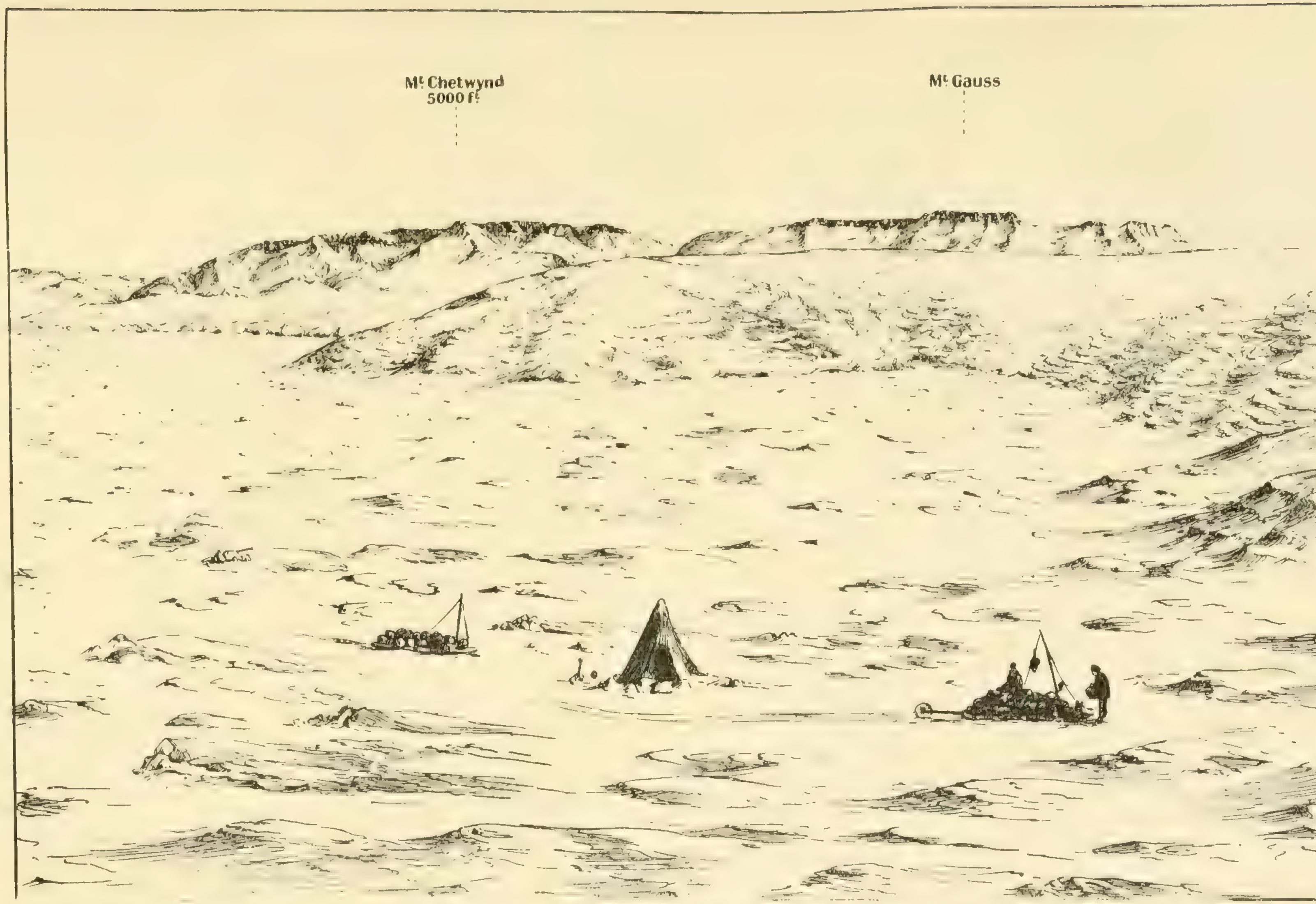


FIG. 30. SOUTH SIDE OF THE NORDENSKJÖLD ICE BARRIER TONGUE AS SEEN FROM THE SEA ICE, LOOKING WESTWARDS

In the background are the plateau hills crowned with basic rock, with huge arêtes descending to the piedmont ice. The sastrugi on the sea ice are caused by the southerly blizzards northwards, and due to marine erosion effected, when the sea is free of ice, by the fierce blizzard winds.

Fig. 30 shows, amongst other things, the numerous and large sastrugi raised there by the southerly blizzards.

The blizzard first breaks up the sea ice, then piles it as drift pack against the southern side of the Tongue. The jagged tilted slabs of this pack ice shelter the drifting snow, and give origin to sastrugi of exceptional size. It is obvious that the drift snow which has helped to round off the weather side of this Tongue is carried in enormous quantities across it, forming immense drifts to leeward, that is, on its northern side. It may be suggested that these drifts, forming at first on sea ice, if the sea ice does not break away the same year, may eventually pass into a species of barrier formation, partly ice, partly old snow.

That this Tongue is afloat is, we think, proved by the entire absence of any trace of tide-crack at its southern side. Along its northern side the sea ice was slightly cracked, but probably this was merely due to small differential movements between the sea ice and the Tongue, as, even if they both rise and fall together with the tides, the inertia of the latter is so much greater than that of the sea ice, that some cracking of the sea ice at its junction with the Tongue may be reasonably expected.

We conclude, therefore, provisionally that this ice is afloat. A glance at the plan and the sketches shows that it is not only the blizzard wind which drifts snow over the Tongue, but the plateau wind also. The latter wind blows from off the plateau coastwards down the depression of the Mawson Glacier, and tends to build the Nordenskjöld out in an easterly direction. This plateau wind blows from a direction about W. 10° N.

The following plan and cross section indicate the probable structure of the Tongue (Fig. 31).

The surface of the Nordenskjöld Ice Tongue is on the whole very flat and even, in striking contrast in this respect to the Drygalski.

In the area between the rounded hummocks of greenish ice forming its southern margin and the consolidated layers of old snow forming its northern edge the surface is formed entirely of hard snow covered with a thin glaze, due to thawing and re-freezing of the snow. Its surface shows broad, but very gentle, undulations, with intervals of about a quarter of a mile between the summit of one undulation and that of the next.

Here and there, especially near its southern margin, hummocky sastrugi project 5 or 6 feet above its general surface. Towards the centre of the Tongue the sastrugi are comparatively insignificant, only a few inches in height. Certainly the plateau wind in this neighbourhood is quite subordinate in force to the southerly blizzards, as far as one can judge from the sastrugi. This is the reverse of what is the case near the Drygalski. The plateau wind would, therefore, scarcely be strong enough to

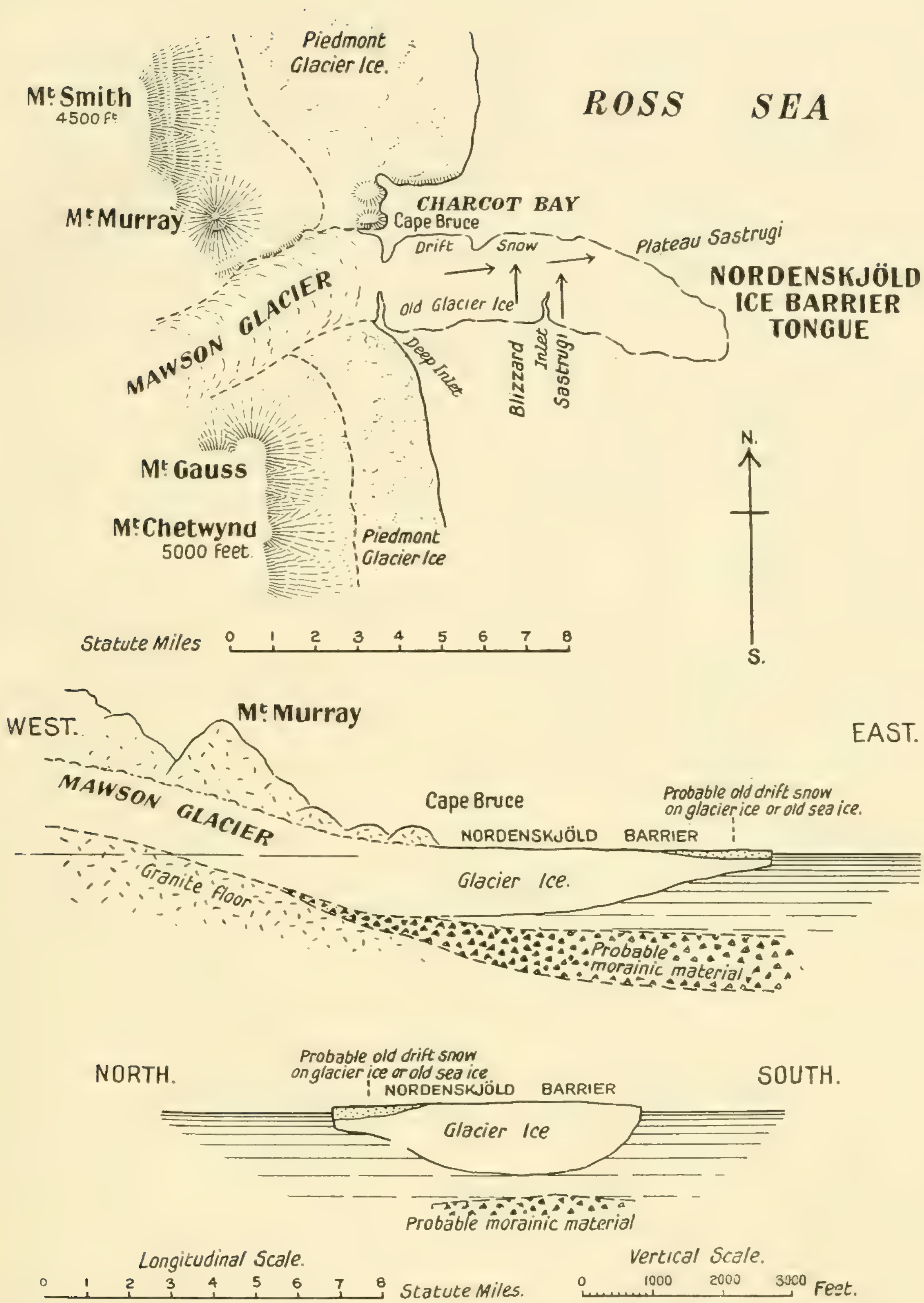


FIG. 31. PLAN AND SECTIONS OF THE NORDENSKJÖLD ICE BARRIER TONGUE

The plan is after Mawson, with slight modifications remove the snow drifted to the north of the Nordenskjöld Barrier by the southerly blizzards.

It is suggested in the sketch sections that at the eastern end of the Tongue, and along its northern margin, the drifted snow resting on thin glacier ice, or old sea ice, may in itself form the bulk of the Tongue there for some distance inwards from the sea cliff. If the width of the Mawson Glacier, as shown on the plan, be compared with that of the Nordenskjöld Ice Tongue, the widths agree so closely that it seems unlikely that any considerable addition can have been made to the Tongue there by drift snow. There can be little doubt that along this northern edge, where the height of the ice-cliff is only 50 feet, snow must contribute to form some part of it.

A question which the plan of this Tongue at once suggests is, in view of the thinness of the neck by which it is attached to the Mawson Glacier, why does not the whole mass break off bodily and float away? Unfortunately time did not admit of our examining its inland end. It is probable that its western end is aground, either on a rock bottom, or more probably on its own bottom moraine, or fluvio-glacial bank.

There are slight traces of crevasses to be seen only near the southern margin. It appears to represent a senile stage in the history of a glacier afloat, once part of a large piedmont aground.

The next sketch shows a deep valley, the Cotton Valley, which comes in to join the Mawson Glacier Valley near the base of Mount Murray.

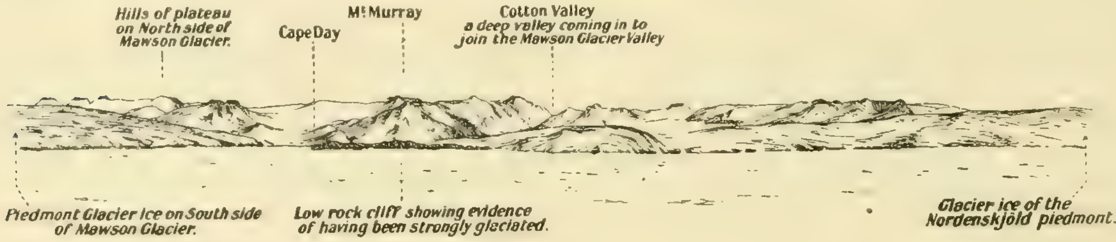


Fig. 32

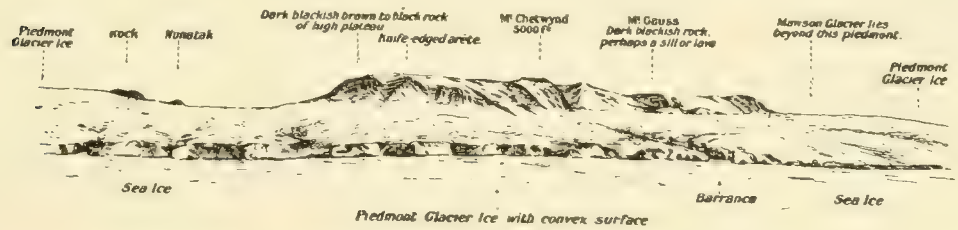
West coast of Ross Sea, looking west, at point on sea ice 13 miles south of the Nordenskjöld Ice Tongue

From this sketch it would appear that the Nordenskjöld Ice Tongue is all but detached from the Mawson Glacier.

In the next sketch (Fig. 33), 5 miles south of the Nordenskjöld Barrier, thick masses of piedmont aground are seen between the coast and Mount Chetwynd (5000 feet). A deep ravine (ice barranca) intersected the piedmont near the coast to the right of Mount Chetwynd.

At the point where the dark capping is seen on the right of the section there was an appearance suggestive of a cirque. There can be little doubt that here there is a great thickness of basic rock, overlying what appears to be a sedimentary formation, which rests in turn on a foundation of granite rock. To the left of the section are two long and deep glacier valleys. The right-hand valley, the Fry Glacier Valley, is of the nature of an outlet glacier. When we were looking directly up it we could see that it cut its way right across the horst, and apparently ascended to the snow-fields at the back of the plateau. It is a long, narrow glacier with straight, clean-cut rock walls, resembling in general appearance those of the Ferrar Glacier.

The granite mountain which lies immediately in the foreground to its right



Piedmont glacier ice with plateau hills behind, at 13 miles south of Nordenskjöld Ice Barrier Tongue

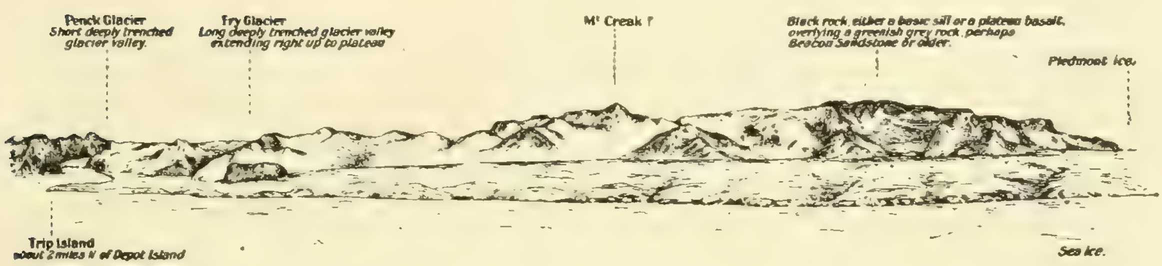


Fig. 33. West coast of Ross Sea, at 22 miles south of Nordenskjöld Ice Barrier Tongue, from the Penck Glacier northwards, showing a continuation of the piedmont ice with stratified rocks, probably Beacon Sandstone, to the right. Piedmont ascends to over 1000 feet before it reaches the foothills of plateau rocks

had evidently been intensely glaciated, as also has Tripp Island, off the mouth of the Penck Glacier.*

The latter appeared more to resemble an alpine glacier. It was very deeply entrenched, but did not appear to cut right through the horst.

Plate XV. we owe to the faithful copying with great accuracy by Mr. K. Craigie of a negative much too faint to yield a satisfactory print. The glacier behind the cyclometer of the sledge is the Penck Glacier. The Fry Glacier

* It is doubtful whether this sketch, made in 1908, is correct in showing Tripp Island so close to the piedmont. Priestley found in 1912 that Tripp Island was surrounded by sea ice, and about 2 miles distant from the nearest piedmont. There can be no doubt that the piedmont has shrunk noticeably between 1908 and 1912.

junctions with the Penck between the two headlands to the left of the left-hand figure.

Depot Island appears to form the eastern limb of a strong anticline in the gneissic granite. It is remarkable for the extraordinary numbers of large enclosures of a diorite containing very large crystals of sphene.* Large enclosures of quartzite, up to fully 10 feet in length, are present in the gneissic granite of the western limb of the anticline.

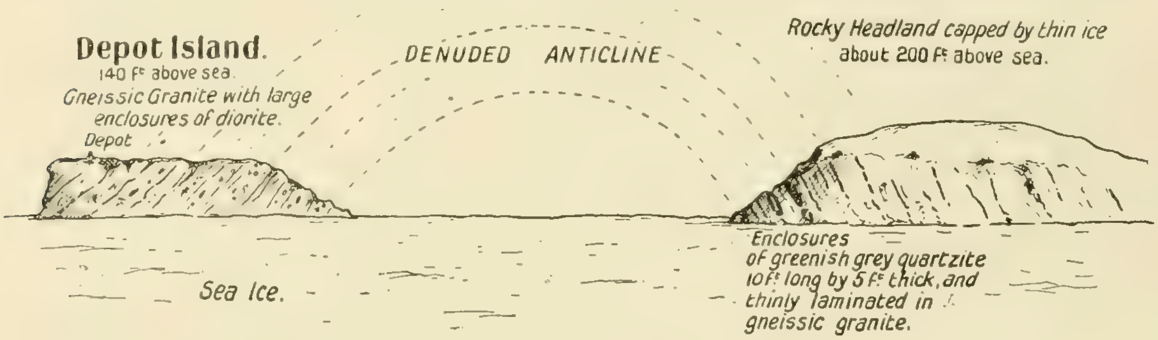


Fig. 34. VIEW LOOKING SOUTH

Depot Island and the adjacent headland to the south, Cape Ross, have both been intensely glaciated. Depot Island is 140 feet above the sea, and Cape Ross about 200 feet. An interesting feature at this point, and from here to Granite Harbour, 15 miles farther to the south, is that the piedmont, which is here extensively developed, is clearly seen to rest for considerable distances on a solid platform of granite.

Cape Ross, 2 miles south of Depot Island, is formed of gneissic granite, with

Fig. 35. VIEW OF COAST NEAR DEPOT ISLAND
Taken from point 2 miles 300 yards to the south of the island

dark grey bands rich in biotite, and with light veins of coarse pegmatite and porphyritic crystals of felspar. The cape is intersected by two sets of dykes, one set of a hornblendic-lamprophyre type, the other yet to be determined.

The general appearance of this gneiss is shown on Fig. 36.

At a small rocky point about 5 miles farther south, midway between Cape Ross and Gregory Point, we examined the piedmont ice where it rested on the granite

* A photograph by Mawson showing these enclosures is given in his petrological volume of this Memoir.

Fig. 1. WEST COAST OF ROSS SEA

With Penck Glacier on left, and plateau hills with large cirque on right

Fig. 2. VIEW TAKEN FROM SEA ICE

Looking south towards northern edge of the Nordenskjöld Ice Barrier Tongue. Height of cliff 50 feet. [D. Mawson

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platform. The granite cliffs here were low, approximately about 50 feet high. We found the edge of the piedmont ice here about a quarter of a mile back from the cliff face. We found a gully, as seen in the sketch, cut out of the solid granite to a depth of about 20 to 30 feet. It seemed of the nature of a huge glacial grove. It trended

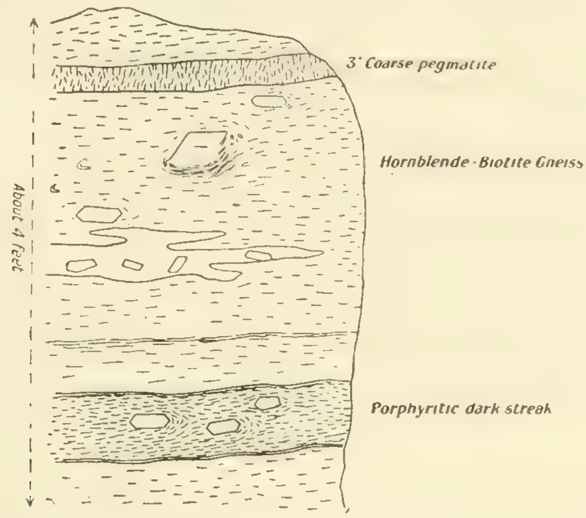


Fig. 36. GNEISSIC GRANITE AT CAPE ROSS, TWO MILES SOUTH OF DEPOT ISLAND

from about W. by S. or W.S.W. to E. by N. or E.N.E. The gully, although the piedmont had evidently retreated quite recently, had no sign of boulder clay in it, but the bottom of the gully and the rock platform above it on either side was strewn with large erratics, for the most part very much rounded, and suggestive of bottom moraine. The ice of the piedmont at its retreating edge seemed on the whole fairly

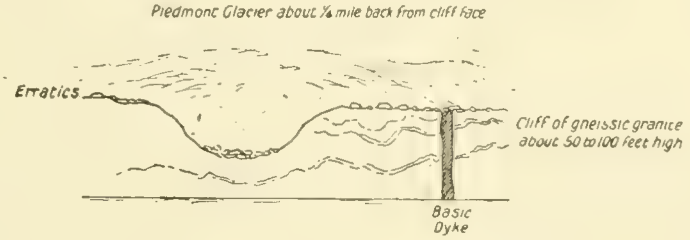


Fig. 37. GLACIER-CUT CHANNEL IN GNEISSIC GRANITE

Exposed to view through very recent retreat of piedmont, 7 miles south of Depot Island

free from rock sediment, but was too much concealed under old snow to yield a good section.

Resting on the top of the gneiss platform, from which the piedmont is now rapidly retreating, were numbers of erratics, and amongst them a large boulder of granite, shown in the sketch below (Fig. 38).

It exhibits rocks of three different ages. First and oldest, a dark greenish-grey porphyritic gneiss. This has been cut by veins of fine-grained reddish granite with green mica. These veins in turn have been intersected by coarse red aplites. The patch at the top left-hand side of the block is not another variety of rock, but simply another face of the boulder.

If this greenish-grey porphyritic gneiss is of the same age as the gneissic

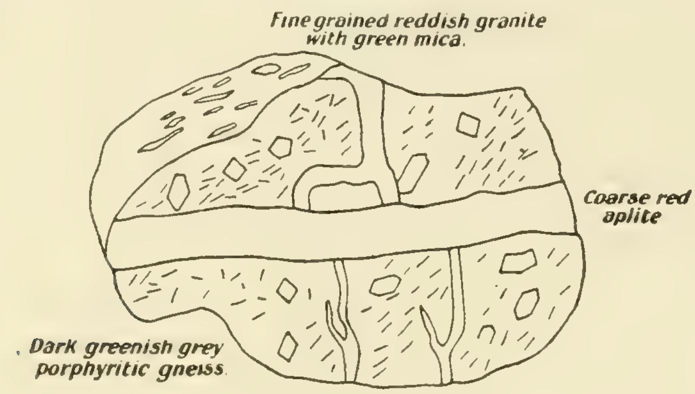


Fig. 38

granite of Cape Ross, and the latter is the equivalent of the gneissic granite of Depot Island, we have here evidence of the following succession amongst the eruptives, the oldest being mentioned first :—

1. Basic sphene-diorite.
2. Grey gneissic granite.
3. (*a*) Fine-grained reddish granite with green mica ; (*b*) coarse red aplite.

These last two rocks probably belong to the important group of the red granites so widely distributed along this coast.

The next sketch, at about 11 miles south of Depot Island, is taken from the sea ice off Gregory Point.

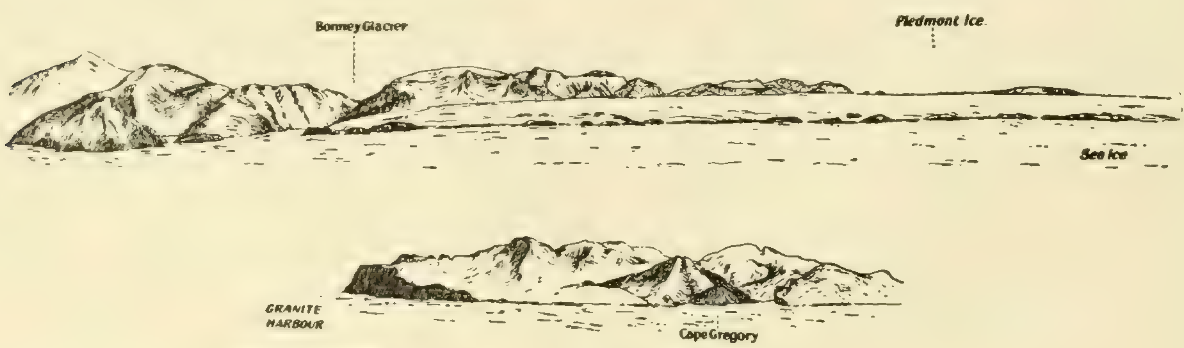


Fig. 39

It shows the general appearance of the piedmont aground, resting on its low-lying coastal platform, formed here of intensely glaciated granite. It has a width here of about 7 to 8 miles.

At Gregory Point it terminates against the area glaciated by the Mackay Glacier and the Bonney Valley and Glacier.

Next, at 15 miles south of Depot Island, we reach Granite Harbour, a magnificent inlet, with the Mackay Glacier at its head. This glacier lies in a very typical over-deepened valley, with a far wider valley above, lying at a height of about 1500 feet above the present surface of the ice of the Mackay Glacier. The sketches * speak for themselves as to this evidence, and better testimony is borne by the excellent photographs of the *Discovery* Expedition (National Antarctic Expedition, 1901–4, Plate XXXVI. Figs. 1, 2, and 3). Figure 3 particularly shows extremely well the great terrace of the wide original valley above the over-deepened valley, with the strongly facetted hills rising above this upper terrace. The spectacle afforded by the Granite Harbour is truly magnificent, and most impressive and interesting for students of ice and its work. The sheer glacier-cut walls on the north side of the Mackay Glacier and Granite Harbour, and the steep slopes of the rocks bounding the over-deepened valley on the south, show that the present glacier must extend much below sea-level.

As no complete set of soundings † were obtained at the head of the bay in which the glacier lies, it is impossible to form more than a rough guess at this thickness, but the angle of slope of the rocks on either side of the valley and the height of the ice cliff at its seaward end being taken as some criterion, it is probably of the order of somewhere about 1000 feet. Ice-falls were conspicuous, crossing the valley just below the remarkable line of nunataks. The wonderful nunatak, Suess Nunatak, shows, as seen in the sketches, two vast glacier-scooped concave surfaces respectively on its northern and southern sides, and a conspicuous hollow occupied by a small snow-field at its summit. Suess Nunatak could be seen to be formed of some black rock, probably part of a dolerite sill. Higher up the valley, to the right, stratified rocks, evidently of the Beacon Sandstone formation, make their appearance, traversed by dark dykes and sills. The cross section of this remarkable valley, based on Mawson's theodolite determinations from distances which varied from 5 to 10 miles, is shown in Fig. 40.

The following three sketches were made successively from north to south, the uppermost sketch representing the northernmost view.

There can be little doubt that the ancestor of the Mackay Glacier during the maximum glaciation had a cross section at least six or seven times the area of the present glacier.

Without discussing the whole question of over-deepened valleys here, or the origin of the great upper terrace, it may be remarked that so far as the area

* The focal plane of our camera refusing to work in the great cold at the time of our visit in October, we had to rely on sketches only.

† H. T. Ferrar states, in Nat. Ant. Ex. Natural History, vol. i., Geology, p. 94, "This harbour is fiord like, and has depths of over 100 fathoms within a quarter of a mile of the shore."

examined by us is concerned, it appears that during the maximum glaciation the whole of the old U-shaped valley, 10 miles in width, was filled with glacier ice to a depth of at least 1500 feet. The upper terrace may have been, no doubt has been, subsequently modified by cirque glaciers, but it was probably not cirque glaciers which originally excavated this gigantic terrace. The evidence of the erratics proves that at Ross Island the whole level of the Ross Barrier in that region was formerly 900 feet higher than at present, the Ferrar Glacier perhaps 3000 feet higher, the Beardmore Glacier 2000 feet higher.* In the face of this evidence, as well as of the complete over-riding with glacier ice during maximum glaciation of the Larsen, Bellinghausen, Crummer, and Priestley Massif, to heights of at least 1500 feet above the present surface of the adjacent glaciers, the valley of Granite Harbour must necessarily have been almost completely filled with ice far above the

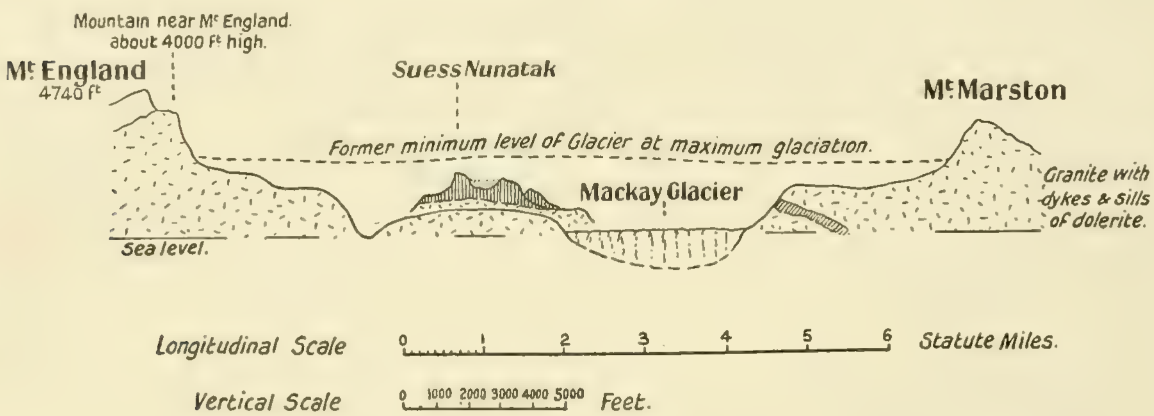


FIG. 40. SECTION ACROSS MACKAY GLACIER, SHOWING WELL-MARKED, OVER-DEEPENED VALLEY

The "trogschulter" to right of the glacier is about 800 feet above sea-level

level of the great terrace. The facetting of the rock-spurs which rise considerably above the level of the terrace is also very conspicuous.

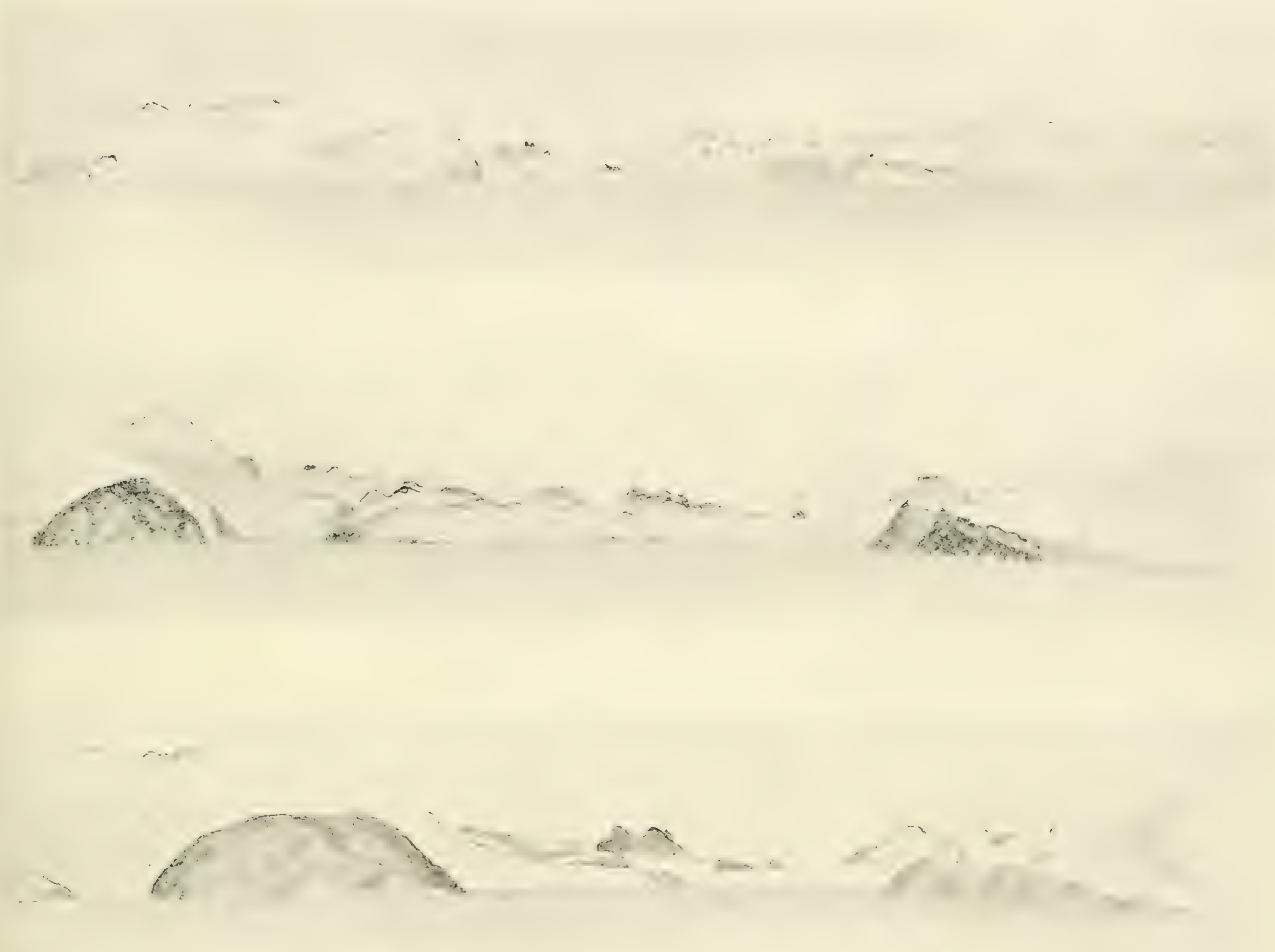
At Cape Roberts, just to the south of the entrance to Granite Harbour, a low headland of gneiss shows evidence of having been lately striated by ice coming from a direction of about W. 10° S. Numerous erratics of kenyte of some size were lying on this headland at about 20 to 30 feet above sea-level. They may have been transported by floating ice from Ross Island during the recent submergence of the coast, of which the raised beaches are evidence.

Fifteen miles S.S.E. of Cape Roberts is Dunlop Island (Fig. 41).

The strait which separates Dunlop Island from the mainland, about 1 mile in length and ¼ of a mile in width, is very suggestive of a glacial valley formed by the

* Suess Nunatak, rising fully 2000 feet above the level of the adjacent Mackay Glacier, has been glaciated over its summit, which indicates a former greater thickness of ice in this valley as compared with its present thickness of about 2000 feet.

PLATE XVI



GRANITE HARBOUR AND THE MACKAY GLACIER

Lying in an over-deepened valley, with the wide "alb" valley formed chiefly by the "ice-flood," when at its maximum

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ancient Ross Barrier when it over-rode the whole of this region. Glacial valleys probably excavated by the same agent are to be seen at Cape Royds. Since the retreat of the Ross Barrier the piedmont ice has pushed across the strait and glaciated the gneissic granite *in situ* on the island in a direction from about W. 35° S. to E. 35° N.

The island is formed of shingle and redistributed glacial boulders and gravel. The gravel is formed of small pebbles about half an inch in diameter, and the boulders are mostly from 3 inches up to 18 inches in diameter.

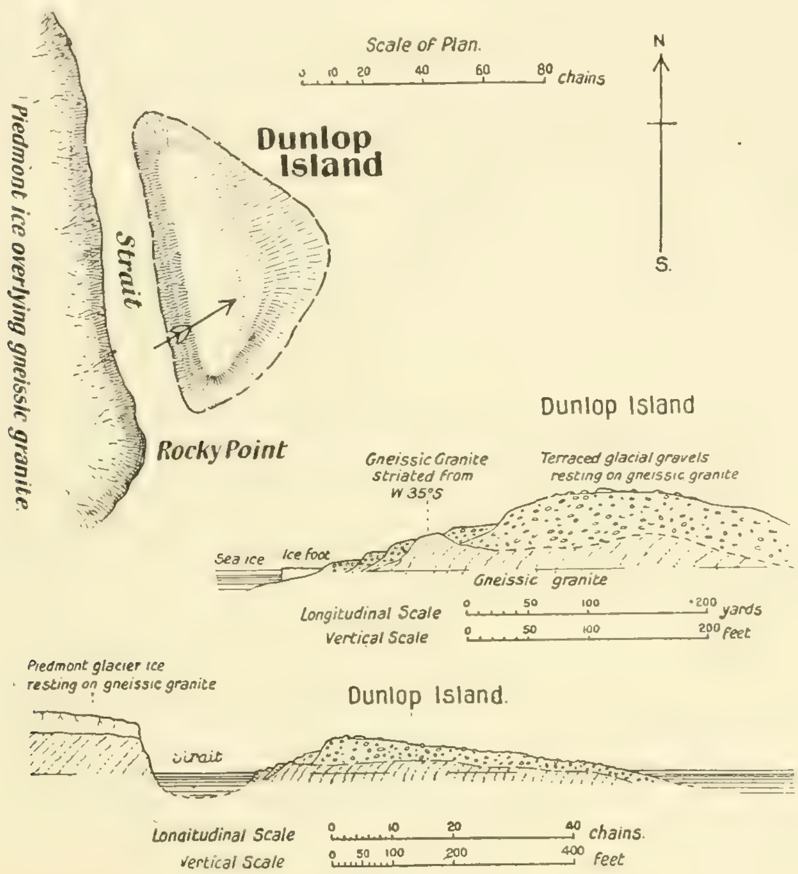

FIG. 41

One boulder of granite measured 6 by 5 by 3 feet.

Its upper surface is strongly grooved in a south-east and north-west direction. These main grooves are crossed by another set coming from about W. 35° S., the direction of glaciation followed most recently by the piedmont ice subsequent to the retreat of the Ross Barrier. The north-west to south-east grooves pointed straight to Hut Point, 60 miles distant to the south-east, and it may be significant that a few fragments of scoriaceous basalt and dense olivine basalt, both of which occur *in situ* at Hut Point, were found here by our colleague, Dr. Mackay, among the boulders. We think it may be concluded that the strait which separates Dunlop Island from the mainland was probably formed by the Ross Barrier. The coarse and fine gravels forming the greater part of the island have probably been formed from glacial material redistributed in sea water subsequent to the retreat of the barrier, and during a submergence of 100 feet or upwards. At some time during this submergence the gravel and boulder bank must have been over-ridden by the glacier ice of the piedmont, and the large granite boulder firmly imbedded in the bank became cross-striated. Then the piedmont ice retreated, and during re-emergence tidal scour has separated the large gravel bank from the mainland, and has terraced the side nearest the strait.

To the south of Dunlop Island the piedmont ice is very extensively developed, covering a large area inland to at least as far south as New Harbour. The general appearance of this part of the coast is shown in a photograph by the *Discovery* Expedition (National Antarctic Expedition, 1901–4, Album of Photographs and Sketches, Plate XXXIII. Fig. 3, photo by L. C. Bernacchi).

To the north of Marble Point we observed at least three low outcrops of granite peeping out from beneath the piedmont. The piedmont therefore is still resting on a coastal platform formed largely of rock. (Marble Point is formed of calc-schist and contorted mica-schist intruded by epidotic granite and aplite.)

At Cape Bernacchi,* a few hundred yards to the south-west of the rocky point, the shore is strongly terraced.

The following section was then measured there by the Northern Party :—

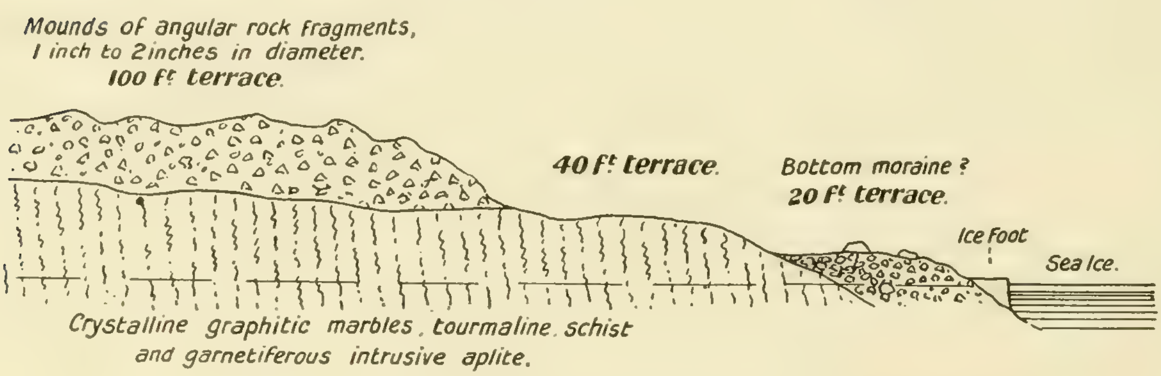

Fig. 42. SECTION SHOWING TERRACES AT CAPE BERNACCHI
The total length of the section is about 300 yards

The lower terrace is composed of heavily glaciated pebbles and boulders, with occasional erratics up to 5 feet in diameter. This appears to have been pushed along under an ice sheet.

The middle terrace is formed of Pre-Cambrian or possibly Cambrian crystalline

* Cape Bernacchi is formed of coarsely crystalline saccharoidal marble with graphite flakes, and also of schorlaceous schist. Both are strongly intruded by whitish granites. A good deal of epidote has been produced along the planes of contact.

rocks intruded by aplites, and the top terrace is built of angular material, the fragments being only from 1 inch to 2 inches in diameter. This material is irregularly heaped together in small mounds.

The two lower terraces are very suggestive of recent emergence of the land, but marine fossils were not observed here, but were discovered by one of us (R. E. Priestley) at Dry Valley, about 12 miles to the south-west.

CHAPTER V

GLACIOLOGY (*continued*)

THE FERRAR GLACIER AND CAPE ROYDS AREA

THE FERRAR GLACIER AND DRY VALLEY

We now approach the southern end of the low-lying part of the great horst. As already stated, this relatively low-lying part extends from Mount Nansen on the north to the Royal Society Range on the south.

The Royal Society Range is a huge horst within a horst, rising to altitudes of over 12,000 feet above sea-level. The precise trend of the tectonic disturbances which cause the downthrow to the north of the Royal Society Range is not known, but the great fracture on which Mounts Erebus, Terra Nova, and Terror are situated trends nearly due east and west. This fault line should intersect the west shore of McMurdo Sound between Cape Bernacchi and New Harbour. The huge massif of the Royal Society Range shoulders away the inland ice streams, compelling them to make a long detour in part to the south through the Skelton Inlet, in part to the north through the Ferrar Glacier and its branches. For a distance of at least 30 miles south of the Ferrar Glacier (possibly 50 miles, if the Koettlitz Glacier is not an outlet glacier from the plateau) there is no breach in this mighty wall of rock. This stemming action, forcing the inland ice streams to flow along lines of weakness in the rocks induced by parallel faulting just north of the Royal Society Range, contributes to make this area an important outlet region. An examination of Ferrar's geological map shows that the lower part of the Ferrar Glacier, with its trend prolonged inland up the glacier South Arm, the North Fork Glacier with Dry Valley, and three other valleys which adjoin it in succession northward, together with the Mackay Glacier, have an approximately parallel trend. This trend is about E.N.E., with a tendency to become more easterly as Granite Harbour is approached. For the upper 50 miles of its course the Ferrar Glacier has a W.N.W. to E.S.E. trend. It is clear from the physiography of the district that the Ferrar Glacier is now but a shrunken remnant of its former self.

Ferrar states * in speaking about the corrie glaciers at the north side of the head of the Ferrar Glacier at the Inland Forts, "All flow southwards, but fail to reach the ice of the main valley, and are now building up crescentic moraines at

* National Ant. Ex., Geology, p. 73.

their terminations. The interest of the glaciers lies in the fact that, though they now flow southward, they were formerly forced northward by the Ferrar Glacier into another drainage system."

The same remark may be made about the Valley of the Blue Glacier. That wonderful spurless valley was probably excavated by a former branch of the Ferrar Glacier escaping over the rock ridge at Descent Pass. If this view is correct, the height of Descent Pass above the present level of the adjacent ice of the Ferrar Glacier is some roughly approximate measure of the recent shrinkage of the ice in that region. The exact height of Descent Pass is not given on the Section 1 of Plate VII. (*op. cit.*), but to judge from the scale is about 2000 feet above the present level of the glacier. The bold headland of Solitary Rocks, in itself too small to harbour sufficient ice for self-glaciation, has obviously been intensely glaciated in recent time over its summit. This rises about 2000 feet above the level of the adjacent ice.

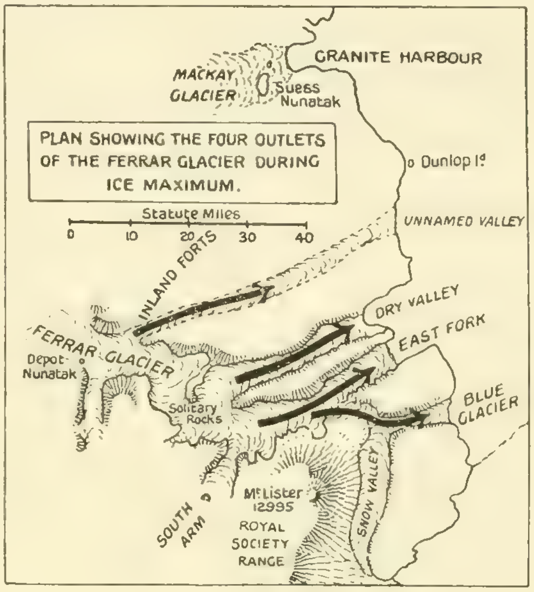

Fig. 43

Depot Nunatak, at the head of the glacier, is obviously an ice-flood gauge on a small scale, and its strongly glaciated summit stands 500 feet above the level of the adjacent ice. It follows that 2000 feet indicates the very minimum former height of the glacier ice in the Ferrar Valley above its present altitude. In an earlier paper * Ferrar estimated the former height of ice in the Ferrar Glacier Valley as 3000 feet above its present limits.

The modern Ferrar Glacier system thus resembles the disintegrated drainage at the delta of some large river. The Ferrar formerly discharged ice into the sea from four mouths—the Blue Glacier, the East Fork, Dry Valley, and an as yet unnamed valley to the north which took off the drainage of the ice near the Inland Forts towards Dunlop Island.† Diagrammatically this drainage is represented on the sketch map Fig. 43.

An excellent account of this important outlet or spillway glacier has already been furnished by H. T. Ferrar. The additional information now given was obtained by the Western Party on their journeys up the Ferrar Glacier and up Dry Valley. The discovery was made that the Solitary Rocks are not islands, but are connected with the north wall of the glacier by a ridge of granite over a thousand feet high.

* Roy. Geogr. Jour.

† This has subsequently been named Wright Glacier by T. Griffith Taylor of Scott's Expedition.

It was also concluded that the Solitary Rocks were not capped by Beacon Sandstone, but wholly formed of granite.*

The Solitary Rocks were proved by an actual traverse to be the butt-end of a peninsula banking up the ice above and forcing it round to the southern side, where it descends in a series of ice-falls.

Access was gained to the Solitary Rocks at two points. These consist of alternate bands of black and yellow rock, which are identified on Ferrar's map as dolerite and Beacon Sandstone; but on December 22nd, on climbing down the ice-cliff and crossing the frozen stream at the foot of the cliff, and climbing up the talus acree and collecting from the lower yellow band of the Northern Solitary, the observer found the rock to be a granite similar to that of the Kukri Hills.

From this note about the alteration of the geological boundaries we may pass on to a general description of the Ferrar Glacier.

The entrance to the Ferrar Glacier Valley, seen above, is about 5 miles in width. The facetted character of the steep walls of the valley, the entire absence of overlapping spurs, the resemblance of the whole valley to a vast, slightly curved groove † gouged out of the plateau to a depth of fully 6000 feet, bear strong testimony to the vast power of its rôle in the evolution of earth forms in Antarctica.

THE FERRAR GLACIER

The following description is based on the observations of the Western Party, Armytage, Brocklehurst, and Priestley.

The lower 10 miles of the Ferrar Glacier, below the first ice-falls, consists of ice which, as far as we could judge from the surface, is not glacier ice, and it seems probable that the present end of the true glacier is at those same ice-falls.

The junction between the sea ice and the commencement of this ice is sometimes a distinct cliff several feet high, against which snow-drifts are banked, but more commonly a gradual slope. It appeared, even on our outward journey, that this ice was truly crystalline ice, due to the re-freezing of thaw-water containing large quantities of half-melted snow. The surface just above the commencement of the ice is, on those patches where it is free from snow, exactly comparable with that of the southern half of Blue Lake, Cape Royds. The hexagonal ice is very prominent, and forms in places almost spherical patches many feet in diameter, and with a convex surface which is sometimes formed of beautifully regular hexagons, or, when the crystallisation is less regular, of frond-like masses of crystals of all shapes, generally

* The view that the Solitary Rocks were an isolated nunatak and were capped by Beacon Sandstone was exactly the conclusion that one of us (Priestley) favoured when seeing the mass as it presented itself to the sledging parties of the *Discovery* Expedition. It was only a closer subsequent examination from a different view-point that proved this inference to be incorrect.

† Nussbaum's expression, "Wie mit ein Hohleisen auf einmal ausgearbeitet," seems strictly applicable to this valley.

Fig. 1. ENTRANCE TO FERRAR GLACIER, LOOKING WEST OVER THE SEA ICE

Fig. 2. EFFECT OF THAW. FERRAR GLACIER AT THE SOLITARY ROCKS, WESTERN MOUNTAINS

[Photo by Brocklehurst

[*To face p.* 88

roughly hexagonal, similar to the ice photographed at Clear Lake. When the hexagonal ice has been removed by ablation, snow-tabloids and bubbles of various size are common, and occasionally the secondary ablation-formed ripple surfaces so common at Cape Royds are developed. At other places there appears to be a development of what is either coarse granular *névé* or minutely hexagonal ice.

As the ice-falls were approached the bare surfaces became fewer, and finally disappeared until the ice was covered with several feet of snow, the upper foot more or less hardened into a crust, whilst underneath this crust was at least 3 feet of loose, largely-granular snow. At this place the pressure from the glacier above had caused considerable undulations in the surfaces, and we passed several crevasses.

We had a fairly clear glimpse down one of these crevasses, and the structure of its walls was very puzzling. Instead of the uniform sheet of ice that was to be expected, the portion of the walls exposed to our view seemed to consist of flattened lenticles of ice with layers of snow in between, and it was not until the return journey that any explanation of this peculiar structure was suggested.

On the way back to Butter Point we passed this part of the valley during a very hot summer's day, when the thaw was most powerful, and almost the whole of the surface for several miles below the ice-falls was occupied by a series of pools of thaw-water full of drift snow, and it seems probable that this thaw explains both the ice surface we passed over and the structure of the crevasse walls. Under the ice formed in this manner there may be a substratum either of glacier ice or of sea ice, but every piece of evidence points to the probability of the first few feet at any rate being formed in the way just described.

Above the ice-falls the true glacier ice set in, but very little of ice or *névé* was exposed for some miles, as the surface of the glacier was hidden under a uniform coating of snow.

For some time before any surface moraine was reached the presence of an englacial one was indicated by numbers of circular patches of hexagonal ice indicating where the boulders of the moraine had sunk beneath the surface. Always we found that, when a moraine had persisted for some distance without being fed from other moraines or from the cliffs under which it had passed, the number of boulders above the surface became less and less, until the moraine had become wholly englacial. It is an interesting fact that the hexagonal structure in the ice was never present when the boulder had just sunk beneath the surface, but was only superinduced after the frozen thaw-water had been formed a long time. It seems therefore to be a secondary structure, due either to a molecular change in the thaw-water ice itself, or to the re-crystallisation of the lower portions of the snow-drift collected in the depression usually left where the boulder had disappeared.

Another feature very well marked at this time was the recementation of old cracks and narrow crevasses by the thaw-water, with a distinct and very fine lamination parallel with the crack. The same thing occurred in the lakes at Cape

Royds, and was particularly noticeable in one or two of the master-cracks of Coast Lake.

In crossing the glacier from north to south, opposite the lower Cathedral Rock, we crossed three moraines, and could see one more lateral moraine along the south side of the glacier below Descent Pass. We followed the strongest of these moraines for some distance, but beyond Descent Pass it made a sharp bend to the south, and became lateral, or sub-lateral, along the upper Cathedral Rocks, having evidently been pushed out below by the ice coming down from Descent Pass.

A few miles above the Cathedral Rocks is another series of heavy ice-falls; the ice immediately beneath them is seamed with two series of strain-cracks, those in the series parallel to the length of the glacier being by far the most numerous. The other series is at right angles to the first.

A similar structure was observed between D bluff and the Solitary Rocks in the northern lobe of the glacier where the ice slopes sharply towards its northern edge. A series of parallel compound cracks cross it diagonally from the upper Solitary Rock towards the lower end of the D bluff. The transverse cracks forming the compound diagonal ones increase in width, as they move towards the north, until many of them join up, forming long crevasses. These transverse cracks vary in width from mere lines to crevasses 2 feet wide.

The only occasion on which sounds, suggestive of appreciable movement of the glacier ice, were heard was in a camp at the foot of the ice-falls which force their way around the southern side of the Solitary Rocks. The ice here, owing to the narrowing of the valley, is subjected to tremendous pressure, and rather fine ice-falls are developed. From the ice all round our tent sounds like pistol-shots and the popping of champagne corks were heard, evidently caused by the ice relieving strain by fracturing, and the strain structure mentioned as occurring below the second ice-falls was also very prominent.

EFFECTS OF THE THAW ON THE ICE OF THE FERRAR GLACIER

Plate XVIII. Fig. 1 shows the effect of the thaw, about Christmas time 1908, near the Solitary Rocks in the Ferrar Glacier Valley.

The effect of the thaw depends of course on the amount of direct sun's heat, and largely on the state of the atmospheric currents, as well as on radiation of heat from rock and rock dust. The conditions most favourable seem to be two or three calm days with a full allowance of sunshine. At the end of such a period the thermometer we had registered 40° F. at the end of the second day, and the glacier appeared to be melting under our feet. The thaw, on the other hand, practically ceases, except locally under favourable conditions, when the cold overflow breeze from the plateau has been blowing for a good many hours. Its effects were so

FIG. 1. RIVER OF THAW WATER AT SOLITARY ROCKS, FERRAR GLACIER

[Photo by Brocklehurst

FIG. 2. HANGING GLACIER OR CLIFF GLACIER

A tributary of the Ferrar Glacier at the Cathedral Rocks. Dec. 28, 1908

[Photo by Brocklehurst

[*To face p.* 90

varied and so different on different occasions, that the only way to describe them fully and adequately seems to be to treat the subject more or less in narrative form.

The first result noted was the formation of hollows partially filled with thaw-water round the boulders of the moraine, a process which finally has caused the disappearance from sight of whole moraines.

On December 18th, 1908, opposite the upper Cathedral Rocks, we sledged for some time up a fairly steep rise of clear ice, which was seamed with small stream channels up to 2 feet in diameter, and running mostly along partly recemented crevasses and cracks. Many of the bottoms of the channels were covered with fine detritus, and in places the channels widened into round ponds, some of which contained water. The channels ran very irregularly, but seldom ran transversely across the glacier for any great distance at a time, their general trend being up and down.

The 20th was fairly calm with flaky snow, and by the morning of the 21st there was 2 inches of snow on the ground, and when the sun began to play on the walls of the valley, the thaw set in in good earnest. We reached the north wall of the glacier at five o'clock in the afternoon of the 21st, and were pulled up short by a precipice between 200 and 300 feet high. At the foot of the glacier ran a river 20 or 30 yards wide, and on the face of the glacier considerable thawing was taking place. Every deeper crack and boulder hole was filled with water, and this water could be heard streaming down the face of the glacier to the stream which was roaring beneath the ice-cliff.

The effect of the radiation from large rock masses is strikingly illustrated at the Solitary Rocks. The ice is separated from the rock by a gully about 50 feet deep, with a stream flowing at the bottom. Next comes the lateral moraine, which is very thick, and still within the region in which the rock-heat is felt. The combined influence of the rock material of the moraine and the radiation from the Solitary Rocks has been to melt the surface of the glacier until the part occupied by the moraine forms a depression from 3 to 6 feet below the level of the main glacier surface, which commences as a convex rise so abrupt as to be almost perpendicular. After this the ordinary billowy surface sets in, and the next stones met with form a sub-medial moraine, which is not sufficiently thick to effect any general lowering of the surface, although each stone is surrounded by its own hollow filled with thaw-water, and along the middle meanders a small stream filled with morainic gravel, which has cut a channel about a foot deep through the glacier ice.

The thaw reached its height the same day, and the notes taken on the spot are as follows:—

"An almost incredible amount of ice must be being removed as water. The ground everywhere is honeycombed with large circular holes full of water, with the large boulders or smaller morainic matter at the bottom. These holes vary from the size of pin heads to large hollows 6 or 8 feet in diameter and a couple of feet in depth. In those which have become deep enough for the water to be shaded from the direct rays of the sun a re-freezing process has set in, long acicular needles of ice forming from the small grains of gravel and crossing and recrossing in the most beautiful patterns. In others we saw hexagonal plates being formed on the surface of the water, as well as the needles radiating from the sides and bottom. The last quarter or half mile of our day's sledging we have been passing over and through a series of streams which cover the ground almost without intermission for the whole distance, and it was only by treading on the tops of the ablation ripples that we were able to keep dry, and even with that precaution we succeeded but indifferently. To the roar of rushing water which we heard from the ice-cliff now succeeds the more insidious trickle of the thousands of streams which are steadily finding their way by devious paths over the convex face of the glacier to join the main streams below.

Late in the evening of the 21st of December we walked down to the edge of the glacier just at the corner made by the isthmus joining the Solitary Rocks to the mainland. At the corner of the glacier bulge, and below the granite isthmus, was a lake which was fed by at least four streams from a large hanging glacier opposite. These streams we could see from our position were yellow with silt, and a very large amount of fine detritus must be carried into the lake and on into the New Harbour Dry Valley by the stream which has its origin in the lake. A fifth stream of water could be heard flowing underneath us from one side of the Solitary Rocks, and innumerable tributary streams were flowing over the face of the glacier cliff. By the night of the 21st the 2 inches of snow which fell during the 19th and 20th had either been removed as thaw-water, or left as a thin coating of rough ice, opaque through the inclusions of air; and the ablation-rippled surface has been much intensified, the ripples being converted into ice-waves, with several inches difference between the top of the sharp crest and the bottom of the trough."

When we awoke on the morning of the 22nd a strong cold breeze was blowing down through the gullies leading from the inland plateau, and this breeze continued until the 26th. The thaw practically ceased when the breeze sprang up (except in those districts locally affected by heat-radiation from the rocks), and no further remarkable evidences were noted until the last stages of our return down the glacier valley.

During this gale ablation and the removal of snow by drift were very rapid, and the patchy snow-drifts passed on our way up had been largely reduced in size before we passed them on our way down the valley. Many, indeed, had been entirely removed, and the only evidences of their former occurrence were the corresponding patches of ice free from ablation ripples. The thick drifts piled against the southern side of the bluff under the peaks D_1, D_2, and D_3, Ferrar's report, had had at least 18 inches of its upper surface removed, and sastrugi a foot or more high had been evolved.

Another effect of the quick change from thaw to cold wind was the formation of a fringe of outstanding feathery ice-crystals along the margin of many of the open

PLATE XIX

Fig. 1. CLIFF GLACIER FALLING ON TO SURFACE OF FERRAR GLACIER

Fig. 2. THAW STREAM ON THE FERRAR

[To face p. 92

cracks and holes; this is evidently caused by the deposition of the vapour from the holes as it cooled when escaping into the open air.

On the evening of December 28th we camped at the foot of a hanging glacier east of Cathedral Rocks (Plate XVIII. Fig. 2). Along the edge of the glacier here a fair-sized stream was flowing, and this stream broadened into a lake in the depression at the foot of the ice-cascade; and again a few hundred yards below it formed a pond 40 or 50 yards across. The lower lake is full of snow, and appears to have been formed in a circular depression by the silting up of loose snow-drift and the impregnation of this drift with water from the recent thaw brought down by the stream which runs through the depression. This marsh was connected with the lake at the foot of the glacier by one or two deep channels bridged with snow in places. These channels were so deep that no bottom was found with an ice axe; they are probably partially recemented crevasses acting as drainage channels for the upper lake and the thaw-water flowing into it.

An interesting feature in these cliff glaciers is that while the ice is constantly descending on to the surface of the Ferrar Glacier below it does not raise any extensive mound of ice there, but is quickly absorbed into the main mass of the glacier, which meanwhile retains the same gently sloping surface as before.

Another of these cliff glaciers is illustrated in the next figure, which shows the same feature. The phenomenon is on a far grander scale than would appear from the photograph, the distance from the tent in the foreground to the glacier being considerable. The height of the rock cliffs on either side is of the order of several thousands of feet.

Such instances speak volumes for the plasticity of glacier ice even at somewhat cold temperatures. Overthrusting alone would fail to account for the rapid absorption of these ice masses into the main glacier.

On the 30th December the thaw again became powerful. All the ice we traversed was seamed with drainage channels forming an intricate network as far as eye could see on either side of our course, and between these channels the surface was honeycombed with boulder-holes, 1, 2, and even 3 feet deep, and full or partially full of water.

About 2 miles above the ice-falls all the tributary channels within our sight converged into one main channel, along which flowed a stream 3 or 4 yards wide, with a bed of gravelly morainic matter; this main channel was between 1 and 2 feet deep, and had deeply undercut sides.

From the edge of the ice-falls a comprehensive view of the thaw phenomena was available. Besides the stream already described there was another of equal or superior size to the south of the middle of the glacier, and to the north of it was a series of three streams, each a couple of yards wide, and within 2 or 3 yards of each other. These streams drained the middle of the glacier, and a large quantity of the water they brought down was impounded into fair-sized lakes below the ice-falls.

To the north of us a line of broken ice along the lateral moraine betrayed the presence of a stream bed sufficient to carry away thirty or forty times as much water as was draining off the middle of the glacier, while to the south the ice was furrowed by an interlacing network of streams and ponds, which rendered no explanation necessary of why difficulty was experienced in sledging up and down that side of the ice. The southern river could be heard flowing parallel with us 10 miles farther down the valley, where it probably opens a way through the sea ice and mingles with the sea water.

The lakes were met with for some miles along the valley also, and caused great inconvenience, as they were filled and covered with snow, and so constituted so many traps for our unwary feet.

When collecting snow from one of the larger boulders of the moraines, at the entrance to the East Fork of the Ferrar Glacier, an interesting exaggerated example of the increase of some grains of ice at the expense of others was observed. This boulder was heaped about with snow-drifts of the loose, largely granular snow referred to in discussing the drifts in the older sea ice. Inside the drift, near the boulder, is a regular arrangement of zones, increasing in the size of the grains as the boulder is approached, until finally the grains—without cohering—reached a diameter of from one-quarter to three-eighths of an inch. In the inside 2 inches of the drift the grains had cohered and formed true ice. Pressure here is almost a negligible quantity, and the effect must be almost entirely ascribed to the heat of the sun and heat radiation from the boulders.

In regard to the moraines in the upper part of the Ferrar Glacier near Solitary Rocks, several pieces of fine-grained dark basaltic rock were observed, which fact points to the occurrence of basalts among the volcanic rocks of the upper regions of the glacier. The great height up to which these ice-worn specimens were found indicates to some extent the shrinkage that has taken place in the ice of this great glacier in recent times.

MORAINES IN THE EAST FORK OF THE FERRAR GLACIER VALLEY

These form deposits, a portion of which is visible as a series of small hills protruding above the ice-surface, which hills, from their occurrence in a fairly straight line, appear to be the more prominent peaks of a partially submerged ridge.

The hills are composed of large quantities of debris derived from the local granites and schists, and also yielding specimens of two or three varieties of tuff (consolidated volcanic ash), basalt, kenyte, and an olivine and augite-kenyte which occurs sparsely at Cape Royds, and which have been so named because it contains large porphyritic crystals of augite and olivine, besides the more common anorthoclase felspar ; and also porphyries of varieties unknown *in situ* in the valley itself.

Similar moraines occur at Dry Valley and at the stranded moraines.

Dry Valley. The area was originally occupied by the north-eastern fork of the Ferrar Glacier, from which the ice has now retreated, and at present it is covered by a thick deposit of morainic debris. One of the most interesting features of Dry Valley is the occurrence there of a raised beach. This will be described in detail in the part of this work relating to raised beaches.

It may be stated here that enormous numbers of the delicate shell *Pecten Colbecki* with both valves attached to each other were found in position and quite unbroken up to 50 feet above sea-level.

The general appearance of this valley is shown in Plate XX. Fig. 2.

There were large mud-flats bordering the ice-foot in this valley, and these reached their greatest extent where they were augmented by the deltaic material of the many streams draining the valley, and on them, a few feet above the present sea-level, numerous specimens of amphipods and sea-spiders and one small fish were secured, all in a much desiccated condition. It is not necessary to postulate a recent rise in the level of the land to account for these specimens, since in the short period when the sea is released from the control of its icy winter covering, a strong wind blowing directly into the bay would inevitably cause a rise in the level of the water sufficient to assure the submergence of those portions of the mud-flats immediately adjacent to the ice-foot. Upon the recession of the sea numerous animals would be left stranded in any slight depression in the recently covered flats, and evaporation and ablation would remove the sea water during the late summer and autumn, leaving the desiccated remains of the animals, and giving rise to an efflorescence of salt on the surface of the mud. Indeed the sequence of events might very well have been caused by the very blizzard which raged from February 20th to the 22nd, 1908, when the *Nimrod* was driven north.

The remaining features of the Dry Valley moraines are very much a repetition of those of the Stranded Moraines, but on a much larger scale. The interesting discovery was made that at a height of between 500 and 600 feet there was an abundance of erratics foreign to the valley, namely, kenyte and basalt and tuffs appertaining to these two types.* These rocks had in no wise diminished in relative proportion inland, as compared with the rocks obviously derived from the sides of the valley, or from the higher reaches of the glacier.

Only two of the many thaw-water channels which furrow the district are still filled with running streams. The rest at the most are occupied only by a string of stagnant pools, while numerous depressions of smaller extent, with a heavy efflorescence of salt coating the gravel, mark the site of former pools.

The most northerly and most flourishing stream in the Dry Valley has cut a channel of 50 feet deep through the stratified gravel, the sides of which slope

* The Western Party of the Scott Expedition 1910–13 have since examined this district in detail, and Debenham found kenyte and basalt *in situ* in the upper reaches of the glacier.

steeply at angles between 45° and 75°. The water here was unfit to drink, owing to the amount of fine sediment held in suspension. As the stream became sluggish when breaking up into numerous branches and meandering across the alluvial stretches of land at its mouth, this fine sediment could quite easily be observed settling down in sufficient quantity to add appreciably to the delta even in the course of a few days.

Stranded Moraines in McMurdo Sound. The moraines are several miles long and of considerable breadth, while many of their numerous small hills reach a height of between 100 and 150 feet. They consist of a heterogeneous collection of debris of numerous varieties of rocks, and the material ranges in size from blocks containing many cubic feet of rock down to the finest dust. They are separated from the piedmont glacier which here fringes the mountains by a stream channel cut out almost to sea-level, and the water which has accomplished this erosion is evidently the result of the summer thaw, the stream being fed during that season both from the glacier and from the snow-drifts on the western side of the moraines. This stream is undercutting the ice, and from the exposures of morainic material on its western bank it appears probable that the mantle of debris continues right up to the flanks of the foothills of the west.

The debris being mostly of a dark colour the amount of thaw in summer is considerable, and the whole district is seamed with stream-channels which, during the few sunny days in the height of summer, are filled with running water. Every basin-like hollow between the ridges and peaks is filled with a lake of size corresponding with that of the hollow. In spite of the loose nature of the debris the lake basins are enabled to hold water, because at all periods of the year the ground at a depth of a few feet is frozen hard. Even in the summer the whole mass of the debris, except an outer mantle, is firmly cemented in consequence of the freezing at a slight depth of the percolating water supplied by the melting snow-drifts.

Proof of this is seen where the streams have cut fairly deep channels in the moraines. In the walls of these channels lenticles of opaque ice fairly free from gravel, and varying from an inch or two to a couple of feet in thickness, are to be seen in many places, while in other places, if a few feet of the outer mantle of the stream-cliff are removed, the gravel behind is found to be firmly cemented.

Most of the streams run northwards, and at the northern end of the moraines quite a thick alluvial deposit, having a strong resemblance to a series of miniature deltas, is to be seen along the ice-foot awaiting subsequent removal to the sea. The amount of material removed from the moraines in this way must be very considerable. Another agency which must be fast reducing the size of the moraines is the direct heat of the summer sun on the cliffs at the northern end. Frequently, while we were camped near the moraines, small avalanches of gravel and mud fell on to the ice-foot, and many tons of material brought down in this manner must be carried away when the ice-foot breaks up in the late summer months. The wind

FIG. 1. 3000 FEET UP FERRAR GLACIER, SHOWING MORAINE
This is at the Western Party's Christmas Camp. 3000 feet above sea level

FIG. 2. DRY VALLEY

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also plays an important part in the transport of finer material, the snow for several miles to the north of the moraines being full of grit, which is so abundant that it accelerates considerably the melting of the drift-snow and the surface of the ice.

There is a much greater proportion of pebbles and large boulders in the upper layers of the morainic material than in the lower, as seen in section in the northern cliff exposures. This phenomenon is partially explained by the fact that the finer material would gradually be carried down by the thaw-water and used to increase the compactness of the lower layers at the expense of the upper ones; but in addition it is probable that when the glacier which borders the moraines was actually providing an outlet for the ice accumulating on the mountains above it, it brought down its quota of morainic material from local sources, which local material would reach the moraines rather in the condition of large fragments than as the finely divided debris which is essentially the result of the prolonged trituration for which a long journey is necessary. This latter explanation finds support in the abundance of local erratics on that portion of the moraines nearest the shore, erratics which are identical with the different great formations which crop out in the sides of the glacier furrowing the western mountains. The southernmost portion of the moraines is almost entirely composed of angular basaltic and kenyte debris on the seaward side, the local boulders becoming more common as the landward side is approached, though at the northern end of the moraines these boulders become very numerous even on the extreme seaward side. As for the material which makes up the main mass of the moraines, a great proportion of it must have come across the Sound, because while there is no evidence of any other great outburst of kenyte material besides that of Mount Erebus, large quantities of kenyte and kenytic fragmental rocks were picked up during our short stay here of the Western Party.*

An important characteristic in addition to those already noted is the very isolated occurrence of some of the erratics.

Some small conical heaps consisting entirely of fragments of one kind of rock were undoubtedly, from the angular nature of the fragments, the final results of the frost-weathering of very large original blocks. Not so in all cases, however. In the case of one basalt tuff particularly I noticed that it was found entirely covering two or three small hills at the south-eastern corner of the moraines, and it was found nowhere else. The pieces were all rounded or sub-angular, and they were too scattered to have been the result of the weathering of a few large boulders.

One fact points to recent elevation of these moraines. At the north-eastern end of the moraines a number of flat-topped hills and ridges were of the same height, and all capped by several inches of a brownish deposit, which proved on examination to be a fungus similar to those found in the lakes at winter quarters. The whole district seems, therefore, to have been at quite a recent date a lake bed. The lake has been elevated and drained, and its bed has been dissected by streams, whilst

* The evidence secured by Debenham suggests that this material also may have a local origin.

the higher land which formerly existed to the east and constituted the boundary of the lake has been worn down and removed during the recent elevation of the moraines by a combination of the successive summer thaws and marine erosion.

Thus in the case of all three of these moraines, those of the East Fork of the Ferrar Glacier, those of the Dry Valley, and the Stranded Moraines, the conclusion is irresistible that a considerable portion of the material composing them has either been brought many miles up the coast or has been carried right across the Sound. The three agencies which alone could be responsible for this transport to any large extent are : (1) Shore-drift. (2) A considerably greater extent of the ice-sheet and all its affluents, such as glaciers, barriers, &c. Of such an extension there are abundant evidences, of which we may here mention the finding of granitic and schistose erratics at a height of 1100 feet on the slopes of Erebus. (3) The third agency is the transporting power of icebergs and pieces broken off the ice-foot. At Cape Royds, especially around Flagstaff Point, large boulders of kenyte were frequently seen being carried out to sea on pieces of the ice-foot, and some of the icebergs were observed to contain much fine rock debris.

This occurrence of kenyte boulders of some size as far north as Granite Harbour has already been noted. The probable explanation of their distribution will be considered when the past history of the Great Ice Barrier is being reviewed.

The Piedmont. The piedmont ice which has been traced continuously from the Drygalski Ice Barrier to New Harbour, a distance of 150 miles, narrows in very much south of New Harbour. Whereas to the north of this its width has been from 10 to 15 and even up to 20 miles, it is only 2 to 4 miles wide south of the Ferrar Glacier. This narrowing in width is no doubt connected with the presence of that great horst within a horst, the Royal Society Range. Before considering the remarkable ice slabs and Snow Valley to the east of the Royal Society Range we may refer to the piedmont south of the entrance to the Ferrar Glacier Valley known as the Butter Point Piedmont.

This is part of the great fringe of glacier ice which borders the great coastal shelf of Victoria Land. It has its origin on the slopes of the Northern Foothills several hundred feet above sea-level,* and at Butter Point is about 2½ miles wide. To the south it fringes the sea for 6 miles, and then takes a turn to the S.S.W. as the landward border of the Stranded Moraines, finally ending at the entrance to the Blue Glacier. To the north it continues for a dozen miles as a fringe to the foothills which form the southern border of the lower portion of the Ferrar Glacier Valley.

A view of this piedmont looking westerly from McMurdo Sound is shown in Plate XXI.

At the sea it is a cliff which varies in height from 6 to 20 feet, and during the early days of our stay at Butter Point this cliff was overhung by a fine snow-cornice. During the summer thaw a large number of very fine icicles were formed beneath

* From about 1000 feet to about 1500 feet.

Fig. 1. THE BUTTER POINT PIEDMONT SOUTH OF THE ENTRANCE TO THE FERRAR GLACIER VALLEY

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the overhanging edges of this cliff, and at one spot where the cliff was about 12 feet high these icicles grew until they reached the drifts on the sea ice and became 6 or more inches in thickness. The effect of the summer sun on the icicles was curious. When freshly formed they were quite clear and sound, and if they were broken in half no structure could be seen on the broken surfaces. After a day or two's exposure, however, to the direct rays of the sun they developed a radial fibrous structure, which was very marked and comparable with that of a belemnite. At a further stage of their melting they became so rotten that icicles with a diameter of 3 or 4 inches would crush easily in the hand, having been reduced apparently to a mere shell.

Remarkable examples of the plasticity of ice were to be seen along the ice-cliff in the early days of January. We have already mentioned that many of the icicles had grown until they had reached the snow-drifts on the sea ice below the cliff. As the thaw got in its work on the cornice from which these icicles depended large portions of it fell off, and many other portions gradually subsided.

The icicles below the fallen portions were of course smashed to fragments, but many of those beneath the parts which subsided more slowly were bent into the most weird shapes imaginable. We have frequently seen icicles converted in less than twenty-four hours into snake-like shapes, or bent at right, and even at acute, angles without the slightest sign of fracture within the icicle itself. The place at which the bending took place merely became slightly flattened and widened, as does the bend in a glass rod.

The surface of this piedmont was very rough. Near and parallel to the edge of the cliff at the place where our depot was placed were one or two cracks several inches wide.

The ice was full of sediment, and in consequence of this the top 2 feet became very rotten indeed during our stay at the point.

REVIEW OF THE PIEDMONT OF THE WEST COAST OF ROSS SEA*

This piedmont is restricted to the low-lying part of the great horst, from the Blue Glacier, south of the Ferrar Glacier to the Drygalski Ice Barrier, a distance of 160 miles.

It is hard to say exactly where the snow, creeping down the eastern slopes of the coastal hills, passes from the condition of hard snow into that of glacier ice, but on the assumption that the change takes place at the flattening of the foothills to the surface of the coastal plain, the width of the piedmont, where it attains its maximum development, that is, south of the Drygalski Ice Barrier, may be taken as about 20 miles. It narrows to about 10 miles east of Mount George Murray.

* This has since been named the Wilson Piedmont in memory of Dr. E. A. Wilson, Chief of Scientific Staff of Captain Scott's Last Expedition.

This width is maintained until the Nordenskjöld Ice Tongue is approached, and there it almost ends near Charcot Bay and Cape Bruce.

To the south side of the Nordenskjöld Ice Tongue it reappears, having there a width of from 7 to 8 miles, extending with slightly varying width from here to New Harbour. Its surface area cannot be far short of about 1500 square miles. Its upper surface is for the most part convex from the foothills to the sea-cliff. It is rough and irregularly pitted. Probably dust blown off the ranges contributes to this end. In places, as between Mount Chetwynd and Mount Creak, it is seamed with channels apparently formed by thaw-water. (See Fig. 33.) They seem to be of different origin to the shearing channels already described as conspicuous features at the Drygalski Ice Barrier Tongue. Probably they are formed by thaw-water streams having their origin in the steep slopes of the plateau rocks above the foothills at the head of the piedmont.

Seawards the piedmont terminates either in low cliffs, from 10 to 50 feet in height, or in a steep, convexly curved slope. The piedmont rests on a foundation which is certainly in part formed of solid rock. It is also certain that at intervals some morainic material of the nature of bottom moraine is present, but there is no evidence of its attaining any considerable thickness. Nothing of the nature of till (or boulder clay) was observed under the piedmont. At the same time it must be admitted that the deepest hollows below sea-level in which boulder clay would be most likely to accumulate are still hidden under the ice. The piedmont cannot be in a state of active movement, as no single instance was observed of its having ridged up the sea ice in contact with the base of its cliff, a result which would certainly follow from rapid forward movement, as was observed in the case of the old sea ice at its junction with the southern side of the Drygalski Ice Barrier. In the vicinity of the outlet glaciers the piedmont of course merges insensibly into the ice of those glaciers. The question which now arises is, what is the origin of the piedmont?

Two suggestions may here be offered :—

(1) That it is a shrinking remnant of the part of the old Ross Barrier where it was fed chiefly from the snows from the western plateau.

(2) That it owes its origin (*a*) partly to local snowfall on the platform on which the piedmont rests, (*b*) partly to snow drifted (i) by plateau winds, (ii) by the southerly blizzards.

This second suggestion may be termed the snow-dune theory.

In reference to the first suggestion, it is certain that the Ross Barrier has at one time covered the whole of the plain upon which the piedmont now rests from a little south of the Ferrar Glacier mouth to at least as far north as the Drygalski Glacier.

When it is said that the ice of the Great Ice Barrier formerly covered the plain, on which the great piedmont of the west shore of Ross Sea rests, it is to be understood that the ice of this piedmont did not come necessarily from the south, but was derived, in part at all events, from the huge outlet glaciers of the inland plateau west of Ross Sea. But this ice was certainly confluent with that of the Ross Barrier.

An examination of the map (Plate III.) shows that the eastern portions of all the great glaciers entering Ross Sea along its west coast show a trend somewhat to the north of east as far as Cape Irizar. Thus the East Fork of the Ferrar Glacier, the North Fork and Dry Valley, the Mawson Glacier, and the Davis Glacier all have an E.N.E. trend, whereas the trend of the coast-line is almost exactly north and south. It is suggested that this deflection towards the north is due to the shouldering action of the Ross Barrier with its powerful thrust from the south.

In regard to the second theory, that the piedmont is formed partly of local snow which has fallen on the surface of the coastal plain, partly of snow drifted from the inland plateau across the ranges, it may be stated that there can be no doubt that vast quantities of snow are conveyed from inland seawards by the action of the plateau wind. Where the plateau wind blows straight down the gateways in the great horst formed by the outlet glaciers, such as the Ferrar, Mackay, and Mawson Glaciers, &c., it carries with it a continuous stream of snow crystals, the air being as thick as a hedge during blizzards on these glaciers, for four or five consecutive days on occasions. Such snow when it reaches the coast is distributed far and wide over the surface of the sea ice. It was this somewhat thick covering of snow with its high sastrugi which prevented our taking the motor car more than about one-third of the way across McMurdo Sound towards the mouth of the Ferrar Glacier. In the late summer, when the sea ice has broken away from near the mouth of the glacier, any snow carried from inland down the glacier by the plateau wind is of course blown out to sea and quickly melts in the salt water. Where, however, the elongated tabular mountains of the great horst, with their steep, almost precipitous, eastern slopes form a lee to the westerly plateau wind, their snow-drifts must necessarily accumulate on a grand scale.

Professor Hobbs has already suggested that much of the Antarctic ice along the shore-line of the continental mass is formed from drift snow. There can be little doubt that such is the case. During the few days that the Northern Party were at or near the Backstairs Passage Glacier it was noticed that when the plateau wind was blowing at times with blizzard force it carried dense masses of drift snow down this pass in the range. Vast quantities of this snow were swept out over the surface of the piedmont to the open sea about 15 miles distant, but a considerable amount of it must have lodged on the surface of this glacier. Whether or not any portion of the piedmont ice of to-day is actually the relic of the old ice mass, which was formerly an integral part of the Ross Barrier, is a question which cannot be proved, though it is by no means improbable that some of the ice is an actual survival of the former Ross Barrier sheet. It may be regarded as proved that a considerable portion of the nourishment of the piedmont glacier ice is received from blown snow, and the ice in some sense may therefore be considered a snow-dune ice.

CAPE ROYDS, EREBUS, CAPE BARNE, TURK'S HEAD, GLACIER TONGUE, HUT POINT, AND MINNA BLUFF EVIDENCE

Glacial conditions, past and present, were especially studied by us in the neighbourhood of our winter quarters at Cape Royds. The observations of Ferrar and Dr. E. A. Wilson had made us familiar with the fact that Ross Island shows evidence of two distinct types of glaciation. The first is the glaciation effected in former times by the Ross Barrier, when its surface stood fully 1000 feet above the present level of McMurdo Sound, and when its northern edge extended at least as far north as probably Cape Washington. Even at the present time the southern side of Ross Island, between Cape Armytage and Cape Crozier, is being subjected to glaciation by the northern edge of the Ross Barrier. That this glaciation is still active is evident from the immense crevasses and pressure ridges at the meeting-point of the Ross Barrier cliff and the rocks of Ross Island on Cape Crozier. The pressure ridges already figured by Scott and Ferrar near Pram Point also indicate active glaciation still in progress in that region.

This glaciation of Ross Island, effected by the Ross Barrier, has left most interesting traces of the former presence of the ice sheet in the form of deeply trenched elongated rock basins, now occupied by lakes, as well as by magnificent terraces covered with blocks of granite, schist, gneiss, Beacon Sandstone, &c., transported as small to large boulders from the old land masses of the mainland to the south and west. During the maximum glaciation Ross Island must have stood out from the surface of the Ross Barrier as a huge nunatak. The flotsam and jetsam from this great ice flood has formed the remarkable terrace near the one thousand feet level. When one surveys the small rock basins, some scooped below sea-level, such as Sunk Lake, Deep Lake, &c., as well as the canal-like grooves cut in a meridional direction through the kenyte lava, one cannot but be impressed with the considerable erosive power of thick glacier ice, thrust forward by the enormous glaciers which fed it to the west and south.

Secondly, there is evidence of a local glaciation still in progress. This is due to glaciers formed from snow precipitated on the surface of Ross Island, as well as to drift snow which has streamed over the surface of the Ross Barrier, and has then escaped seawards towards McMurdo Sound, over the long volcanic ridge which extends northwards from Cape Armytage to beyond Glacier Tongue, a distance of about 15 miles. One would, therefore, expect to find, at Ross Island, the glaciers most active where there is now the heaviest precipitation of new falling snow, as well as of drift snow derived from earlier falls. The parts of Ross Island nearest to Ross Sea and McMurdo Sound receive a small snowfall, at Cape Royds equal to perhaps about 7 inches of rain (rain never actually falls in this region, but the measurement of the snow is given in its equivalent of rain). As a matter of fact, Mount Bird and the coast-line from there to Cape Crozier is more or less buried

PLATE XXII

Fig. 1. GLACIER TONGUE, ROSS ISLAND

Fig. 2. WEST SIDE OF GLACIER TONGUE
Showing snow cornice formed by southerly blizzards

[T. W. Edgeworth David

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under glacier ice. The southern and south-western slopes of Erebus are also still being heavily glaciated, but the north-west slopes of Erebus are almost free from glacier ice.*

Since the retreat of the Ross Barrier back to its present edge, to the south of Cape Armytage, the glaciers radiating from the south-west slopes of Erebus have invaded the vacated territory, cutting through the old marginal moraines of the Ross Barrier, and forming later moraines. These are built up partly of fragments of kenyte lava, partly out of redistributed material of the old marginal moraines of the Ross Barrier.

We may commence with the most active glaciers examined by us, viz. those on the south-west slopes of Mount Erebus, extending as far south as Glacier Tongue.

Glacier Tongue. Glacier Tongue is a very remarkable instance of a glacier jetty on a comparatively small scale. It is about 5 miles in length from east to west, and from a quarter to about three-quarters of a mile wide from north to south. Its surface is slightly convex, rising from its seaward end eastward to its point of attachment to the land. At the point where our depot for the southern journey was established on it, a little over 1 mile east of its western extremity, it was between 40 and 50 feet above sea-level at the highest points observed. The material of which it is formed is true, blue, glacier ice. This was found to be crevassed for at least 4 miles outwards from its point of attachment to the land. On its north side Glacier Tongue is levelled up by the drift snow carried by the south-easterly blizzards, this being of course the weather side of the Tongue. On its northern or leeward side the Tongue terminates in a low cliff, frequently with overhanging snow cornices. Its northern wall is deeply indented at intervals so as to form natural small docks, and advantage was taken of this by the *Nimrod's* party. It was found possible to warp the ship close up to the cliff by ice anchors, and she could ride out the fiercest blizzard here in comparative safety. The accompanying illustrations show the appearance of this cliff late in February 1909.

During the winter months this low cliff, for the most part, is completely masked by sloping drifts of snow; as summer thaw proceeds, and the ice breaks up, the foundation of sea ice under the drifts cracks up, and carries the overlying consolidated snow-drift out to sea, until eventually a low vertical cliff is left, as shown in the photograph. We thus see repeated on a smaller scale the same phenomena at Glacier Tongue as those already described at the Nordenskjöld Ice Barrier Tongue. The accompanying sketch after H. T. Ferrar (Fig. 44) shows the shape and situation of Glacier Tongue.

Two questions of special interest suggest themselves in regard to Glacier Tongue. First, what is the source of supply of its ice? Second, is it aground or afloat?

In regard to the first question, it may be stated that the width of the land at the

* It was for this reason that that portion of the mountain was selected as the route for the ascent of March 1908.

back of the glacier, measured in the direction of the trend of the glacier, is only 3 miles, and of this about 1½ miles slopes down towards the Ross Barrier instead of towards Glacier Tongue. This eastern half of the land cannot therefore directly contribute much ice to nourish Glacier Tongue. How then can a mass of ice which projects 5 miles into the sea, and has a width on the average of about half a mile, and a thickness of from 400 to 800 feet, be nourished by a land surface only 1½ miles in width?

The explanation of this remarkable phenomenon is probably to be found in the following geographical structure of the country in its vicinity: Glacier Tongue is to leeward of a comparatively low gap in a long peninsula. The southern end of

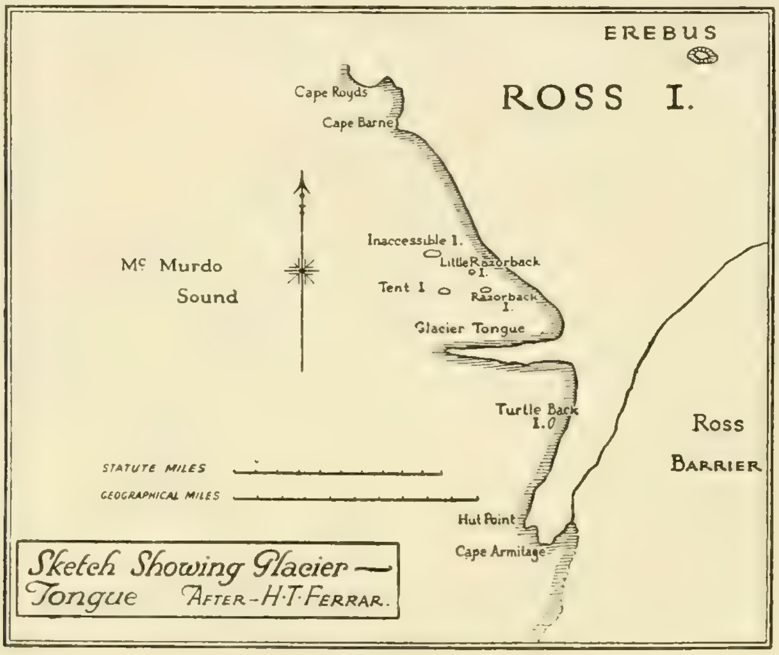

Fig. 44

this peninsula is from 1000 feet to as much as 1300 feet above sea-level. In a northerly direction it gradually descends to a comparatively low gap opposite the point of attachment of Glacier Tongue, then the land ascends somewhat rapidly towards the summit of Mount Erebus, over 13,000 feet above the sea. Erebus of course offers an immense obstacle to the wind currents, and the blizzard wind which near Hut Point blows from about S.S.E. is deflected, as shown by the trend of the sastrugi near Glacier Tongue from S.S.E. into a nearly east and west direction, consequently immense streams of snow-laden air flow over the south-western slopes of Mount Erebus as well as over the depression at the base of the long peninsula, terminating southwards in Hut Point, and contribute largely the necessary *névé* for the nourishment of Glacier Tongue. Some ice is also derived from the heavy snow-drifts which lie on the south-west flanks of Erebus, adjacent to the shore end of the

Tongue. On this theory Glacier Tongue is therefore chiefly formed of drift or dune snow.

Another possible theory as to its mode of origin is that it is a shrinking remnant of a lobe of the old Ross Barrier which formerly overflowed the saddle to the east of Glacier Tongue. Such a lobe might have been deflected from east to west, just as are the modern blizzard winds by the resistant massif of Erebus directly opposed to its northward movement.

In regard to the question as to whether Glacier Tongue is aground or afloat, it may be stated that on February 13, 1908, soundings were taken at a point a little over half a mile back from the west end of Glacier Tongue, which reached bottom at 157½ fathoms. The arming of the lead brought up a quantity of serpulæ and siliceous sponge spicules; in fact, the bottom of the sea there must be as white as snow with the siliceous sponge spicules. Obviously we are confronted here on a smaller scale with a similar problem to that which has already been discussed in connection with the Drygalski Ice Barrier Tongue. The surface of Glacier Tongue nowhere exceeding about 40 feet above sea-level in this locality, the thickness of the ice cannot be greater than about 400 feet at this spot, whereas the depth of the sea is 945 feet. If this same depth was maintained right under the glacier, there should be a depth of 585 feet of sea water between the bottom of the glacier ice and the floor of the sea.

As already stated, at about 3 miles back from this seaward end the surface of Glacier Tongue rises 70 to 80 feet above sea-level, and if the sea shallows slightly in an easterly direction towards the land, as is likely, the eastern portion of the glacier is probably aground. The chief question now is, is the western half of the glacier afloat or aground? Obviously the presence or absence of a well-marked tide crack should settle this question. Certainly a small, but not well-defined, tide crack was noticed by us on the northern side of Glacier Tongue. It was suggestive of a slight, though not strongly marked, differential movement between the sea ice and the glacier ice. One would have expected a more pronounced tidal crack had Glacier Tongue at this point been resting firmly upon the bedrock. When we were on the *Nimrod*, lying under the lee of Glacier Tongue, we tried to determine whether or not the glacier was rising and falling with the tide, as evidenced by the level of the ship's rail in relation to the marginal cliff of the glacier and the position of the wave-worn groove with its icicles at the base of the glacier cliff in relation to sea-level. We were unable to notice any appreciable difference in level in either case during a rise and fall of the tide. We must therefore conclude provisionally that the western part of the Tongue is afloat.*

* This view has subsequently been confirmed by Captain R. F. Scott's British Antarctic Expedition of 1910–13. Two miles in length of the seaward end of Glacier Tongue broke away during a blizzard on March 1, 1911, and was found later by T. Griffith Taylor's party near Cape Bernacchi, at the entrance to the Ferrar Glacier Valley, about 50 miles to the W.N.W.

The problem now presents itself as to how it is possible for a long, narrow, floating mass of ice—if it is floating, its seaward portion being only from one-quarter to half a mile wide—to resist the force of the blizzard winds and strong accompanying currents which in summer time, after the breaking up of the ice, sweep down McMurdo Sound. One would imagine that under these conditions Glacier Tongue would quickly break off at its seaward end, and float away as bergs. We find, on the contrary, that in the interval of between four and five years which had elapsed between the date of Captain Scott's expedition in the *Discovery* and that of our visit, the length and breadth of the Tongue had been pretty uniformly maintained. It is quite possible that here, as is assumed to be the case at the Drygalski Ice Barrier Tongue, the Tongue has pushed out a bottom moraine, or submarine esker, like a great railway embankment, and is sustained rigidly on this for at least one-half, possibly for as much as three-quarters, of its length.

It is still difficult to understand, even on this hypothesis, why the tip of the Tongue does not snap off and drift away. Many more soundings are needed on both sides of the glacier, and particularly on its seaward extremity, before this problem can be solved.

Turk's Head. About 6 miles north-westward of Glacier Tongue is the Turk's Head Glacier. The steep slopes above the Turk's Head Nunatak are heavily glaciated, and the glacier is strongly crevassed. It seems that here, and in the direction of Cape Barne farther north, the glaciation on the western slopes of Erebus attains its maximum. The probable cause for this, as has already been suggested, is to be found in the vast quantity of drift snow, which has swept on to this part of Erebus from the surface of the Ross Barrier to the south. Thus the gathering ground which supplies the ice for this glacier, for Glacier Tongue, and for the Cape Barne Glacier, may not be merely restricted to the western slopes of Erebus, but may be potentially a considerable surface of the Ross Barrier.

A huge ice cave more than 50 feet in height is a conspicuous feature in this Turk's Head Glacier. It is situated just at the point where the glacier descends from the rocky shore into the sea, and has doubtless been excavated by waves impelled by blizzard winds, at a time when there was open water to the south of the glacier. As shown in the accompanying photograph, the ice at this point is heavily crevassed.

At the foot of the glacier was a large iceberg, so much crevassed that its top was a series of sharp pinnacles. There seems no reason to doubt that this berg had been recently broken off from the Turk's Head Glacier, and it is very possible that two other bergs composed of glacier ice, seen stranded a little to the north of Turk's Head, were derived from the same source. The ice in this glacier close to where it leaves the land must be about 150 feet in thickness.

The view on Fig. 2 of Plate XXIII. shows how completely swathed in ice

FIG. 1. TURK'S HEAD GLACIER
Showing large wave-worn cave on side, facing southerly blizzards, at point where glacier reaches the shore

FIG. 2. SMALL GLACIER
Entering McMurdo Sound to south of Turk's Head Glacier, looking north-east to Mount Erebus

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and *névé* the terraced slopes of Erebus are in this region, and illustrates another small glacier of the Norwegian type descending into McMurdo Sound.

Very little rock is visible at all excepting close to the shore-line.

Passing now about 2 miles farther to the north-west, one reaches the spot called by Captain Scott the Skuary.*

The Skuary. The Skuary is an area of bare land abutting on the southern border of the Cape Barne Glacier, and some 6 or 7 miles south of our winter quarters at Cape Royds. The exposed land is about $2\frac{1}{2}$ square miles in extent, and is covered, except at the cliff faces along the shore, and some of the more important and steeper of the hills and ridges, with a thick mantle of morainic material which, as far as could be judged in a cursory visit, seems to be mainly of local origin. Some small fragments of tuff were observed belonging to a variety occurring *in situ* at Turk's Head; but there seems to be a total absence of the continental type of plutonic, hypabyssal, and sedimentary erratics with which Cape Royds is strewn. The evidence points to recent glaciation by a local Erebus glacier subsequent to the maximum extension of the continental ice sheet, and, in fact, the Skuary is still bounded on the side adjacent to Erebus by what is probably the shrunken remnant of this same glacier. The moraines consist almost entirely of a compact brownish kenyte, a type prevalent in the immediate neighbourhood. This kenyte is somewhat lighter in colour than that met with at Cape Royds. It is rendered porphyritic by light coloured and clear felspars, is most beautifully weathered, and the gravel which cover the depressions of the beds of the various little rills which drain the area are full of felspars, mostly cleavage fragments, but some of them were whole felspars with their edges distinctly rounded off as if by the action of running water. It is remarkable that all these felspars were chemically so unaltered that they were almost transparent. They were mostly of a very light yellowish colour. Scattered about the Skuary are a number of small cones, consisting chiefly of angular fragments of brownish kenyte, with here and there a fragment of fairly fine-grained tuff. Along the margin of the glacier, where it bounds the rocky area, there is a somewhat regular row of from ten to twenty similar cones, separated from one another by a distance of only a few paces. Probably most of them are eskers exposed to view through the retreat of the glacier, but the presence of one undoubtedly intrusive parasitic cone makes one cautious in attributing the formation of all these cones to glacial action.

When the Skuary was visited on November 18, 1908, the thaw had just set in in earnest. This particular day was cloudy, and the streams of thaw-water had consequently been frozen, but the ridged appearance of the snow-drifts, and the presence of ice in stream channels, all testified to the thawing influence of the sun's heat during the past one or two days. On November 18th there was still a quantity of snow left, but the Western Party, when passing this spot at the

* Captain Scott has more recently changed this name and substituted the name Cape Evans.

beginning of December, remarked that scarcely any snow remained, in spite of the fact that wind laden with drift snow had been blowing for three or four days at the end of November.

Cape Barne. Immediately to the north of the Skuary is the important Cape Barne Glacier. This is also fed by the snows which lodge on the south-western slopes of Erebus. It is about $2\frac{1}{2}$ to 3 miles in width, extends several miles inland, and terminates seawards in a magnificent ice-cliff. This measurement represents the whole width of the cliff face from the cape to the north to the Skuary to the south-east. The height of the cliff varies from about 50 feet to about 150 feet. Where highest, about 3 miles beyond Cape Barne, it has advanced as a tongue several hundred yards beyond the most westerly limit of the rest of the glacier cliff. A view of the highest part of this ice-cliff is shown on Plate XXIV. Fig. 2, with Cape Barne in the distance.

The summit of Cape Barne is 300 feet above sea-level.

Plate XXIV. Fig. 1 shows a general view of this cliff looking southwards from half-way between it and Cape Barne.

A study of the sea ice at the base of the cliff did not show any evidence of pressure ridges having been developed through forward movement of the glacier mass. There was of course a well-marked tide crack, showing that the glacier was aground. It may be concluded that the ice of the Cape Barne Glacier, if in a state of movement, as is rendered probable by the presence of the crevasses, is moving so slowly as not to crumple up the sea ice in front of it. That movement, if any, is very slow is also proved by the fact that during the whole time Cape Barne Glacier was under our observation, from September 1908 until early in December, no large masses of ice were seen to break away from the cliff. Had there been much movement in the glacier, obviously the upper part of the cliff would soon have overhung its base, and under gravity large fragments would have become dislodged, and would have broken up the sea ice at the base of the ice-cliff.

From Cape Barne, which bounds the Cape Barne Glacier on the north, to Horseshoe Bay, a total distance of about 4 miles, the coast was examined by us in some detail, the area being near to our winter quarters, and the geological map (Plate XCV.) was constructed by us from a plane table survey.

From the Cape Barne Glacier to Horseshoe Bay the coast-line is mostly formed of bare kenyte lava. At our winter quarters at Cape Royds we were particularly fortunate in having exposed to view a region intensely glaciated, which had formerly been buried to a depth of fully 1000 feet under the ice of the Ross Barrier.

The region abounded in ice-eroded lake basins and tarns, as well as in large grooves, like small canals cut by the ice out of the kenyte lava. A typical groove is shown in Fig. 1 of Plate XXV.

This canal-like groove measures in width about 6 to 8 feet, in depth about 5 feet.

The granite erratic in the photograph measures 4 feet by 3 feet by 2 feet.

PLATE XXIV

Fig. 1. CAPE BARNE GLACIER
Looking south-eastwards towards Cape Evans

Fig. 2. ICE CLIFF AT WEST END OF CAPE BARNE GLACIER
With Cape Barne in the distance. Cliff over 100 feet high

[T. W. Edgeworth David

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The height above sea-level is about 200 feet. The surface of the kenyte, on account of the great absorption of heat by day and the rapid cooling at night, bringing about a quick disintegration of the rock through mechanical expansion and contraction, has lost nearly all its former glacial *striæ* through this frost weathering. Only in one instance were well-preserved grooves observed on the surface of a granite block, wedged into an angular hollow of the kenyte in such a way that it still retained the direction of the grooves produced by the great ice sheet when at its maximum. The light colour of the granite has led to its being subjected to less extremes of temperature than the black kenyte, hence its surface is much better preserved. The way in which this boulder has become embedded in the kenyte and then hollowed out and grooved, is shown on the special map of this area. The direction of the grooves is from S. 25° E. to N. 25° W., true. The general trend of movement of the ice is also indicated by the bearing of the long axis of the glacial lakes. Thus the long axis of Terrace Lake trends about N. 30° W., that of Deep Lake and Sunk Lake trends about N. 15° W., Islet Lake about N. 35° W. The long axis of the largest of these lakes, Blue Lake, runs about N. 40° W., that of Clear Lake also N. 40° W. The trend of the main wide shallow valley, glacially excavated, that extends from Backdoor Bay to Horseshoe Bay, is about N. 10° W. It may be said generally that the trend of the glaciation on the whole appears to have been about between N. 10° W. and N.N.W.

An interesting feature in the lake basins is Sunk Lake. As shown in the cross section from C to B,* the surface of the ice of Sunk Lake is 18 feet below sea-level, and the rock bottom of the lake probably 50 to 60 feet below sea-level. This lake is distant only 3 chains from the shore-line. While, as will appear later, there is abundant evidence for a recent uplift of the land in this region, there is no evidence of recent subsidence. The heavy downthrow fault which bounds Ross Sea on the west, with its displacement of the order of 7000 to 8000 feet, appear to have antedated the great glaciation. The fact that the bottom of this Sunk Lake rock basin is below sea-level seems good evidence for the hollowing capacity of glacier ice. Careful search was made by us over this intensely glaciated region of Cape Royds for any trace of true boulder clay, but we entirely failed to discover any. It must be remembered that the Cape Royds area was not by any means the lowest depression glaciated in this region by the Great Ice Barrier. As shown by the soundings of the *Nimrod*, at a point about 8½ miles north by west from Cape Royds, and only 3 miles distant from the nearest land, McMurdo Sound is 459 fathoms (2754 feet) deep, whereas the ice at Cape Royds was 1000 feet thick a few miles to the north, and to the west it was about 3750 feet thick. Under these circumstances the bulk of the bottom moraine, possibly of the nature of boulder clay, would be submerged under McMurdo Sound, and the morainic material stranded near Cape

* See Plate VIII. in section on Meteorology, and detailed map of the Cape Royds area, Plate XCV.

Royds would be chiefly of the nature of lateral moraine. Obviously the high level terraces shown on the map about $1\frac{1}{4}$ to $1\frac{1}{2}$ miles easterly from Cape Royds are of the nature of marginal moraine, marking the former level to which the ice flood reached up the slopes of Ross Island, at that time a gigantic nunatak. At the same time it seems strange that a mass of glacier ice 1000 feet thick, moving for centuries over nearly level rock surface like that in the vicinity of Cape Royds, did not produce, by crushing the kenyte rock to powder, a tough boulder clay.

If fine comminuted rock material (rock flour) was originally produced here under the ice sheet it must have been washed subsequently to lower levels by sub-glacial thaw-water. All that is left at present, in the way of morainic material around Cape Royds, are thin and comparatively insignificant patches of small boulders intermixed with kenyte rubble. These are only of about a couple of acres in area, and not more than about 1 foot in thickness.

Farther east, up the foothills of Erebus, are much more extensive elongated mounds and terraces, belonging to the old marginal moraine proper of the old Ross Barrier. The general appearance of these moraines is shown in the frontispiece to this volume. These terraces and mounds vary very much in thickness, from a few feet up to 50 or 80 feet.

In connection with these moraines of the western slopes of Erebus, Ferrar quotes a statement by Dr. E. A. Wilson, that he observed near Cape Royds, during the period of summer thaw, streams of water emerging from underneath these moraines. Dr. Wilson concluded that probably there were still masses of glacier ice buried under the moraines.*

A feature of these moraines which puzzled us very much was the appearance of what may be termed paths. These paths ran at various angles in relation to the slope, either vertically or obliquely.

Some suggested that they were tracks left by seals crawling inland, others that they represented cracks due to irregular movements resulting from the thawing of underlying masses of ice withdrawing support from the overlying moraine; the whole settling under gravity may have developed irregular cracks which became channels for thaw-water, and thus the paths may have been formed.†

The moraines, which were obviously of the nature of marginal moraines left by the great ice sheet, comprised a vast number of erratics, which have been described elsewhere, in the second volume, by Professor Woolnough. They comprise pegmatites, often containing garnet, aplite, syenite, sodalite-syenite with wohlerite, quartz-diorite, granophyric granite, porphyry, granophyre, felspar porphyry, minette,

* It was observed by one of us (Priestley) that the uplifted marine shell-beds of the Cape Barne district rested on ancient ice, probably a relic from the maximum glaciation.

† It may also be suggested that these "paths" may be due to alternate expansion and contraction of the morainic material. From this point of view they may be of the nature of infilled contraction cracks.

FIG. 1. GRANITE ERRATIC
4 ft. × 3 ft. × 2 ft., lying in glacially eroded wide groove in Kenyte lava, High Hill, Cape Royds [David

FIG. 2. ERRATIC OF RED GRANITE NEAR BACKDOOR BAY, CAPE ROYDS [David

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vosgesite, porphyrite, diabase-porphyry, solvsbergite, sapphire-bearing trachyte, spherulitic trachyte, porphyritic basalt, actinolite-schist, tremolite-schist, phyllite, several varieties of red and grey granites, granulites with scapolite and pyroxene, and of course a plentiful admixture of kenyte and kenyte-tuffs. In places very coarse porphyritic gneisses are met with amongst these erratics. Sedimentary rocks had been collected from here in the form of fragments of Beacon Sandstone more or less converted into quartzite, quartzite perhaps older than the Beacon Sandstone, containing much titaniferous iron, fragments of saccharoidal marble, marble partly silicified, oolitic limestone partly replaced by quartz and much resembling the Cambrian Durness limestone of Scotland, as well as fragments of dark grey cherty rocks. These old moraines containing these considerable varieties of eruptive rocks, together with old sedimentary rocks, are in sharp contrast with the moraines derived from Erebus proper. The latter are almost exclusively formed of kenyte lava and tuff, with an occasional sprinkling of trachyte or basalt.

In addition to these moraines forming terraces on the west slope of Erebus, uplifted beaches occur at intervals amongst the terraced moraines. These are described in detail under the heading of "raised beaches." Foreign boulders occur, varying in size from a few inches up to 5 feet in diameter. The largest of these foreign boulders are formed of the red granite which is so abundant on the mainland.

It will be noticed on the map of the Cape Royds district that these erratics of red granite have a linear direction as regards their present distribution, the trend of the line being about N. 30° W.

The question may be asked, why did the Great Ice Barrier Glacier in McMurdo Sound, in the neighbourhood of Cape Royds, move in a direction west of north instead of due north, following the trend of the Sound, with possibly a slight set to the east of north due to the component of pressure from the great western glaciers of Victoria Land? The probable explanation is, that during the period of maximum glaciation the western slopes of Erebus, like its other portions, harboured large glaciers, which moved off down the slopes towards McMurdo Sound in a westerly direction; the westerly component of pressure supplied by them was sufficient to slightly deflect the northward moving ice of McMurdo Sound in a westerly direction. (See Fig. 2 of Plate XXV.)

A large erratic of kenyte on the south-east side of Pony Lake, near our winter quarters, measured 49 feet in circumference and $10\frac{1}{2}$ feet high.

The dimensions of some of the granite erratics near Cape Royds are as follows:—

1. Red Granite, 6 feet 9 inches by 3 feet 4 inches by 2 feet.
2. Red Granite, 11 feet in diameter.
3. Grey Granite, 2 feet 6 inches by 2 feet by 1 foot 3 inches.
4. Aplite, 2 feet 6 inches by 3 feet by 1 foot 3 inches.

That these moraines of foreign erratics extend for some distance to the west of

Cape Royds is very probable, for in summer, when the sea ice and ice-foot had been swept away, one could see huge boulders of the granite submerged at some distance from the shore, their light colour making them easily distinguishable from the surrounding kenyte.

The moraine terraces above Blue Lake appear to be made up principally of angular fragments of a dark, fine-grained volcanic rock, with phenocrysts of augite and olivine. Among these fragments were a good many hexagonal prisms of the same rock remarkably regular, some of them from 2 to 3 feet long. A number of blocks of tuff were also present. The commonest and largest blocks were a yellowish, fine-grained friable tuff.

Along the eastern shore of Clear Lake it was noticeable that the only prominent erratics, other than basalt and kenyte, were a yellowish-green trachyte, which appears to have been the oldest of the Erebus series of eruptions. Fragments of diabase or quartz-dolerite, from the huge sills of that rock on the mainland, were of frequent occurrence.

In regard to the moraines left by the glaciers from Erebus when, subsequent to the recession from McMurdo Sound of the former Ross Barrier, they were able to over-ride the ground which it formerly occupied, we observed in the southern portion of Blue Lake seven mounds of kenyte rubble. These we called eskers. The general shape and distribution is shown on Fig. 45.

The eskers appear to be composed of fine kenyte rubble, and may have been deposited by sub-glacial streams from an old glacier formerly descending from Mount Erebus into the southern basin of the Blue Lake.*

Passing northward from Cape Royds we reach Horseshoe Bay. Here, for the first time since leaving Cape Barne, the volcanic series of Mount Erebus disappears once more under a permanent cover of glacier ice. The latter is the piedmont glacier of Horseshoe Bay. This glacier forms an ice-cliff on the eastern portion of Horseshoe Bay from 50 to 60 feet high. This is the terminal face of an almost inert mass of ice fed by the *névé* fields of the north-western slopes of Erebus. That the ice is not in active movement is proved by the general absence of crevasses, of which only small examples were observed. One of these had its sides fringed with beautiful feathery ice crystals, which had evidently grown from the moisture in the comparatively warm air coming up from the bottom of the crevasse. This moisture became deposited on projecting points of the crevasse walls.

Another phase of growth of these secondary ice crystals produced hexagonal plates, sometimes as much as 7 inches in diameter, and comparable with those found on Murray's dredging line. The latter crystals are illustrated in Fig. 1 of Plate XXVI. Fig. 2 is a view across Horseshoe Bay looking towards Cape Bird.

This piedmont glacier appears to be continuous as far as to Cape Bird. Near

* We were unable to ascertain the nature of the foundation on which they rested. It may have been either rock or ice.

PLATE XXVI

Fig. 1. ICE CRYSTALS
Formed on dredging rope taken out of sea water, Cape Royds
[Photo by D. Mawson

Fig. 2. VIEW ACROSS HORSESHOE BAY
North of Cape Royds, looking north towards Cape Bird
[Photo by David

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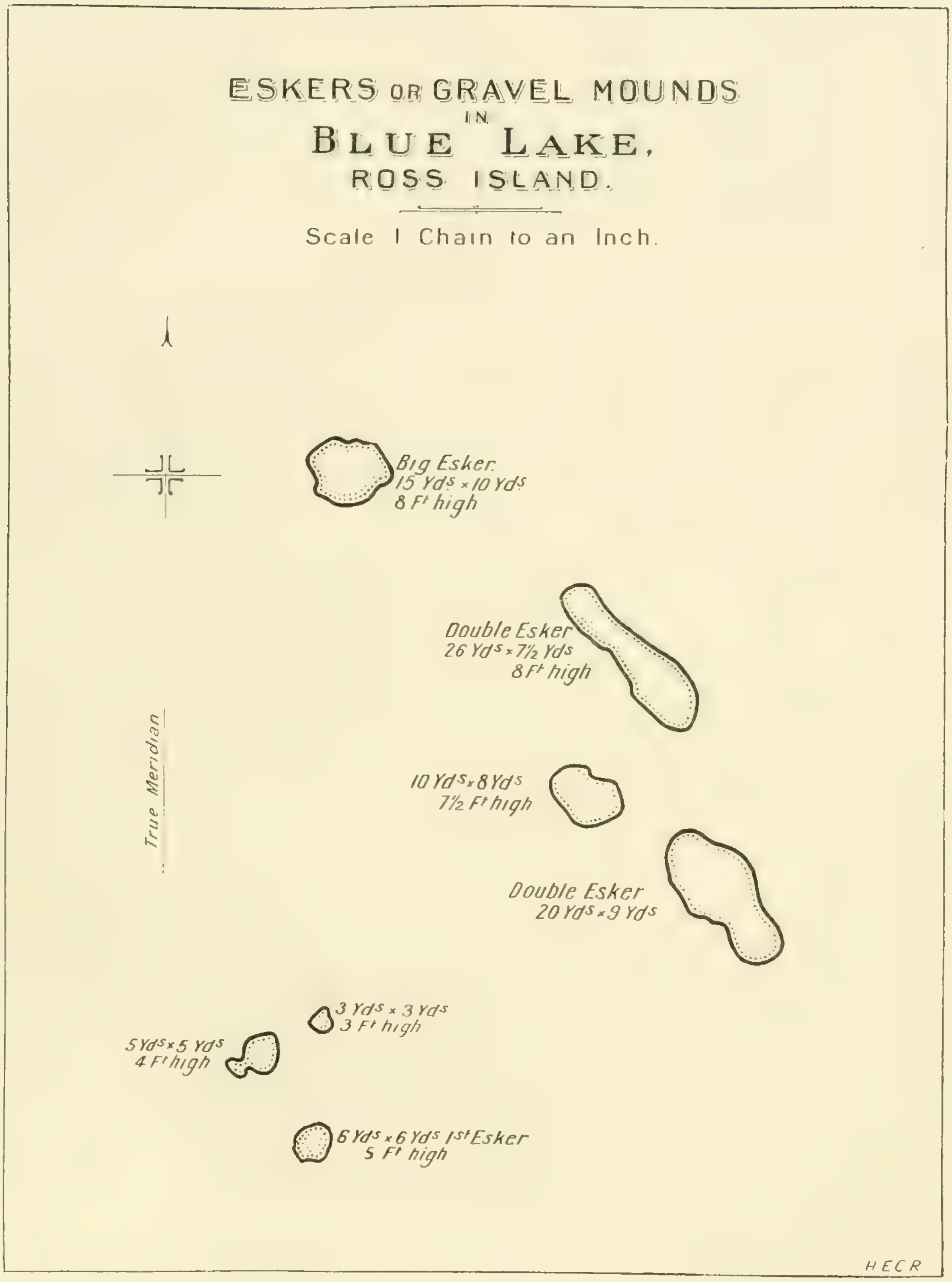
ESKERS OR GRAVEL MOUNDS
IN
BLUE LAKE,
ROSS ISLAND.
Scale 1 Chain to an Inch.
True Meridian
Big Esker
15 Yds × 10 Yds
8 Ft high
Double Esker
26 Yds × 7½ Yds
8 Ft high
10 Yds × 8 Yds
7½ Ft high
Double Esker
20 Yds × 9 Yds
3 Yds × 3 Yds
3 Ft high
5 Yds × 5 Yds
4 Ft high
6 Yds × 6 Yds 1st Esker
5 Ft high
HECR

Fig. 45

the farthest point north along the coast visited by us, just beyond Horseshoe Bay, we found several foreign erratics, including many pieces of undoubted Beacon Sandstone.

We now pass on to Cape Bird. The photographs of Plate XXVII. show the general appearance of this cape near the point where Macintosh and McGillan landed previous to their sensational trip overland to Cape Royds. In picking up their depot and tent Mawson obtained a series of specimens of rocks from the shore-line. The dominant rock was later described by Jensen. These rocks were mostly erratics composed of trachytes, of strongly alkaline kulaites or trachy-doleritic rocks, sub-alkaline basalts and dolerites, some enstatite-bearing, some olivine-bearing. Erratics foreign to Ross Island were not observed.

In the upper figure it will be noticed that there is a well-marked terrace, suggestive either of its being a raised beach or a parallel road. It is very similar to the feature observed along the east coast of Backdoor Bay, and appears to be a similar height above sea-level. The height of the Backdoor Bay terrace was about 50 feet. It will be seen that the glacier, mantling around the parasitic volcanic cone in Fig. 1, does not reach sea-level. In Fig. 2 a small parasitic cone is shown immediately over the boat. The absence of foreign erratics, as far as we could judge at Cape Bird, is probably to be explained by the slight westerly deflection imparted to the Ross Barrier by the pressure of the ice descending the west slopes of Erebus. This would of course tend to push the great marginal moraines of erratics, foreign to Ross Island, away to sea at some little distance from the coast, before the Ross Barrier reached Cape Bird. Cape Bird proper is 25 miles distant, in a north by east direction, from Cape Royds. The spot from which Mawson collected the erratics described by Dr. Jensen was approximately 10 miles south by west from the cape, and almost opposite to Mount Bird.

SUMMARY OF THE FERRAR GLACIER AND CAPE ROYDS REGION

We are now in a position to review briefly the structure of the inland ice and glacier ice, past and present, between Scott's farthest west, on his western journey, and the moraines of the western foothills of Erebus abounding in erratics foreign to Ross Island. The same features so conspicuous on the section from the South Magnetic Pole area to the Drygalski Ice Barrier Tongue are repeated. On the left and west is a high plateau, rock-free, and covered no doubt to a considerable depth by the inland ice sheet. Its level is singularly uniform, varying from a little over 7200 feet to about 7550 feet. This remarkable uniformity of level is maintained for no less a distance than 110 miles.

Next, eastwards, one reaches the great horst. This rises at first in the Lashley Mountains to an altitude of 8590 feet; still farther east, in Mount Davis, to 9000

FIG. 1. GLACIER AND TERRACE NEAR CAPE BIRD
The terrace may mark a former shore line

FIG. 2. GENERAL VIEW OF THE COAST NEAR CAPE BIRD
With parasitic volcanic cone in distance

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feet, while in Mount Lister the horst culminates in a peak nearly 13,000 feet high. This peak is only an elevated horn on a plain, the level of which ranges from 11,000 up to nearly 13,000 feet. Towards the seaward ends of East Fork and Dry Valley there is a remarkably deep notch in the coast-line. This is known as New Harbour, and measures 10 miles wide by about 8 miles. One cannot but infer that this remarkable inlet is due to the prolonged excavating action of the two most energetic branches of the Ferrar Glacier, as it was when the ice flood was at its maximum, viz. East Fork and North Fork. The inlet is in every way comparable with that of Granite Harbour, but is on a somewhat larger scale. As already stated, the *Discovery* Expedition obtained soundings of over 100 fathoms within a quarter of a mile of the coast of Granite Harbour, which suggest that this harbour is a deeply eroded glacial fiord. Unfortunately no soundings, as far as we are aware, have as yet been obtained at New Harbour. Unless the wide fiord has been largely filled in with moraine material by the retreating branches of the Ferrar Glacier, there can be little doubt that deep soundings should be obtained close inshore here, as at Granite Harbour.

Soundings obtained by Captain F. P. Evans of the *Nimrod* show that to the north of Granite Harbour, at 6 to 8 miles from the land, the depth of the sea ranges from 360 fathoms up to 462 fathoms. His soundings between Cape Bird and Cape Royds show that there is a uniform depth of from 460 to 470 fathoms along the east side of McMurdo Sound at only 4 miles off the land. The few soundings which he obtained midway between Granite Harbour and Cape Bird prove the existence of a remarkable submarine ridge. The depth of water over this ranges from about 110 fathoms to 170 fathoms.

Three possible explanations suggest themselves to account for this submarine ridge :—

1. That it is a tectonic ridge due to the upward warping of the sunken segment.

2. The sunken segment between Ross Island and the mainland in this region may not have been warped, but may have been originally flat. The depth of 110 fathoms may represent the approximate amount to which this segment was depressed below sea-level originally, and the depth in excess of those met with in the soundings near Granite Harbour and along the west coast of Ross Island may be due to the increased erosive force of the McMurdo Sound portion of the Ross Barrier where it received the extra loads and pressures from the glaciers of the mainland on its west margin, and those of Mount Erebus on its eastern side.

3. It is possible that the maximum depth recorded, such as 472 fathoms near Cape Bird, approximately represents the depths to which the sunken segment of McMurdo Sound originally descended, and the shallower central portion may represent a vast amount of moraine material which has been transported on the Ross Barrier from the south carried from the direction of Minna Bluff, Mount Discovery, and Mount Morning,

as well as from islands such as Brown Island and Black Island. Ferrar on his geological map of this region shows extensive moraines trending northward, from Black Island and Brown Island up to the edge of the "pinnacle ice," belonging to the Ross Barrier. A large portion of the surface of this pinnacle ice is heavily loaded with moraine material. During the thousands of years that the Ross Barrier was at or near its maximum, and flowing from the direction of Mount Discovery far to the north of McMurdo Sound, it must have transported a vast amount of moraine material northwards, and dumped it on to the floor of the Sound. On this view the submarine ridge is largely a medial moraine derived from Minna Bluff and Black and Brown Islands.

Possibly both 2 and 3 causes, as suggested, may have co-operated in producing this remarkable contour of the ocean floor.

Beardmore Glacier. We can now leave Minna Bluff and discuss the glaciology of the continuation of the Antarctic Horst southerly to the Queen Alexandra Range where it is intersected by the Beardmore Glacier, and then trace this glacier to the inland ice, as far as Shackleton's farthest south, in latitude 88° 23′, longitude 162° E.

As already illustrated in the photographic album of the *Discovery* Expedition, the eastern slopes of the horst, as far south as the mouth of the Beardmore Glacier, show evidence of the presence of numerous outlet glaciers from the inland ice, and also afford clear proof that glaciation has recently been waning. This is well shown by the photographs, chiefly taken by Shackleton, as well as by the excellent sketches by Dr. E. A. Wilson. Shackleton's photographs show very well that between the edge of the Barrier and the land trends a deep almost impassable chasm for a great distance. The origin of this is probably twofold :—

1. The rocks in contact with the Barrier Ice became highly heated in the rays of the sun, especially during the four months of perpetual sunlight, and consequently thawed the ice for a considerable depth where it has been in contact with the rocks. This is probably the chief cause of the existence of the gigantic moat which in most places bars access from the direction of Ice Barrier to the land.

2. In part the moat may be due to the Ross Barrier being actually forced or sheared away from the shore-line by great glaciers descending from the high plateau to the west to join the western edge of the Barrier. In this case the moat may be of the nature of a shearing plane like those already recorded in the case of the Drygalski Glacier. The chasm between land and barrier in Shackleton's photograph (Plate CVII.)* undoubtedly illustrates a canal of the latter type. It is suggested in the description accompanying this plate that the chasm may be considered in part a tide crack "or line of constant rupture between the ice and the floating barrier, and that it was formerly attached to land along the shore." There can be little doubt that it is quite analogous on a larger scale to Relief Inlet in the

* The Voyage of the *Discovery*.

Drygalski Ice Barrier Tongue. In the work to which reference has just been made these structures are described as movement chasms. Their width is given as about three-quarters of a mile and their depth from 80 to 100 feet.

It is probable that the inlets known as Skelton, Mulock, Barne, and Shackleton Inlets are all of the nature of outlet glaciers. The fact that both on the west and east sides of Ross Island vast quantities of boulders were discovered, up to heights of 1000 feet above sea-level, of granite and other rocks from the mainland is interesting proof of how, when the Ross Barrier stood about 800 feet above its present level, glaciers descending from the inlets just mentioned carried morainic material from the great horst in a general N.N.E. direction, the erratics probably crossing the long sill terminating in Minna Bluff, and then impinging on the western and eastern foothills of Ross Island. At the same time it is possible that these erratics were derived from granitic hills due south of Ross Island, such as those at the mouth of the Beardmore Glacier. The latter hypothesis is less probable than the former, as before the erratics had travelled the great distance of nearly 400 miles, which separates the Beardmore Glacier mouth from Cape Royds, they would probably have thawed their way down for some depth into the ice of the former Great Ice Barrier. Had they reached Cape Royds along this route they would probably have reached it as bottom moraine.*

In his account in *The Heart of the Antarctic*, vol. ii. p. 12, Sir Ernest Shackleton states that the surface over which his party travelled over the Ross Barrier was continually changing. He noticed that at first there was a layer of soft snow on top of a hard crust, with more soft snow underneath that again. This pie-crust snow has already been commented on in the description of the Northern Journey. It is perhaps due to an actual melting of the snow just below the surface, when the general air temperature is below freezing, as well as to deposition of ice vapour ascending from a short distance beneath the snow surface. He states, "When the sun was hot the travelling would be much better, for the surface snow got near the melting-point and formed a slippery layer not easily broken." Probably a certain amount of actual thawing, when the general air temperature was below freezing-point, had taken place in this instance, the thawing being due, as already explained in the account of the Northern Journey, to the low specific heat of ice. The quantity of soft snow met with on the Ross Barrier to the north of the Beardmore Glacier was no doubt due to streams of drift snow which are poured by the plateau winds out of the Beardmore Glacier Valley on to the surface of the Ross Barrier. Shackleton states that the surface of the Barrier near the land was broken up by pressure from the glaciers, but right alongside the mountains there was a smooth plain of glassy ice caused by the freezing of water that had run off the rocky slopes when they were warmed

* They would also have become buried probably under some hundreds of feet of snow before they reached the edge of the Barrier.

under the rays of the sun. "This process had been proceeding on the snow slopes that we had to climb in order to reach the glacier. Here at the foot of the glacier there were pools of clear water around the rocks, and we were able to drink as much as we wanted, though the contact of the cold water with our cracked lips was painful." At the time when this thaw-water was observed on the rocks at the edge of the Barrier, the temperature was ranging during the day from about 20° Fahr. at 8 A.M. to about 25° Fahr. at noon. The party that ascended Mount Erebus observed similar phenomena to that recorded by Shackleton, of a smooth plain of glassy ice at the foot of the steep rock slope of the old cone of Erebus at a height of over 6000 feet above the sea. At the time we believed this frozen lake to have resulted from the congealing of water from some hot spring, but it is far more likely that it was formed from thaw-water in summer draining off the dark rocky arêtes, and forming a lake at the base of the steep slope.

On the journey of the Southern Party over the surface of the Ross Barrier, Adams carefully noted the bearing from time to time of the chief sastrugi. These for the most part trended from S. or S.S.E. to N. or N.N.W. In the case where the party were opposite one of the great inlet glaciers it was noted that the direction of the sastrugi at once changed, or a double set of sastrugi were present. The blizzard sastrugi still trended from a general south or south-easterly direction, whereas the sastrugi caused by the cold air coming down from the plateau along the valleys of the outlet glaciers* had a trend parallel to that of these glacier valleys, that is, from a general westerly or south-westerly direction. In ascending the Beardmore Glacier it was found that all the chief sastrugi had their long axes parallel to the general trend of the valley. On the plateau, south of the farthest land seen, the sastrugi followed chiefly two directions, either between S.S.E. and S.E., or trending from due S. to S.S.W. Their general trend is shown on map. These directions are shown on Plate VI. illustrating Chapter II.

The glacier itself is about 100 miles in length, with a maximum width of about 25 miles. Its average width is about 12 miles. Shackleton observed that where the Beardmore Glacier junctions along the coast-line with the Ross Barrier it has raised enormous waves, by the force of its thrust, in the surface of the Barrier for fully 20 miles out from the shore-line. Again one is impressed here, as at the Reeves Glacier, with the stupendous erosive power of the glacier ice. This is shown on a grand scale in the beautiful photograph by Marshall, taken from the Barrier to south of Mount Hope (Plate XXVIII.), and also (Plate XXIX.) from the summit of Mount Hope looking up the Beardmore Glacier.

One is at once struck by the sheer cut cliffs above "Lower Glacier Depot" on the right, where the dark shadow of the precipice bounding the glacier to the left is thrown across the surface of the glacier which recalls that of Mount Larsen. This cliff is approximately about 4000 feet in height. Next, one is impressed

* That is, the true Föhn wind.

PLATE XXVIII

JUNCTION OF ROSS BARRIER

With coast of mainland near Mount Hope, at entrance to the Beardmore Glacier. Mount Hope on left half of picture. The gap to right of centre a small side passage on the Beardmore Glacier. There is a strongly marked terrace, perhaps an old shore line, at the foot of Mount Hope

[Photo by Eric Marshall

[*To face p.* 118

PLATE XXIX

VIEW FROM TOP OF MOUNT HOPE UP BEARDMORE GLACIER LOOKING S.S.W.
Mount Hope, 2758 feet, is strewn with erratics. A well-marked "alb" terrace (or ice flood terrace) is seen just above the cirque on the extreme right

[Photo by Dr. Eric Marshall

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by the remarkable ice-cut shelf to the right of Lower Glacier Depot, and to the extreme right of the photograph. This, on a larger scale, exactly recalls the similar structure noticed above the Mackay Glacier at Granite Harbour. It is evidence of valley in valley structure, or an over-deepened valley on a large scale. There can be little doubt that the Beardmore Glacier has formerly been so much higher than it is now, that it has completely overflowed the top of Mount Hope, burying it deep under ice. Mount Hope is about 2760 feet above sea-level, and its summit not only bears evidence of intense glaciation, but it is strewn with a variety of foreign erratics, including fragments of diabase and limestone. It is in itself a magnificent glacial "flood-gauge." The stranding of these numerous erratics on its surface, all of which show evidence, when not recently weathered, of intense glaciation, has been due to the material being probably pushed up over the top of Mount Hope rather than dropped from above on to its surface during a retreat of the glacier ice. The glaciated foreign boulders, therefore, on Mount Hope are conclusive proof—no better could well be had—that the Beardmore Glacier here formerly stood 1800 feet above its present level. It must be remembered that this is a very conservative and quite a minimum estimate of the former thickness of the glacier ice. This makes the former occupation of the great shelf to the right of Lower Glacier Depot by the solid ice of the Beardmore Glacier not only probable, but reasonably certain. This cliff, then, may perhaps be looked upon as glacier-cut.

Immediately below this shelf is evidence of a cirque. On the platform between the glacial-cut high level cliff and the great monolith of granite behind Lower Glacier Depot a small corrie glacier can be seen creeping down to join the Beardmore Glacier. The question here suggests itself, what was actually the approximate former thickness of the Beardmore Glacier when the ice flood was at its maximum? If one sees in a progressively deepened river valley high terraces of old gravel lying at, for instance, 1000 feet above the present bed of the river, and observes also that the river is now forming terraces at its present level, one obviously would not be justified in coming to the conclusion that the depth of the old river was formerly represented by the difference in level between its old gravel terrace and its modern one. One might argue in such a case that depth of water in the river was formerly 1000 feet. It may be the case with the Beardmore Glacier, as in the illustration of the river, that since the period of maximum glaciation it has materially deepened, that is, over-deepened, the original wide and comparatively shallow V-shaped valley. Since the diminution of snow supplies on the plateau the volume of the glacier has been much restricted, so that it has been unable to work over the whole of its old floor, confining its attention entirely to the low-lying portion of its present "trogtal." Again one is tempted to speculate as to whether the high level glacial terraces of the modern trogtal were originally excavated synchronously with the trogtal by glacier ice filling the main valley, or whether the large valley was excavated entirely first, and the smaller modern valley over-deepened in it later, or whether, in the third case, the modern trogtal and the "alb" terrace are being excavated simultaneously, the former by the ice of the main glacier stream, the latter by corrie glaciers. It appears to the authors that the cliff face above the corrie glacier is due to some more powerful erosive action than that of the well-known work of the cirque glacier at its sides and base, aided by changes of temperature and thaw phenomena. The foreign erratics on the top of Mount Hope force upon one the conclusion that thick masses of glacier ice have at one time attained to this level. It seems further probable that the level of this terrace was not the lowest level of the great glacier, the ancestor of the Beardmore, during the maximum of the ice flood. One may arrive at some approximation to the thickness of the Beardmore ice during maximum glaciation from the following consideration :—

According to the levels taken by means of the hypsometer the ice surface of the Ross Barrier, near the outlet of the Beardmore Glacier, does not much exceed 200 feet above sea-level. This would give a thickness for the ice where it fanned out at a distance of some 20 miles from the shore of the Ross Barrier of from 1600 to 1800 feet. Opposite to Mount Hope itself the thickness of the ice is probably considerably greater. If we are correct in surmising that during the ice flood the ice was thick enough to flow steadily over the top of Mount Hope, it was probably at that time at least 3000 feet, certainly 2000 feet, higher than it is now.* One may, however, reasonably assume that during the maximum of the ice flood the ice of the Beardmore Glacier was from 3000 to 4000 feet in thickness, possibly more. Traces of waning glaciation were observed not only in the form of the foreign erratics stranded on the top of Mount Hope, but also in the shape of enormous lateral moraines. These moraines in the neighbourhood of the Cloudmaker ascended to 200 feet above the present glacial level, and evidently mark a very recent retreat of the glacier. Had the moraines been very ancient the blocks of stone would have crumbled down into the form of fine rubble as the result of the great diurnal range of temperature. An immense medial moraine was observed between the Cloudmaker and the great nunatak, Buckley Island, formed partly of coal-bearing rocks, partly of limestone. This moraine was traced over a distance of 60 miles up to the head of the glacier to the large nunataks of Mounts Bartlett, Buckley, and Darwin. It was in one of the sandstone blocks in this moraine, derived from the Beacon Sandstone, that a small piece of fossil wood, figured later in this volume, was obtained.† The boulders of the moraine here in December 1908 were

* It does not of course follow that it was necessarily from 2000 to 3000 feet thicker than now, as one has to allow for perhaps a fair amount of glacial erosion subsequent to the climax of the ice flood.

† The presence of small plant structures resembling rootlets in the adjacent shales suggests that the tree to which this wood, apparently coniferous, belongs was not drift wood, but grew *in situ*.

Fig. 1. LATERAL MORAINE ON WESTERN SIDE OF THE BEARDMORE GLACIER
The hills on the left are of granite

Fig. 2. THE CLOUDMAKER, 2500 FEET UP BEARDMORE GLACIER. HEIGHT, 9970 FEET

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PLATE XXXI

PANORAMA, BEARDMORE GLACIER

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XI

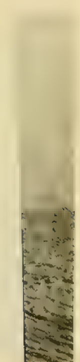

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PLATE XXXII

BEACON SANDSTONE COAL MEASURES (GONDWANA) OF MOUNT BUCKLEY
A great nunatak at head of Beardmore Glacier. The steep slope of the glacier is obvious in the foreground

[*To face p.* 121

mostly melted into the ice, disappearing below the surface, but there was much fine yellowish rock dust on the surface of the ice.

An examination of the photographs of the rocks in the neighbourhood of the Cloudmaker clearly suggest a much more intense glaciation here formerly than now. See Plate XXX. Fig. 2.

A very interesting feature in connection with the north-west entrance to the Beardmore Glacier Valley at Mount Hope is the existence of a high shelf of rock intensely glaciated around the foot of Mount Hope facing the Barrier. Beautiful ice-cut facets can be observed on the left side, that is, the north-east side of Mount Hope. This part has received the double thrust of the Beardmore Glacier from the S.S.W., and the Great Ice Barrier from the S.E. One would expect under these circumstances to see evidence, such as the photograph actually shows, of the most intense glaciation. Possibly the rock shelf represents a plane of marine erosion during the temporary submergence of the land in interglacial time. Subsequently the shore platform may have been uplifted and then glaciated. It will be noticed that over all the 380 miles from the Blue Glacier down to the Beardmore Glacier there is no trace of the remarkable coast platform piedmont conspicuous from the Blue Glacier northwards to Mount Nansen. The only suggestion so far of the existence of a coast platform is the rock shelf on the north side of Mount Hope. The fine panoramic view taken by Dr. Eric Marshall, seen on Plate XXXI., shows on the left the Dominion Range, which gradually slopes down to the extreme left towards the Mill Glacier. Next on the right are three well-marked nunataks, Mount Darwin (8023 feet), Mount Buckley (8384 feet), and Mount Bartlett (7869 feet). Mounts Buckley and Bartlett and the stratified formation at their base are formed of Beacon Sandstone, with seams of coal, laminated carbonaceous sandstone, and fireclay. These overlie a massive Cambrian limestone described later in this volume. It would obviously be a matter of very great interest to decide the elevation to which the *névé* fields have originally attained around these gigantic nunataks. The nunataks rise to a height of about 3000 feet above the ice at the head of the glacier.

There can be little doubt that the high platform of coal-measure rocks, immediately behind the two tents in the picture and below the top of Mount Buckley, has formerly been completely over-ridden by the ice, and it may be concluded that the ice was probably 1500 feet higher here formerly than it is at present. The stemming action exerted by the great nunatak just described against the flow of the inland ice northwards down the Beardmore Valley has led to the development of comparatively steep ice slopes near the nunatak. The nature of these ice slopes is well shown on Plate XXXII. The coal-measure rocks of the Buckley Nunatak rise to the left of the central figure in the illustration, and in the middle distance, just above the central figure, the long dark line may be observed of the medial moraine in which the fragment of fossil wood and coaly sandstone were found. The range of Beacon Sandstone, belonging to the nunatak on the left, is the one on which Wild observed the seven seams of coal, from one of which he obtained specimens by chopping them out with his ice axe.

The Wild, Marshall, and Adams Mountains, rising respectively to heights of 11,217 feet, 10,494 feet, and 11,809 feet, afford fine examples of tributary glaciers and cirques, while farther north, beyond the Bingley Glacier, the mountains rise to 13,500 feet in Mount Dorman and 14,624 feet in Mount Kirkpatrick to the west of the Cloudmaker. The sharp peak near Adams Mountains affords a particularly fine example of rocky arêtes.

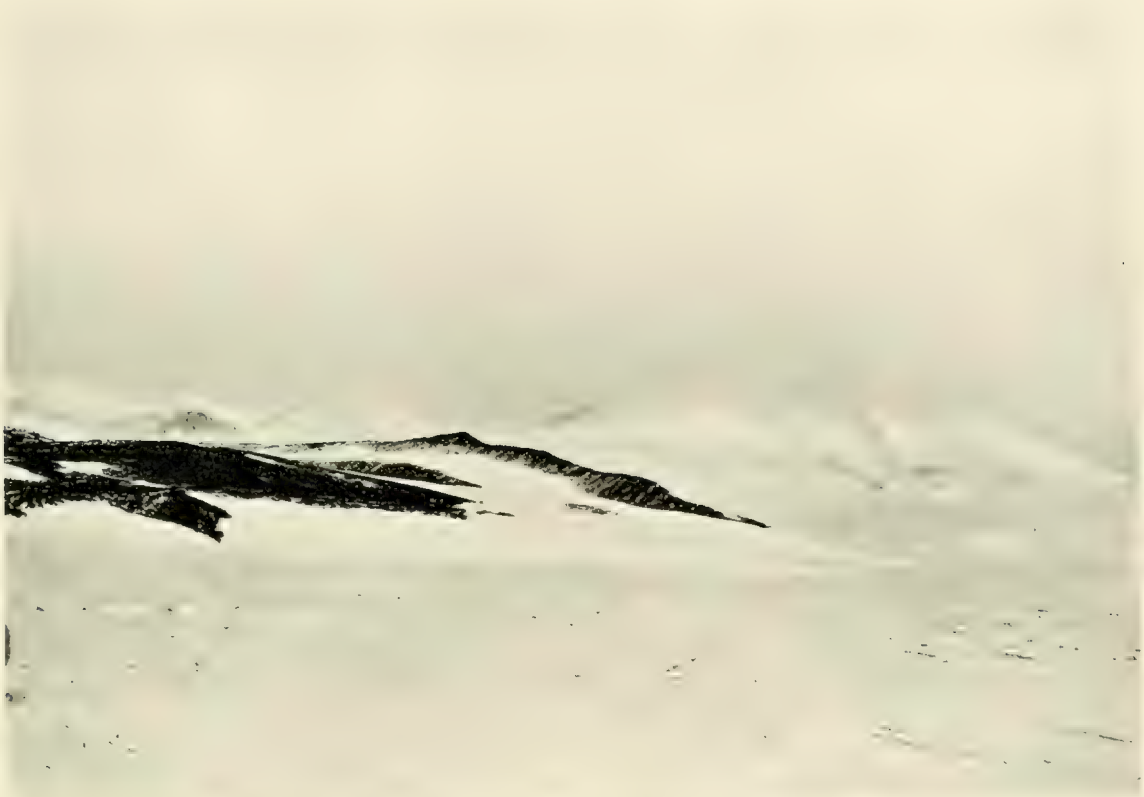
Ice-falls were encountered in farther ascent above the great nunatak, Mount Buckley, for over 50 miles farther to the south up to a level of about 8000 feet. The inland ice therefore, at least as far south as this in that locality, must be in a state of fairly rapid movement.

At their farthest point south in lat. 88° 23′ S., long. 162° E., the Southern Party must have been at or close to the highest point of the inland ice at that spot, in fact at the "ice divide."

The terribly crevassed surface met with by Shackleton's party on the Beardmore Glacier proves that the whole glacier must be in rapid movement, as of course is also evidenced by the vast pressure waves raised by this huge glacier at its confluence with the Ross Barrier and for 20 miles beyond. Huge as must be the annual output of ice from the glacier, it is only a small proportion of the former yield when the surface of the glacier was some 3000 feet higher than it is at present. Amongst other evidences of recent considerable shrinkage are the intensely glaciated terraces of rock, many hundreds of feet above the present level of the glacier. These are well shown on Plate XXXIX.

The subject of the past history of the Beardmore and other outlet glaciers draining into Ross Sea, and there constituting the Ross Barrier, is so indisputably linked up with the history of the Ross Barrier itself, that we may now pass on to consider that most wonderful of all known floating piedmonts.*

* The extent of the Barrier discovered by Lieutenant Filchner at the head of the Weddell Sea is not yet known, but it is improbable that it is as large as the Ross Barrier.



3000 FEET UP BEARDMORE GLACIER

Cloudmaker in background to right. The glaciated rock terraces are foothills above the Cloudmaker

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CHAPTER VI

GLACIOLOGY (*continued*)

THE ROSS BARRIER

The Ross Barrier was formerly known as the Great Ice Barrier. In 1841 Sir James C. Ross sailed eastwards along the great cliff of the Ice Barrier for about 470 miles. In 1899 C. E. Borchgrevink followed the Barrier eastwards to Borchgrevink Inlet, near where Ross reported "strong appearance of land." In 1902 the late Captain R. F. Scott coasted along the Barrier for nearly 500 miles, penetrating beyond Ross' farther point east, and discovering King Edward VII. Land. He made a detailed survey of the Barrier edge, determining the height of the cliff at many points, and taking a number of soundings. He arrived at the important conclusion that the Barrier was afloat, except at its extreme east and west margins, and rises and falls with the tide like a gigantic landing-stage. His own observations from a balloon, and those of Lieutenant A. B. Armitage in the course of a short sledge journey near the east extremity of the Barrier, revealed the important fact that the surface of the Barrier was not there uniformly level, but undulating. Scott says: *—

"South of the rising slope ahead of the ship I had expected to see a continuous level plain, but, to my surprise, found that the plain continued in a series of long undulations running approximately east and west, or parallel to the Barrier edge: the first two undulations could be distinctly seen, each wave occupying a space of two or three miles, but, beyond that, the existence of further waves was only indicated by alternate light and shadow, growing fainter in the distance."

Scott further says that Armitage reported that, in his short sledge journey of about 12 miles, he crossed four of these undulations. They extended in a general east and west direction, and were not in the nature of symmetrical anticlines and synclines. They presented rather the appearance of a peneplain dissected by broad mature valleys. The general depth of the latter was about 120 feet. Later, Lieutenant Royds, of the same expedition, made a sledge journey over the Barrier, from Hut Point to the south of Mount Erebus, in a general south-east direction, reaching the meridian of 176° E. near latitude 79° 33′ S. Scott describes the surface over which Royds travelled as an unutterably wearisome plain, a surface

* The Voyage of Discovery, vol. i. p. 148, London, 1905.

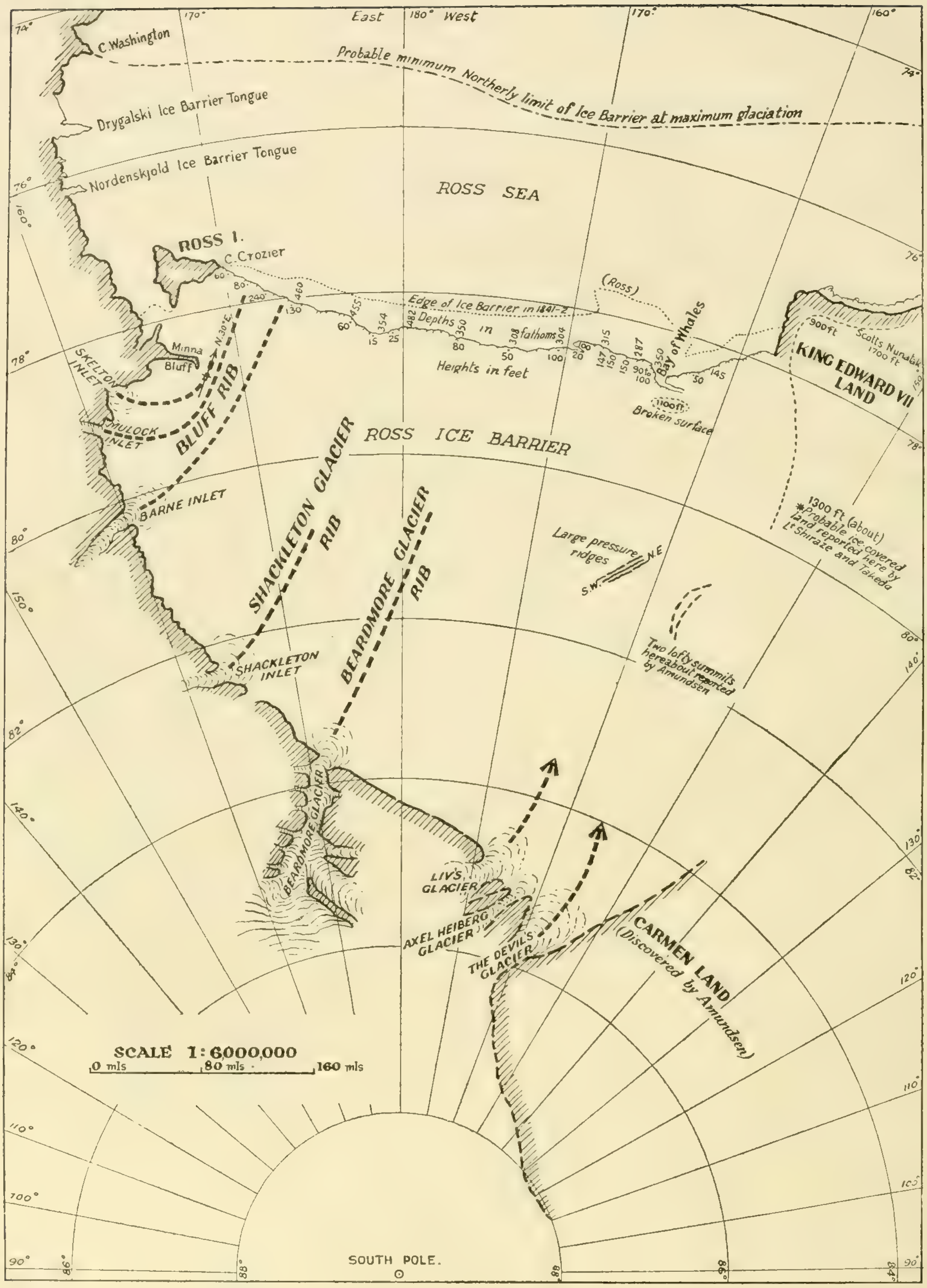


FIG. 46.—Map of Ross Barrier showing glacier ribs, position of edge of Barrier in Ross' time, 1841–42, and probable minimum extension of Barrier northwards, during the maximum glaciation. Amundsen's discoveries are added

such as he describes in his own southern journey. Scott's conclusion that the greater part of the Barrier is afloat, is based on the following considerations:—

1. When his ship, the *Discovery*, was lying alongside the Barrier in Balloon Bight,* its rail was about level with the Barrier surface there, so that he was in an excellent position to judge of any differential vertical movement between the ship and the Barrier. Although there was evidence of a considerable tide, ship and Barrier rose and fell regularly together.

2. The soundings, taken by him along the Barrier face, proved that the water was too deep to admit of the material of which the Barrier is formed resting on the bottom. For example: at a point at the base of the Barrier cliff, 115 miles E.S.E. of Cape Crozier, he found a depth of 455 fathoms. The adjacent cliff was only 60 feet high.

3. His survey of the Barrier showed that, in places, masses of ice, as much as 35 to 40 miles in width, had gone out to sea since the edge of the Barrier was charted by Sir James C. Ross in 1841–2. Scott's numerous soundings in 300 fathoms were consequently made at spots many miles to the south of where the northern margin of the Barrier was situated in Ross' time. The observations made by the *Discovery* Expedition also show that, where the Barrier is constricted, as between White Island and Cape Armytage, it is thrown into a series of undulations, implying a continuous thrust from a southerly direction.

Scott also records (*Voyage of Discovery*, vol. ii. p. 312) vast disturbances in the surface of the Barrier off the eastern slope of Mount Terror: "Here the sheet is pressing up and shearing past the land ice, raising numerous huge parallel pressure-ridges." A fine illustration of this is published in the above work, large edition, vol. ii. p. 303.

On his first Southern journey Scott encountered heavy undulations in the surface of the Barrier opposite Shackleton Inlet, and Lieutenant M. Barne, of the same expedition, met similar heavy undulations and disturbances in the Barrier surface opposite Barne Inlet. Speaking of Barne Inlet, Scott states (*op. cit.*, vol. ii. p. 221): "It seems evident that the whole of this area is immensely disturbed, and it is doubtful whether a sledge-party could ever cross it, unless they were prepared to spend many weeks in the attempt." Barne's sledge journey also proved the important fact that Scott's Depot A, near Minna Bluff, had moved no less than 608 yards in 13½ months. This showed that the whole of the Barrier in this region was obviously in movement. Scott gives the direction in which it is travelling as a little to the east of north.

4. Scott states (*op. cit.*, p. 312) that Lieutenant C. W. R. Royds took some serial temperatures in a crevasse extending from the north end of White Island near Mount Erebus. "Close to the land, he found that the temperature fell with the

* This is now merged into the Bay of Whales, as discovered by our expedition, the spot where Amundsen wintered in 1911, before his famous journey to the South Pole.

depth to a mean of $-9°$ (F.); but, at a distance of 10 miles from the land, he got a different result. Here, at first, the temperature fell, but as the thermometer was lowered its column rose again until, at a depth of 19 fathoms, it showed zero. Deeper than this he could not go, on account of the snow in the crevasse; but I

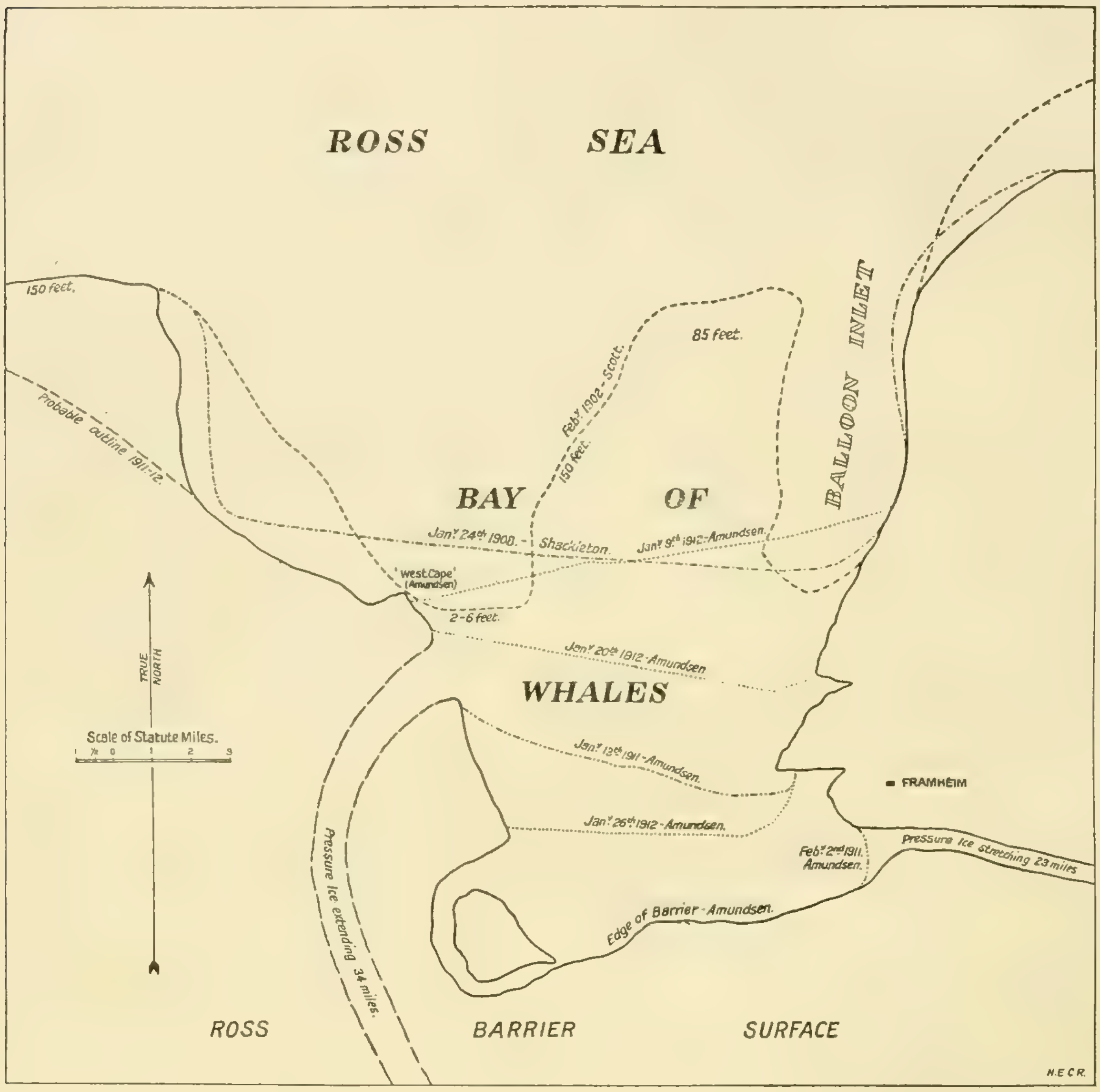


Fig. 47. Plan showing changes in the edge of the Ross Barrier near Amundsen's headquarters at the Bay of Whales since the time of Scott's Expedition in the *Discovery* in 1902. The outline of the Bay of Whales in 1911 is after Amundsen

think it must be conceded that the only reasonable cause for such a rise of temperature as was observed, is the presence of water beneath the ice."

The Shackleton Expedition, in 1908, skirted the Barrier eastwards, hoping to reach King Edward VII. Land, or, failing that, determined to winter at Balloon

Bight. On arriving at the spot where Balloon Bight was formerly situated, we found that it had entirely disappeared; an immense strip of the Barrier had evidently broken away and put out to sea since the time of Scott's visit. The *Nimrod* reached lat. 78° 41′ S., long. 164° 30′ W., *i.e.* about 10 miles south of the latitude of the *Discovery* when at her farthest south in Balloon Bight in 1902. No bottom was found by us at 300 fathoms at lat. 78° 19′ S., long. 162° 53′ W. The approximate shape and extent of the mass of the Barrier which had drifted out to sea between 1902 and January 1908 is shown on the accompanying figure, the present general outline being taken from Amundsen's plan in his work *The South Pole*, vol. ii. p. 350.

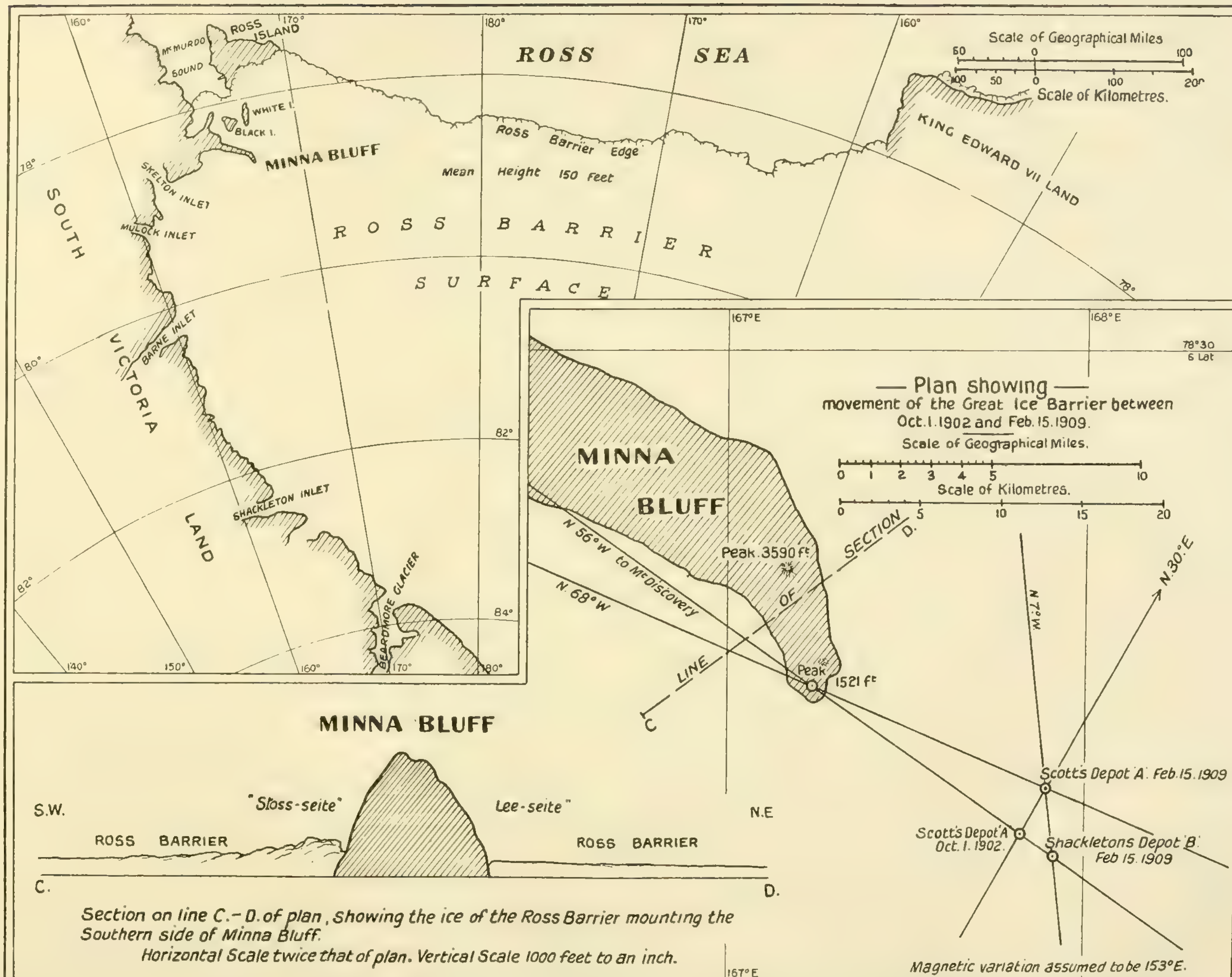
Obviously, it would have been impossible for such a huge mass of the Barrier to have gone out to sea in such a comparatively short time unless it had been afloat. Our discovery of land masses covered by ice, immediately to the south of the Bay of Whales (formerly in part Borchgrevink Inlet), suggests that the east and west valleys in the Barrier, in this region, may be due to the stemming action of the land in resisting the northward movement of the Barrier. This land, immediately to the south of the winter quarters, "Framheim," of Amundsen's Expedition, is shown on his plan as an island or nunatak, completely buried under ice, and 1100 feet above sea-level.

In regard to disturbances indicating movement of the Barrier, Shackleton records that the long volcanic promontory, about 66 miles south of Mount Erebus, known as Minna Bluff, gives rise to heavy crevasses in the Barrier. He describes the surface there as "all hillocks and chasms, the pits often over 100 feet deep." Macintosh and Day, of our expedition, when engaged with Joyce and Marston in laying a depot for the returning Southern Party, at the beginning of 1909, observed that the Barrier surface on the south side—the *stoss-seite*—was raised by the pressure of the ice farther south, apparently more than a hundred feet higher than the Barrier surface on the north—that is, the *lee-seite*—of the bluff. The appearance, as roughly sketched by Day, is shown on Plate XXXIV.

This depot-laying party were so fortunate as to sight, on February 15, 1909, the bamboo pole, with its tattered flag, marking the old Depot "A" of the *Discovery* Expedition. This depot was established on October 1, 1902. It was about 9·2 statute miles from Minna Bluff,* in line with a sharp volcanic peak at the end of the Bluff and Mount Discovery. Thus 6 years and 6 months had elapsed since its erection and the re-alignment of its position by Macintosh. It was found that, in the interval, it had travelled for a total distance of about 3200 yards, that is, 1 mile 1440 yards (2927 metres). The direction of the movement was towards about N. 30° E. This gives a rate of about 492 yards (450 metres) per year, or 1·348

* The original position of Scott's Depot "A" is taken from the plan published in the Meteorological Report, part 1, of the Nat. Antarctic Expedition of 1901–4.

PLATE XXXIV



PLAN ILLUSTRATING DIRECTION AND RATE OF MOVEMENT OF THE ROSS BARRIER yards (1·263 metres) per day. The direction of movement of the Ross Barrier is also shown in Plate XXXIV.

The important question may be discussed here, does this movement of the Ross Barrier, so conclusively proved at Minna Bluff, and in the great pressure ridges and shear planes near Cape Crozier, extend also to the eastern end of the Ross Barrier? Amundsen has shown that at his winter quarters, "Framheim," in the Bay of Whales, movement of the ice is practically negligible. The fact must here be borne in mind that "Framheim" is just to the lee of a large island completely smothered in ice, which appears to have stemmed back all movement in the immediate neighbourhood of Amundsen's winter quarters. Nevertheless the following facts show that some movement is still taking place on the eastern side of the Barrier:—

(1) High pressure ridges were encountered by Amundsen on the surface of the Barrier (*a*) at about 46 miles south of "Framheim."* These were evidently due to thrust of the Barrier ice against the southern and south-eastern sides of the ice-covered island south of "Framheim." That the ice in this region is still in a state of movement, however small, is clear from the description given by Lieutenant Prestrud.† He relates how, on November 8, 1911, at a point on the Ross Barrier about 20 miles southerly from "Framheim," "there was a report about once in 2 minutes, not exactly loud, but still there it was. It sounded just as if there was a whole battery of small guns in action down in the depths below us." This was in the neighbourhood of some small hummocks, no doubt indicating pressure near shearing planes.

At and to the south of lat. 81° S. Amundsen records broken surfaces on the Ross Barrier, with strong pressure ridges. "They extended as far as the eye could see, running north-east to south-west in ridges and peaks."

In the map illustrating Amundsen's lecture to the Royal Geographical Society a slight indication of land is shown in the neighbourhood of these pressure ridges. The existence of an island hereabouts, though conjectural, is highly probable. About 40 miles farther east Amundsen shows high-pressure ridges lying off the land discovered by him between 81° and 83° S., just east of the meridian of 160° W., and probably continuous with Carmen Land. It may perhaps be significant that the trend of the pressure ridges on Amundsen's line of march near 81° S. is from south-west to north-east. This may be due to the strongest thrust coming from the great outlet glaciers, which transect the high ranges on the south-west side of the Ross Barrier.

In regard to the Barrier south of Minna Bluff, Shackleton says (*op. cit.*, vol. i. p. 299) that near lat. 82° 38′ S. they encountered long undulations, "the width from crest to crest being about 1½ miles, and the rise about 1 in 100. The depth of

* The South Pole, Amundsen, vol. i. pp. 256–7; also *ibid.*, vol. ii. pp. 6–12.

† *Ibid.*, vol. ii. pp. 218–19, pp. 23–24, and especially pp. 170–72.

these wide shallow troughs would thus be approximately 40 feet." *Ibid.*, p. 301: "The undulations run about east by south and west by north, and are at the moment a puzzle to us. I cannot think that the feeding of the glaciers from the adjacent mountains has anything to do with their existence. . . ." This observation was made near lat. 82° 51′ S. Reference to the map of the Ross Ice Barrier shows that these undulations commenced at a point about 50 miles E.S.E. of the entrance to Shackleton Inlet, and about 60 miles N.N.E. of the lower end of the Beardmore Glacier. Later, December 2nd, near lat. 83° 23′ S., Shackleton speaks of the undulations being very pronounced, consisting of "enormous pressure-ridges, heavily crevassed and running a long way east, with not the slightest chance of our being able to get southing that way any longer on the Barrier." Obviously these last violent disturbances are directly due to the pressure of the great Beardmore Glacier which forms so important an outlet for the inland *névé* fields.

Shape and Height of the Barrier Ice Cliff. For information on this subject we are chiefly indebted to observations made by the *Discovery* Expedition of 1901–4, and to Ross' observations in 1841–2. There are also a few observations near the Bay of Whales by C. E. Borchgrevink, as well as by our own expedition when cruising between Western Inlet and a short distance to the east of the Bay of Whales in January 1908.

The headland of Western Inlet in the middle of the above photograph is over 100 feet high. At the head of Western Inlet, behind the above headland, the height of the Barrier cliff is only 20 feet. Thus the inlet, which trends nearly east to west, is evidently situated on a trough in the surfaces of the Barrier.

Fig. 2 of Plate XXXV. shows another low portion of the Barrier at the farthest point east, along the Barrier face, reached by the *Nimrod* on January 24, 1908, in lat. 78° 41′ S., long. 164° 30′ W.

On the other hand, in the next photograph is a view of a lofty slice about to detach itself from the Barrier about 200 feet above sea-level.

We named this slice "The Dreadnought." It lay to the west of the Bay of Whales.

According to the heights obtained by Captain Scott, the height of the Barrier cliff varies from 20 feet to 240 feet, and, according to the fewer measurements taken by us, from 20 feet to 200 feet.*

As regards outline, reference to the map (Fig. 46) shows that the Barrier in Ross' time projected northwards in a well-marked lobe between the meridians of 165° and 169° W. The sharp western boundary of this lobe was formed by a sheer cliff trending N.N.W. and S.S.E., while to the east it was bounded by a deep indent. These two features appear to repeat themselves to-day, re-

* According to Commander E. R. G. R. Evans, R.N., now in command of the late Captain Scott's Expedition, no spot higher than 150 feet was seen by them when the *Terra Nova* visited the region early in 1911.

PLATE XXXV

FIG. 1. WESTERN INLET IN THE ROSS BARRIER

Looking south with ice-blink to right. The headland of Western Inlet is about 100 feet in height. Near the head of the inlet the Barrier Cliff is only 20 to 30 feet high [Photo by David

FIG. 2. SMALL INLET IN ROSS BARRIER

To the east of the Bay of Whales. The ice-cliff, at this inlet, comes down within 20 feet of the level of the sea

[*To face p.* 130

PLATE XXXVI

THE DREADNOUGHT

An ice promontory about 200 feet high on the cliff face of the Ross Barrier

[Photo by Wild

[*To face p.* 130

PLATE XXXVII

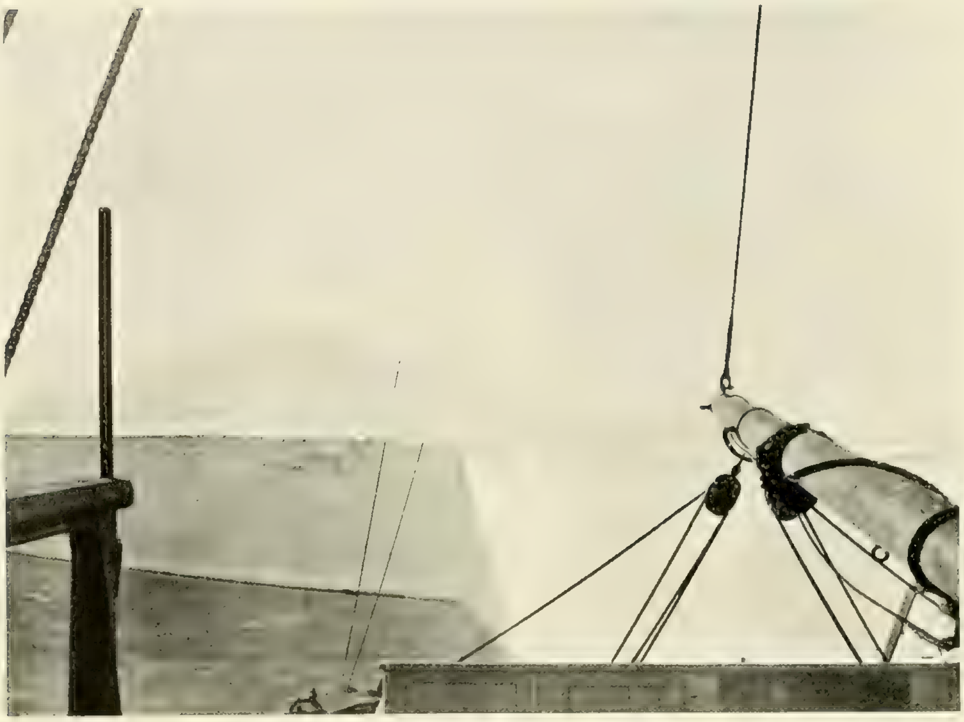


FIG. 1. EDGE OF ROSS BARRIER
About four miles south of Hut Point. March 1, 1909

FIG. 2. CLIFF OF ROSS BARRIER
Between long. 165° to 175° W. Height about 150 feet

[David

[*To face p.* 131

spectively in Western Inlet and the Bay of Whales. It will be noticed that the Barrier between the Bay of Whales and Western Inlet is higher than its general altitude between Western Inlet, on the meridian of 169° W., and the meridian of 175° E. This large lobe is probably due to the glacier ice coming from glaciers like the Devil's Glacier, Axel Heiberg Glacier, Liv's Glacier, possibly also the Beardmore Glacier, combined with the ice derived from Carmen Land and the areas between the latter and King Edward VII. Land.

The ancestor of the Bay of Whales, like its modern descendant, originated, no doubt, in the stemming action of the high ice-covered island to the south of Amundsen's winter quarters at Framheim. Possibly the lobe was nourished almost entirely by glacier ice coming from between Carmen Land and King Edward VII. Land, as well as by drift and new falling snow on the actual surface of the Barrier. Possibly Western Inlet owes its origin to the stemming action of some other, as yet undiscovered, ice-covered island to the south.

The fact that since Ross' time this eastern lobe has retreated no less than 50 miles southwards, shows probably that the ice supplies, on this eastern side of the Barrier, have diminished to an even greater extent than the supplies to its western side.

The absence of high ranges in the direction of King Edward VII. Land and the land farther to its south accounts, no doubt, for the comparative calm of the weather in this region, as well as for its consequent low precipitation.

Some observations may now be given on the internal structure of the material of the Barrier. Plate XXXVII. Fig. 1 shows the appearance of the northern edge of the Barrier, about 2 miles south of Cape Armytage, on March 1, 1909.

The material here appeared to be entirely formed of well stratified old drift snow. It probably rested on a foundation of old sea ice of certainly more than one winter's growth. It was doubtful whether it should be considered as the edge of the Barrier proper. On the short sledge expedition by Shackleton, Armitage, and one of us, it was noticed that there was a gradual slope, about 8 feet high, where the sea ice joined the Barrier, and, between this spot and Pram Point, there was strong evidence of pressure ridges on the Barrier surface. It is usually very difficult to determine the exact limit northwards of the edge of the Barrier proper at this part of McMurdo Sound, as heavy snow-drifts, formed by the blizzards, tend to build up an "apron" of hard snow over the sea ice lying to the north of the Barrier edge. It is probable that the *Nimrod*, in the position shown in the photograph, was still within the area of this snow and sea ice apron.

The cliff of Ross Barrier, between long. 165° to 170° W., shown on Plate XXXVII. Fig. 2, has a height of about 150 feet. This is near about half-way between long. 170° W. and the Bay of Whales. The cliff here was higher than the crow's nest of the *Nimrod*, and was probably about 150 feet above sea-level. The photograph shows that the cliff is composed, apparently down to the water's edge, of horizontally stratified layers of snow, no doubt now largely converted into ice. There is an entire absence of the vertical lamination and disturbed bedding with which one is familiar in true glacial ice in temperate latitudes. At the same time the fact must not be overlooked that in many of the Antarctic glaciers the ice, at all events in its upper portion, shows signs only of horizontal stratification. On the left-hand side of the photograph it will be noticed that the material exhibits a very perfect flat conchoidal fracture. Another proof that, though it may be ice in its lower portions, it is not formed of glacier ice is afforded by the entire absence of vertical fluting of the cliff face. Had even a small amount of rock dust been present in the material, as is usually the case in the land glaciers of Antarctica, this would quickly have formed dust wells when warmed by the sun's beams, and these wells would have been enlarged downwards to form grooves, as we observed to be the case with the vertical faces of true icebergs facing the sun, *i.e.* facing north.

That the Barrier is not altogether formed of old compressed snow is, of course, obvious from the fact that great glaciers like the Beardmore, the Heiberg, the Devil's Glacier, &c., are continually discharging into it vast volumes of glacier ice. It is also proved by direct observation. H. T. Ferrar states: * "The intimate structure of piedmont ice shows that, as far as water-level, it consists of normal glacial ice. On the surface away from the land only fine snow was met with, but close to the shore crevasses and pressure ridges show massive and vesicular ice. The vesicular ice contains air amounting on the average to about 8·5 per cent. of its own volume, and the ice grains are usually less than $\frac{1}{4}$ inch across."

One of us (R. E. Priestley) has recently observed that the material of the Barrier, in the cliffs at the Bay of Whales, is formed of true ice. This locality is, of course, in the immediate neighbourhood of the island buried under ice to the south of Framheim.

The next piece of evidence, though it is not certain that it bears directly upon the question of the origin of the Barrier, is, in itself, very significant. Towards the end of the summer, early in 1908, two tabular bergs drifted from the north down McMurdo Sound, and grounded half-way between our winter quarters at Cape Royds and Cape Barne. During the winter, when the sea was firmly crusted over with ice, we visited these bergs, and were able to examine their internal structure by studying the walls of the wave-worn caves. They appeared to be wholly formed of compressed snow down to sea-level, with a veneer of sea ice in such parts as were exposed to the wash of the waves and the dash of the spray. During the summer of 1908–9 the *Nimrod* made use of one of these bergs as an anchorage for shelter from the blizzards. Soundings alongside the bergs, obtained by Captain F. P. Evans, showed a depth of 13 fathoms, *i.e.* the berg was stranded in water having a depth of 78 feet. The berg rose to almost the same height out of the water, but as its eastern side had been lowered considerably through the tunnelling action of the waves and the collapse of

* National Expedition, 1901–4, Natural History, vol. i., Geology, London, 1907, pp. 67–68.

PLATE XXXVIII

SOUNDING ROUND A STRANDED BERG
In order to see whether the ship could lie there

THE "NIMROD" MOORED TO THE STRANDED BERG
About a mile from the winter quarters. The "Nimrod" sheltered in the lee of this berg during blizzards

[*To face p.* 133

PLATE XXXIX

SCOTT DEPOT "A"
Rediscovered by Shackleton's depot-laying party, Feb. 15, 1909. Depot originally left by Scott on Oct. 1, 1902

[*To face p.* 133

the snow roofs of the tunnels, approximately two-thirds of the volume of this berg was below water, one-third above. Obviously, therefore, the berg from the water-line to its base must have been composed of material far less dense than typical glacier ice.

Some further light on the intimate structure of the Barrier is thrown by the section obtained by Messrs. Macintosh, Day, Joyce, and Marston at the site of Scott's Depot "A." Having re-located this old depot and re-aligned it, the party dug down in order to find what depth of snow had been deposited on the depot during the $6\frac{1}{2}$ years that had elapsed since its erection. They came upon the original snow surface on which the depot was formed at a depth of 8 feet 2 inches (2·5 metres). In order to determine the density of this snow they melted down a considerable quantity of it, and measured the volume of the thaw-water resulting. This showed that the annual accumulation of snow on this part of the Ross Barrier is about 15 inches (380 millimetres) of dense snow, almost *névé*, equal to about $7\frac{1}{2}$ inches (190 millimetres) of rain. This depot is in the latitude of Minna Bluff about 78° 40′ S.

Before proceeding to consider the probable origin of the Barrier, it is necessary to glance at its past history. Throughout almost all the Antarctic regions yet explored, there is abundant evidence of a recent and prolonged shrinkage of the ice masses and *névé* fields. The Ross Ice Barrier is no exception to this rule. Captain Scott's survey on the *Discovery* shows the position of the Barrier edge as he found it in 1902, and on his chart he gives the position of the Barrier edge as originally outlined by Ross as the result of the explorations conducted on the *Erebus* and *Terror* in 1841–2. These two outlines are shown on the map at the beginning of this chapter (Fig. 46), and prove that the face of the Ross Barrier has retreated southwards no less than about 45 miles from 1842 to 1902 at its eastern end. The mean amount of retreat during the above sixty years aggregates perhaps about 20 miles along the whole front of the Barrier. So much for horizontal shrinkage.

The following facts refer to vertical shrinkage. The *Discovery* Expedition proved, from the evidence of stranded moraines 800 feet above sea-level, near Cape Crozier, that the surface of the Barrier at its western end has recently decreased in altitude by about 700 feet. Our observations at Cape Royds, upon the western slopes of Mount Erebus, showed that large lateral moraines, crowded with blocks of granite and other crystalline rocks, transported from the mainland to the south, were continuous for considerable distances at altitudes of at least 1000 feet above sea-level. It may therefore be concluded that, in late geological time, in the neighbourhood of Ross Island and McMurdo Sound, the Barrier has shrunk, vertically, by no less an amount than about 900 feet. At the time of maximum glaciation, there is also evidence that the outlet glaciers from the inland ice, such as the Ferrar Glacier—which formerly fed the Barrier—and the Beardmore Glacier

—which still feeds it—have shrunk vertically, the former by 4000 feet, the latter by at least 2000 feet. The shrinkage definitely proved at Mount Erebus may be taken to apply, more or less, to the whole of the Barrier surface. At the time, then, of maximum glaciation, if the sea-level was in its present position, the height of the Barrier at Cape Royds would have been 1000 feet above sea-level, and at Cape Crozier fully 800 feet. The average depth of the soundings along the present face of the Barrier from Cape Crozier eastwards is about 350 fathoms, or 2100 feet—*i.e.* in water of this depth, one-third of the Barrier material would have been above the water and two-thirds submerged. If it be assumed that the Barrier during maximum glaciation averaged 500 feet above sea-level instead of about 100 feet as at present, then in water of an average depth of about 2000 feet, one-fifth of the ice would have been above sea-level and four-fifths would have been submerged, on the assumption that the density of this ice as compared with the density of the adjacent sea water was not less than 8 to 1. Thus it may be concluded that, by far the greater part of the Barrier during the maximum glaciation being ice, this Barrier ice must have rested and pressed heavily on the floor of Ross Sea. This would still be the case even if it be assumed that sea-level, during the maximum glaciation, was 200 feet higher than it is now, and even if the maximum depth as yet sounded along the Barrier be taken instead of the mean depth. The maximum depth recorded is 460 fathoms. If, therefore, during the maximum glaciation and submergence the Barrier surface at this deepest sounding to the east of Mount Erebus were 800 feet above sea-level, as much as a little over a quarter of the Barrier mass would be above sea-level, an amount quite sufficient to keep the Barrier resting on the bottom, even in this deepest part.

In considering now the origin of the Barrier, two reasonable alternatives suggest themselves. First, the hypothesis put forward by Captain Scott—that the present Barrier is a direct descendant of the old Barrier formed during maximum glaciation, and that when, as the result of diminishing snow supplies, the old Barrier shrunk in thickness as it retreated Polewards, the weight of ice was no longer sufficient to keep the Barrier on the bottom of Ross Sea, and consequently the Barrier floated up off the sea bottom into its present position. Here it is still nourished by the smaller, but still active, glaciers of to-day. Scott, of course, would concede that drift snow contributes to even up its surface, but apparently does not regard this snow as an important contributing factor. The other alternative, to which we incline, is that there may not necessarily be any of the ice or snow in the present Barrier which belonged originally to the old Barrier during the maximum glaciation. The material of the Barrier at its sides is undoubtedly glacier ice. These ice-streams, when they reach the south-western shores of Ross Sea, fan out, the fans coalescing at their margins. Had there never been a maximum glaciation, each individual glacier might have formed a long ice-jetty projecting into the upper end of Ross Sea now occupied by the Barrier, much in the same way as do the present glaciers of

Robertson's Bay. During the maximum glaciation the coalesced ice streams formed a vast piedmont aground, just as, at the same epoch, did the Drygalski, Reeves, Campbell, Corner, and Priestley Glaciers of the Drygalski-Reeves Piedmont. Then, as the glaciers shrunk with diminution of the snow supplies, the piedmont floated up and retreated southwards, as Scott has supposed. Meanwhile the surface of this floating piedmont would form a receptacle like a vast shovel, or fork with much widened prongs, for snow falling on its surface, or drifted off the high plateaux which bound the Barrier region on the south-west, and the lower plateaux on the south-east from King Edward VII. Land to Carmen Land. Little by little, as the glacier ice towards the central and northern portions of the Ross Barrier became melted off from beneath, *névé*, passing into ice at a depth, would gradually take its place. This *névé* would result from the accumulation of superficial snow deposits.

The observations of Macintosh and Day show that the snow which actually falls, or is drifted, on to the Barrier surface, must be an important contributor to its volume. A great deal of the Barrier extends southwards from its terminal face on Ross Sea, for a distance of fully 300 miles (483 kilometres), and even over 500 miles (805 kilometres) in the case of the Devil's Glacier. The Beardmore Glacier, for example, at its lower end, where it joins the Barrier, is 350 miles (563 kilometres) distant from the Barrier face. It may be assumed that the annual amount of compressed snow contributed to the western portion of the Barrier surface, as the result of additions from drift snow as well as from actual precipitation, is about 1 foot (·3048 metre). From the observations of Scott and Macintosh of the rate of movement of the Barrier near Minna Bluff, it may be inferred that the Barrier is travelling seawards at the rate of about 492 yards (450 metres) per year. From this one may argue that snow falling on the foot of the Beardmore Glacier, 350 miles inland, would take 1252 years to reach the edge of the Barrier where bergs discharge into the sea. At this rate, if 1 foot of snow * is added to the Barrier every year, ice from the Beardmore Glacier, which left the foothills about 1250 years ago, if it reaches the Barrier cliffs at the present day, will be covered by a thickness of about 1250 feet of snow, without allowing for the compression of the lower layers into ice. Obviously, this theory gives a considerable thickness of snow to form the seaward end of the Ross Barrier. That the under part of the Barrier, except, perhaps, near its centre, is still formed of glacier ice, is suggested as being possible by the nature of its cross-section from east to west.

This section is based almost entirely on the soundings and altitudes given by the British National Antarctic Expedition of 1901–4 along the face of the Ross Barrier. Reference to this section and to the plan of the Barrier shows that the

* This estimate of an annual addition of 1 foot (·3048 metre) of hard compressed snow, equal to about 7·5 inches (·19 metre) to the Barrier surface, applies only to the Minna Bluff region, as far as the very limited observations up to the present extend, and is *not* necessarily of wide application.

altitude of the Barrier is greatest, and consequently the Barrier ice is thickest, in the direct line of movement of the Barrier ice from the direction of Barne Inlet past Minna Bluff. As already shown by Day's sketch, the Barrier ice, as it approaches the huge resistant mole of Minna Bluff, becomes thrust upwards for a considerable height on the southern slopes of the Bluff, so that on this thrust-side the ice is much higher than it is on the lee (the northern) side of the Bluff. The ice thus thickened on the southern slopes of Minna Bluff is shouldered away by the Bluff, until, as already stated, it takes up a path in a direction about N. 30° E. A continuation of this trend would carry it eventually to the vicinity of the highest part of the Barrier as yet observed, viz. 240 feet.* It will be noticed that the deepest sounding does not exactly coincide with the *present* path of the thickest Barrier ice, but when the volume of the ice from the south-western mountains was very much greater than it is at present, the larger ice stream may have been more

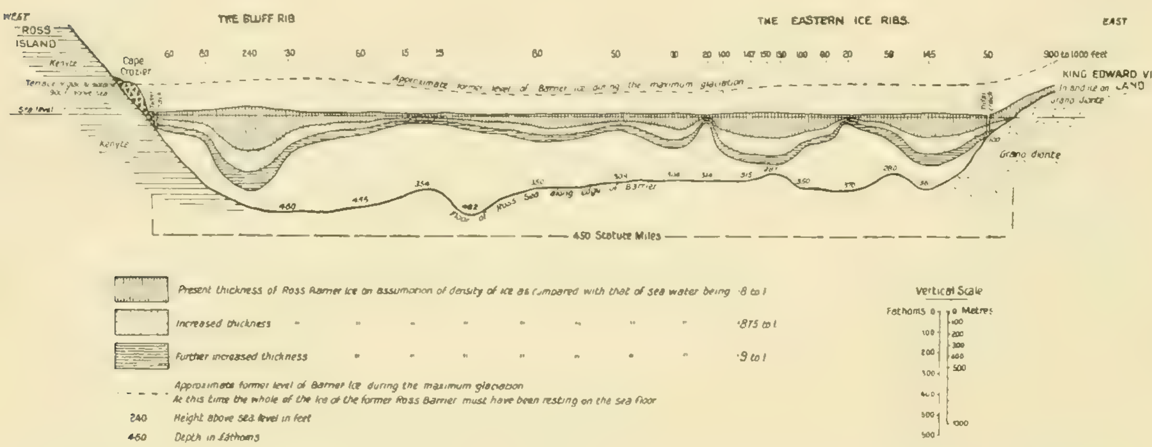


FIG. 48. SECTION ACROSS ROSS BARRIER, EAST TO WEST, THE SOUNDINGS AND ALTITUDES AFTER CAPTAIN R. F. SCOTT

deflected eastwards than the present ice stream, so as to have completely filled the deepest area sounded by Scott along the Barrier face, 460 fathoms, 75 miles E.S.E. of Cape Crozier.† The cross-section of the Barrier suggests that its structure is very similar to that of the Drygalski-Reeves Piedmont. Just as in the latter case one

* We are informed that later measurements taken in detail by Commander E. R. G. R. Evans, C.B., R.N., of the British Antarctic Expedition of 1910–13, when surveying the Barrier cliff in Captain Scott's ship, the *Terra Nova*, show that at present no part of the Barrier cliff exceeds a height of 150 feet. Probably, therefore, the above height of 240 feet is somewhat exaggerated, or it may be the case as the Barrier surface, in many places, has strong undulations trending east and west, the original measurement may have been taken on a cliff cutting the arch of an undulation, and the later on one cutting a trough. The first supposition is the more probable.

† An alternative hypothesis is that the sea bottom under this thickest part of the Barrier has been raised by the thawing out of englacial moraine at the base of the ice sheet by the deep, relatively warm, layer of sea water, as has already been suggested in the case of the Drygalski Glacier.

can trace distinctly the individual ice ribs, belonging respectively to the Reeves Glacier, the Larsen Glacier, and the David Glacier,* so in the case of the Ross Barrier one can probably recognise the traces of "the Bluff rib" derived from the stemmed and deflected ice of the Barne Inlet and other glaciers, from the mountains to the south-west of the Ross Barrier as well as the eastern ice ribs, perhaps derived from the coalescence of the Beardmore Glacier ice with that of glaciers farther to the south-east and east. While it is thus assumed that the higher parts of the Barrier represent fanned-out glacier ribs, the low-lying parts of the Ross Barrier can be explained in at least three, possibly four, ways, as follows:—

First, they may be due to the fans, or ribs, of the respective piedmonts afloat, contributing to form the Barrier, becoming very thin at their edges, as a consequence of prolonged spreading and consequent thinning of the ice as it progressively fans out wider and wider as it advances seawards.

Secondly, these low areas may mark more or less radial strips along the Barrier where the edges of individual floating glacier fans fall short of each other, and so fail to coalesce, the stretches of sea between becoming built over with bay ice, lasting for many seasons, its surface receiving annual additions of drift or new-falling snow. This is obviously the case with much of the Drygalski-Reeves Piedmont.

Thirdly, the low parts alternating with high may be due, and no doubt are in part due, to the existence of considerable undulations in the surface of the Barrier, particularly in the neighbourhood of the Bay of Whales and the Western Inlet. As already stated, Scott recorded that near Balloon Bight these long and wide undulations, trending nearly east and west, had a depth of 120 feet. As the greatest height of the Barrier cliff is usually about 150 feet, it is obvious that, if by the breaking away of bergs from the Barrier face the bottom of one of these troughs were exposed to view, the height of the cliff wall there would not exceed about 30 feet. The existence of Western Inlet in the Barrier 100 miles west of the Bay of Whales is, perhaps, to be explained as the result of differential marine erosion of a corrugated ice sheet, the sea eating back the thinner ice of the troughs more quickly than the thicker ice of the flat-topped ridges.

Fourthly, it is by no means improbable that there is differential etching of the under surface of the Ross Barrier through the solvent action of water coming upwards from a depth, the temperature of such water being slightly in excess of that of the general temperature of the surface water. Reference has already been made to the influence of shoals in deflecting upwards these relatively warmer waters, and so keeping pools of sea water open, almost all the winter, on the lee side of such shoals in regard to the prevalent ocean currents. Comment has already been made on Ross' discovery of warmer water at a depth in Ross Sea, and this conclusion has been abundantly confirmed by subsequent scientific expeditions. There can be no

* To these must now be added the Campbell, Priestley, and Corner Glaciers.

doubt as the result of our observations that the sea ice in summer is corroded by warm water from beneath, and that even in winter, where there is any obstacle on the sea floor which causes an upward deflection of the deeper waters, there the surface temperature of sea water is kept so high that sea ice cannot form. Under these circumstances, there can be no doubt that differential erosion must be a factor in determining the differential heights of the ice-cliff of the Ross Barrier, but that it is probably not an important factor, as is suggested by the fact that where the water of Ross Sea along the Barrier edge is particularly deep (over 400 fathoms), so that conditions would be unfavourable for upward currents, there the Barrier ice is specially thin. There can be little doubt that the thinness of the ice in the central section of the Barrier ice-cliff is chiefly due to the fact that this is just the portion which is farther removed from the sources of ice supply, the great glaciers of the horst and the smaller glaciers of Carmen Land and other lands bounding the Barrier on the east.

SUMMARY

The Ross Barrier is now, for the most part, a floating piedmont, the shrunken remnant of a much vaster piedmont aground. Its surface shows both radial and tangential undulations. The gently swelling radial thickenings of the Barrier represent the prolongations, for hundreds of miles seaward from the shore-line, of the great land glaciers, widely fanned out where they leave the land and plunge into the sea. The tangential or concentric undulations, having mostly an approximate east to west trend, represent pressure ridges chiefly normal to the paths of the main glacier streams which constitute the radial ribs. Partly these undulations represent those great pressure ridges which start from the point where the land glaciers meet the Barrier surface, and, as the whole Barrier slowly moves seawards, become gradually transferred to the edge of the Barrier facing Ross Sea. Partly they represent pressure ridges, due to the stemming action of rocky islands smothered under the ice, like the one discovered by Amundsen to the south of Framheim. Such low-lying areas of the Barrier as have a radial trend owe the relative thinness of the ice, of which they are formed, (*a*) either to the glacier ice ribs becoming thin through fanning at their ends and at their sides, where they become welded together along their planes of contact, or (*b*) to the fact that these adjacent floating piedmont glaciers, failing to touch one another at their sides, nevertheless become linked up by old sea ice, which, being protected from erosion by the glacier ribs or ice jetties on either side, accumulate as "bay" ice from year to year, until it acquires a considerable thickness. This thickness is constantly increased by additions of snow, whether derived by drifting from old falls, or originating in snow new fallen *in situ.* This process appears to be taking place at the present time at the Drygalski-Reeves Piedmont, which is such an important key to the structure of the Ross Barrier, but at the same time, as much of it is covered by moraines, it may be nearly all fanned-out glacier ice.

The Ross Barrier is thus formed literally of "thick-ribbed" ice with transverse pressure ridges. It may be compared to a shield formed of a wicker-work frame covered with hide, in which the rods represent the glacier ice jetties, and the smaller osiers the pressure ridges, while the drift and fallen snow represent the hide.

The exact relation between the amount of ice that is being annually added to the Barrier from its great marginal glaciers, as well as from the drift snow and new-fallen snow on the Barrier surface, to what is lost by ablation, is not yet known. Near Minna Bluff the surface of the Barrier was added to at the rate of about 15 inches (380 millimetres) of dense snow, almost *névé*, equal to 7½ inches (190 millimetres) of rain annually.

At the same time, the evidence already given, in the chapter entitled Meteorological Notes, makes it clear that on the whole, in the western portion at any rate, of Ross Island ablation is in excess of precipitation, as is suggested in particular by the evidence of Sunk Lake, where the surface of the lake ice, only about 60 yards (55 metres) distant from the sea, is actually 18 feet (5·48 metres) below sea-level.

It is also to be noted that no information is at present available as to the rate at which the base of the Barrier ice sheet is being melted in the water of Ross Sea.

That the amount of ice annually lost by melting must be very considerable is obvious from the following consideration:—Evidence shows that the sea ice of Ross Sea, which in a single season attains a thickness of about 7 feet (2·13 metres), is about half melted away during the summer, the melting taking place from below upwards: thus late in January the sea ice, formed during the preceding winter, is found to be full of corrosion hollows. Some of these hollows undoubtedly have been formed by the seals, which have bitten away the ice to form their breathing holes. Abandoned later by the seals, these old breathing holes become roofed over with young ice. But the number of these is negligible as compared with the millions of corrosion hollows which honeycomb the sea ice of Ross Sea late in summer. It would appear that near lat. 77° S., at least 1 metre of ice is annually lost by melting.

Evidence, already quoted earlier (in last part of chapter on Physiography, dealing with Ross Sea), shows that some of the deeper water of Ross Sea must be warm enough to melt sea ice, and therefore, of course, land ice also. This suggests the important consideration that as the result of relatively warm currents flowing southwards under the eastern and central parts of the Ross Barrier melting may be going on there continually during the winter as well as the summer, and an appreciable thickness of ice is probably annually removed from the base of the Barrier through this cause. It would be of great interest and importance to ascertain what this amount is. An approximation might be made by experimenting with blocks of ice, which might be used as "control specimens," at such sheltered spots on the Barrier edge as Western Inlet and Bay of Whales.

A number of these ice blocks could be sunk at intervals at such localities by means of an iron weight suspended below the block, and well insulated from it by a short piece of asbestos rope. The ice blocks could be suspended by steel piano wire, again insulated from the ice blocks by a short piece of asbestos rope, and the upper end of the piano wire could be attached to the base of the Barrier ice-cliff in one of the inlets, or preferably to old bay ice in a secure and sheltered spot in these inlets.

An approximate estimate of the cross-sections of the ice streams of the western side of the Ross Sea region from just south of the Beardmore Glacier to the Reeves Glacier at Mount Nansen may be made as follows:—

Of the Coastal Mountains shown on the section, the total length of which is about 750 miles, about 113 miles are occupied by well-developed glaciers, and of this width no less than nearly 100 miles is made up of outlet glaciers.

These widths have been based on the following approximate measurements:—

Width in Miles.	
15	Beardmore Glacier.
7	Glacier between Capes Lyttleton and Goldie (*).
10	Glacier of Shackleton Inlet.
12	Glacier of Barne Inlet.
10	Glacier of Mulock Inlet.
8	Glacier of Skelton Inlet.
6	Koettlitz Glacier.
2	Blue Glacier (*).
3	Ferrar Glacier.
4	Mackay Glacier.
2	Penck Glacier (*).
2	Fry Glacier.
5	Mawson Glacier.
3	Harbord Glacier.
4	Davis Glacier.
6	David Glacier.
2	Larsen Glacier.
12	Reeves Glacier.
113 miles.	

Glaciers marked thus (*) are "Alpine" or "Norwegian" types of glaciers. The rest are outlet glaciers.

It is possible that in the case of the glaciers entering the "inlets" in the above list the width of the inlet may be greater than that of the glacier which fills it with ice. The margin of error for the estimated widths of all the glaciers is considerable. For example, instead of 113 miles, their total width may not aggregate more than about 97 miles. It is assumed in the calculations which follow that the approximate total width of such of these glaciers as are termed outlet glaciers is about 100 miles.

If the exact cross-section of the ends of these glaciers were known, as well as their average speed of movement throughout the year, one would be in a position to estimate the quantity of ice which they annually discharge on to the western side of the Ross Barrier and into the western side of Ross Sea.

As regards the cross-section of the lower ends of the glaciers, the only data as yet available—and they are very meagre—are for the Drygalski Ice Tongue. This, as shown on our sections, has a mean thickness, in its central portion, of about 2000 feet. It is possible that its thickness at its centre, at a point 20 miles east of the shore-line, may even approximate to 3000 feet, as the central parts of this glacier are about 300 feet above sea-level. One may estimate that these glaciers may average 2000 feet thick for an aggregate width of fully 100 miles. As has been previously stated, we saw evidence that the whole mass was in movement from the fact that during a single night (December 17, 1908), in about 10 to 12 hours, one of the vertical shear planes near its northern edge moved about 1½ feet. If this rate were maintained, it would mean a movement of about 3 feet (·914 metre) *per diem*.

If to this central mass of ice, 10 miles wide, the wedge-shaped portions of the ice on either side, each 5 miles wide, be added, the total cross-section of this glacier, where fanned out into the piedmont, would be about 15 miles (24 kilometres) by 2000 feet (610 metres). This would give a daily discharge of ice in the middle of December, when the rate is probably approaching a maximum, of about 475 millions of cubic feet *per diem* (13,486,264 cubic metres). If this average thickness of 2000 feet be maintained throughout the whole of the 100 miles in width of glaciers, from the Beardmore to the Reeves Glaciers inclusive, the total daily discharge of ice would be less than 3166 millions of cubic feet, and even if one-third of this amount be deducted to allow for thinning of the glaciers towards their sides, the amount would still have the enormous total of, in round numbers, over 2,000,000,000 cubic feet daily. At least one-half of this is probably annually added to the west side of the Ross Barrier, the other half being discharged into the Ross Sea, along its western shore. Thus annually from the Beardmore Glacier to Skelton Inlet, inclusive, the Ross Barrier may receive daily, from the outlet glaciers alone, an amount of ice equal to 1,000,000,000 cubic feet during the middle of December.*

It may be interesting to compare this result with the known rate of movement of the Ross Barrier, and the amount of ice that is there daily pushed forward to the Barrier cliff face, where it breaks off to form bergs.

* As regards other rates of movement of the glaciers of the Antarctic horst, Ferrar states (Nat. Ant. Ex., 1901–4, Geology, pp. 82–83), that at the south arm of the Ferrar Glacier the rate of movement is probably less than 6 feet (1828·77 millimetres) a month, while the Blue Glacier moves less than 4 feet a year. Both these glaciers are exceptionally stagnant, and are not a fair criterion of the rate of movement of the great glaciers like the Beardmore, the Drygalski, the Reeves, &c., which shear and ridge the sea ice or Barrier ice, and push the whole Ross Barrier in places some distance away from the land. This supposition has quite recently been confirmed by the observations of Griffith Taylor and Debenham of Scott's last expedition, that from the middle of December to about the middle of January (1911–1912) the Mackay Glacier moved at the rate of about a yard a day.

The main rate of movement of the Barrier past Minna Bluff has been ascertained to be about 492 yards (450 metres) a year.* Reference to the cross-section of the Ross Barrier, already given on Fig. 48, shows that for its total width of 450 statute miles (724 kilometres) the Ross Barrier has an average thickness of about 720 feet. This would give a superficies for the Ross Barrier vertical cliff face of (in round numbers) about 1,710,000,000 square feet, while the movement at Minna Bluff—probably a maximum area for speed—is 492 yards a year, the rate of movement towards the eastern end of the Barrier must be extremely slow, perhaps almost negligible, as Amundsen suggests.

The rate of 492 yards a year is nearly 4 feet (1·22 metres) *per diem*. It may be assumed that as the eastern end of the Barrier is almost stationary, the mean rate of advance is not more than about 2 feet a day, though it is quite possible, as the Minna Bluff speed is probably a maximum, that it may not exceed about 1 foot per day. At the 2 feet *per diem* rate of advance 3,420,000,000 cubic feet of ice would be added to the sea-cliff face of the Barrier daily. At the rate of advance of 1 foot per day, 1,710,000,000 cubic feet would be the daily addition. As already stated, on the assumptions made, the outlet glaciers from Skelton Inlet to the Beardmore Glacier, inclusive, contribute in summer perhaps about 1,000,000,000 cubic feet daily.

To this must be added—

(*a*) Ice contributed by outlet glaciers not examined by us, such as the ice of the glaciers discovered by Amundsen, the Liv Glacier, the Axel Heiberg, and the Devil's Glacier, and probably other glaciers between the Liv and Beardmore Glaciers, as well as by glaciers between King Edward VII. Land and Carmen Land.

(*b*) Numerous Alpine and Norwegian types as distinct from outlet glaciers, chiefly on the east side, partly on the west side of the Ross Barrier.

(*c*) Strips of old bay ice (sea ice) bridging over what would otherwise be lanes of open sea water between the edges of the glacier ice jetties.

(*d*) Drift snow and new-fallen snow deposited on the actual surface of the Barrier.

Obviously the December summer rate of movement of the outlet glaciers which feed the Barrier cannot be maintained during the winter months, and so the December rate of perhaps 1,000,000,000 cubic feet of ice daily may be distinctly less in winter time.

These figures are of course only roughly approximate, though based on the best measurements available. Nevertheless they serve to show that the suggested sources of nourishment of the Ross Barrier are reasonably competent to support this magnificent floating piedmont, provided ablation over its surface did not

* Ferrar states (*op. cit.*, p. 82) that Lieutenant Barne's measurements show that the Ross Barrier near Minna Bluff moved 608 yards in 13½ months. Our measurements extend over a period of 6½ years.

exceed annual precipitation, and provided also that there were no loss of ice to the Barrier owing to the constant melting of its under surface in the relatively warm deeper water of Ross Sea.

We know that both ablation and melting, chiefly submarine, are now contributing to remove the ice of the Barrier above and below simultaneously. On the whole the Barrier surface * is probably gaining, especially along its southern, south-western, western, and central portions through accessions chiefly of drift snow, partly of snow falling *in situ* on the Barrier.

For example, at Captain Scott's Depot "A," near Minna Bluff, the accession of hard snow, almost *névé*, proved to be no less than 8 feet 2 inches (2·5 metres in round numbers) in $6\frac{1}{2}$ years, that is, almost exactly, 15 inches (380·99 millimetres) of hard snow, which was proved by experiment to be equal to $7\frac{1}{2}$ inches of rain (184·15 millimetres) a year.

As already explained in the Meteorological Notes, the part of the Ross Barrier nearest to the high mountains of the Antarctic horst and nearest to the sea receives the heavier additions of drift snow, as well as of snow falling *in situ*. Amundsen records that the surface of the Ross Barrier, between about 80° and 82° S. lat., and near the meridian of 163° W., did not alter appreciably between April 1911 and October 1911.†

This area, removed so far from the nearest high mountain, is one of comparative calm, and consequently low snowfall and little drift snow.

The loss to the Ross Barrier through the constant melting of its base in the relatively warm water of Ross Sea is probably considerable, possibly even approximating to about 1 yard (·914 metre) to 1 metre a year.

Thus as fully sixty years have intervened between the time of Captain R. F. Scott's survey of the Barrier in 1902 and that of Sir J. C. Ross' original examination of it, at the rate of a yard a year no less than 60 yards 180 feet (55 metres) may have been removed by melting from the base of the Ross Barrier.

Date of latest Phase of Maximum Glaciation. (a) *Vertical Shrinkage of Ross Barrier.* If the mean density of the Barrier Ice be taken as ·85 as compared with the average density of the water of Ross Sea taken as unity, the height of the Barrier cliff may have been lowered by as much as 32 feet (over 9 metres) from this cause alone since the time of Ross' visit in 1842. Unfortunately Ross' survey was not sufficiently detailed to prove whether or not such an actual general decrease in height has taken place. If data were available as to this present rate of dwindling of the ice of the Ross Barrier, some approximate estimate might be formed of the time that has elapsed since the latest phase of maximum glaciation in the Ross Sea region of Antarctica.

As has been abundantly proved already, the surface of the Ross Barrier has

* But this surface gain may be more than compensated for by the submarine melting.

† The South Pole, vol. i. pp. 233, 234, and 382.

shrunk vertically by about 700 feet, near Cape Crozier, since the maximum glaciation. At this time the Ross Piedmont was obviously aground, but, with diminished snowfall on the firnfelds of the feeding glaciers, a time must have come when the Ross Piedmont floated off the bottom and its base commenced to thaw. At the rate of thaw of a yard (·914 metre) a year it would have taken the Barrier only about 400 years to have floated vertically through the amount of about 200 fathoms, which is near the average amount.

To this would have to be added the time needed for the lowering of the Barrier surface from 800 feet above sea-level to about 300 feet above sea-level, that is, a lowering of about 500 feet. There are no data known to us for estimating this.

(b) *Horizontal Shrinkage of Ross Barrier.* On this question the evidence is a little clearer. From 1842 to 1902 the seaward edge of the Ross Barrier has retreated southwards some 20 miles (32 kilometres) on the average in sixty years. Evidence has already been given to show that the Barrier front was formerly at least 200 miles north of its present position. At the above rate of recession the Barrier front may have retreated all the way from the latitude of Cape Washington down to its present position in so short a period of time as 600 years, which seems scarcely credible. Probably the rate of recession at first, when the ice of the Ross Barrier was about 2500 feet thick on the average, was far slower than at present, when its average thickness is only about perhaps 720 feet. Even if the rate was formerly three times as slow as at present, it may all have taken place in about 1200 years. Of course a very considerable amount of time may have elapsed during oscillations to and fro of the Barrier front during the latest of its maxima. Accurate soundings of the whole of Ross Sea would no doubt throw much light upon the positions of the Ross Barrier front during various maxima of glaciation. Such evidence might be afforded by submarine ridges formed of push moraine or dumped moraine.*

Future Observations. It appears to us that in addition to detailed soundings future observers might profitably direct attention to the following problems in connection with the Ross Barrier :—

1. The trend of individual glacier ribs or fans.

2. The trend of the undulations of the nature of gentle pressure ridges and troughs more or less normal to the path of the main glacier streams.

3. The presence or otherwise of sea ice just south of low-lying portions of the Barrier cliff, and the amount of *névé* and ice overlying it derived from old snow. This might be ascertained by boring and recovering the core of ice from the bore from time to time, or by studying the character of the ice in these low-lying portions of the Barrier in the sides of any convenient crevasse situated at some distance south of the Barrier edge.

* It is understood that Commander E. R. G. R. Evans, R.N., of Captain Scott's expedition, as well as Lieutenant Pennell, R.N., of the same expedition, have lately obtained, when sounding on the *Terra Nova*, important information on this subject.

4. Serial temperatures at various depths in the ice of the Barrier might be obtained either from bores or crevasses.

5. Serial temperatures all along the Barrier edge are very much needed.

6. Rate of melting of ice blocks at various depths in Ross Sea along the Barrier edge, as might be ascertained by the method already suggested, which could be employed at sheltered inlets like Bay of Whales or Western Inlet.

7. Direction of currents under the Ross Barrier (*a*) at McMurdo Sound, (*b*) under the main face of the Barrier. This could be ascertained with a deep sea current meter at Bay of Whales, Western Inlet, and the shallow bight where the Barrier is only 15 feet ($4\frac{1}{2}$ metres) high at a point 250 miles E.S.E. of Cape Crozier.

8. The rate of movement, if any, of the Ross Barrier along its eastern margin between Carmen Land and King Edward VII. Land, as well as many more observations of the movements along the western side of the Ross Barrier, are also much needed.

9. The granulation and crystallinity in general of the material of the Ross Barrier at various depths has at present been very little studied.*

10. The relation of ablation (loss) to precipitation (gain), whether the latter results from falling snow, drifting snow, or contributing glaciers.†

No observer interested in the phenomena of the glaciation of Europe during the Pleistocene Ice Age can fail to be struck with the very important analogue of the great Ross Piedmont to the vast sheet which formerly stretched from Scandinavia to the northern part of Great Britain, filling in the North Sea. Just as in the case of the smaller Antarctic Piedmont of the Drygalski-Reeves area, and the far larger Ross Piedmont, one can imagine that, like the Ross Barrier, the old North Sea Barrier was during the ice maximum everywhere aground except where it floated over the depths of the Skäger Rak. One sees the great glaciers of the Christiania region, as well perhaps as those of Christiansand, Stavanger, and Hardanger, sending out far-reaching ice jetties or fanned-out piedmonts towards Great Britain. These ice jetties, at first separated from one another by open lanes of sea water, eventually coalesce, either through their edges coming in contact, or more probably through being linked up to one another by wide strips of old bay ice, the sea ice in such sheltered lanes between the ice jetties not breaking away during the summer, as sea ice does in more exposed areas, but gaining in thickness from year to year. Its thickness meanwhile would be further increased by accumulations of drift snow and falling snow. This probably was the manner of the building of the great ice raft, or rather ice sledge, which drove eventually

* C. S. Wright, Physicist to Captain Scott's recent expedition, has, we understand, an important series of observations on this subject.

† Mr. Wright concludes ("Scott's Last Expedition," vol. ii. p. 449) that the Ross Barrier Edge has neither receded nor advanced between 1904 and 1912. We may remark that it is nevertheless possible it has become thinned through submarine melting.

past the Dogger Bank against the eastern shores of Northumbria, and thrust and glaciated and over-rode part of that coast at a distance of 400 to 500 miles from the Norwegian glaciers, just as to-day the Ross Barrier is thrusting and over-riding and glaciating Cape Crozier at a distance of some 300 miles from the contributing glaciers; in spite of the stemming action of Ross Island which leads to the development of great pressure ridges and shear planes along the zone of contact between land and ice. It must be remembered too that some of the ice at the Ross Barrier edge has advanced fully 500 miles north of where the soles of the Heiberg and Devil's Glaciers leave the shore-line, and that formerly, during the maximum glaciation, that edge was even 700 miles north of where those glaciers left the shore, and that, though aground for this entire distance, the piedmont still could move forward and grind and heavily glaciate the hard volcanic rocks high up on the shoulders of Ross Island.

The individual glacier ribs or ice jetties of the North Sea Piedmont may be compared to the runners of a sledge, while the bay ice between represents the sledge decking. The friction of this superstructure (carrying its load of old snow largely granulated into ice) on the sea floor would be reduced to a minimum by the glacier runners, the bay ice between these "runners" being afloat. (See actual section in this report of the Drygalski-Reeves Piedmont in Ross Sea.) But such runners should scoop out grooves in the sea floor. Do the soundings of the North Sea reveal the presence of such grooves? It is doubtful whether such can now be traced, but it must be remembered that if again we judge by the analogue of the Drygalski-Reeves Piedmont there is a distinct tendency after the grooving effected by a glacier "runner" during a maximum glaciation for the "runner," as it gradually floats up out of its groove during deglaciation, to aggrade that groove, at all events for a distance of many scores of miles to the seaward of the coast-line, and tidal scour and other marine currents should help this work of aggrading. In the case of surface-carried moraine material, which as Antarctic experience shows would soon become englacial, there is no limit to the distance out to sea to which aggradation may take place, other than the length of the extension seaward of the glacier, and the limit of the drift of its icebergs.

It is possible that detailed soundings of the North Sea will yet reveal traces of the grooves of the glacier "runners" under the North Sea Piedmont during the Great Ice Age.

SHOWS THE THAW AT GREEN LAKE, CAPE ROYDS,
DURING THE SUMMER OF 1908–9

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CHAPTER VII

LAKES AND LAKE ICE OF CAPE ROYDS AND CAPE BARNE

Lakes and Lake Ice. The lakes which occupy the ice-gouged depressions of the peninsula of Cape Royds are of special interest. Owing to their accessibility during the winter these lakes were examined in detail, and one or more trenches sunk in all the more important ones.

There are several lakes deserving of a separate individual description, but the majority are small tarns, in winter occupied by a sheet of ice generally less than 3 feet thick. The ice in these tarns, unlike that in some of the larger lakes, was found to melt entirely in the summer.

In all the large lakes, and in some of the smaller, there flourishes a brown to reddish-brown algous plant, which in some cases grows to such an extent that the accumulation of vegetable matter resulting from its decay forms a layer of peat of appreciable thickness on the lake bed. It seems probable that many of the smaller lakes which contain little or none of this alga are not permanent, that is they may be entirely removed during the winter and spring by ablation, or in the summer by thawing. This was proved, in the case of some of the extremely small lakes, by our observation that small depressions—coloured green by an algous growth—had already by late November taken the place of the smallest of the tarns. Many of these, however, were refilled from time to time from the thaw-water of snow-drifts on the slopes above them, and it was only at times of prolonged drought, when there was no snow falling or drifting, that the depressions became quite dry. It is probable that these lakes are in the majority of cases sub-permanent, since the thaw-water from the drifts of late summer, when the sun does not rise high above the horizon, and thus does not exert much heating influence on the rock-basins, would become frozen, and would remain so until the tarns were entirely removed by evaporation, or until the next summer thaw set in. There is no doubt of the permanency of the larger lakes, although there are evidences showing a considerable restriction in size in some cases. These evidences will, however, be dealt with when considering the lakes individually.

The ice and water of most of the lakes is more or less salt, though there are apparently one or two important exceptions, and this saltness is due probably to a combination of two causes: (1) Wind action—decidedly the most important; (2) filching of salts from the kenyte.

1. The wind brings salt to the soil and to the lakes in two main ways. In the short summer, during the heavy blizzard of February 17th, 18th, and 19th of 1908, the sea spray in a frozen state was carried by the wind for considerable distances inland. Such action as this, although the high winds during this season of the year are few in number, must have no inconsiderable effect on the waters of those lakes which melt in summer, for not only do they receive the spray which is dropped immediately on them, but also a large quantity of that which falls on the slopes of the hills surrounding them. The latter is carried into them by small streams of thaw-water in the summer. In that portion of the year, when the sea is frozen over, the method of transport is different, but the quantitative result must be even greater. Every blizzard brings quantities of drift snow which has been lying on the sea ice, and has been infiltrated with the salt extruded from between the crystals of the sea ice, and some of this snow (although large quantities pass on beyond Cape Royds towards Cape Bird and the Ross Sea) is formed into drifts on the lee side of the hills and ridges, and subsequently in the thaw season goes to swell the amount of water in the lakes.

2. The second cause appears to be less significant in the Cape Royds area, as here the denudation seems to be more mechanical than chemical. The chemical leaching by the thaw-water is much better illustrated in the Western Mountains of McMurdo Sound, and will be considered in the section dealing with that portion of our researches. Nevertheless, it is probable that a certain amount, at any rate of the soda salts, is leached out from the kenyte during the short period when the thaw is sufficiently effective to produce rivulets of water leading down from the snow-drifts to the lakes.

The waters of the lakes may be further mineralised by other local causes, which will be dealt with when considering them separately.

The main glacial groove in which the larger lakes are situated passes from the head of Backdoor Bay along the length of Blue Lake, and sends a branch to the coast by way of Clear Lake and Coast Lake, while the main valley continues as a broad depression filled with morainic material in a north and south direction. (See Plate XLI. Fig. 1.) Two lakes near Cape Barne, Sunk Lake and Deep Lake, appear to be situated in a continuation of the same valley, whilst the other important grooves appear to run more or less parallel with this one, as, for instance, that which the tripartite Terrace Lake occupies. (See Plate XLI. Fig. 2.)

The remaining lakes or tarns are situated in the depressions which are essentially characteristic results of the phase of denudation which is so typically illustrated here. All angles and craggy projections have been rounded by the Great Ice Sheet, and a mantle of morainic matter of varying thickness has been deposited on top of the country rock, while through this mantle bosses of the more resistant types of kenyte project here and there.

Green Lake. Green Lake lies about half-way between Blacksand Beach and

Fig. 1

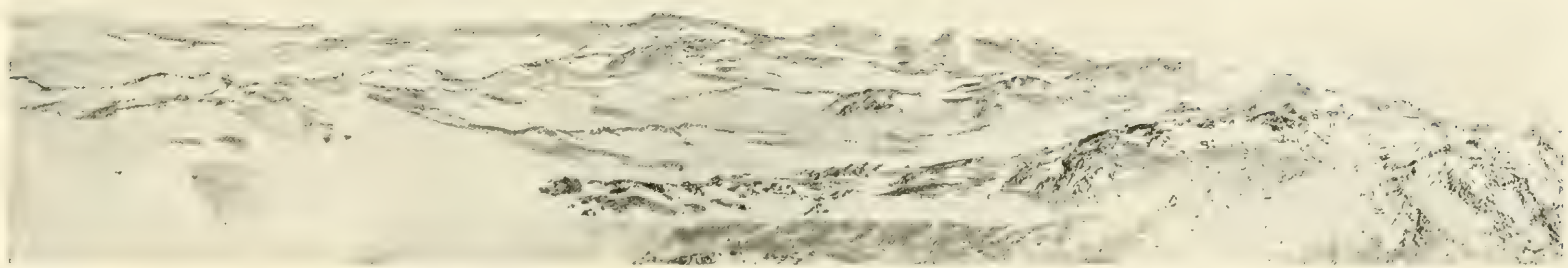

Fig. 2

[*To face p.* 148

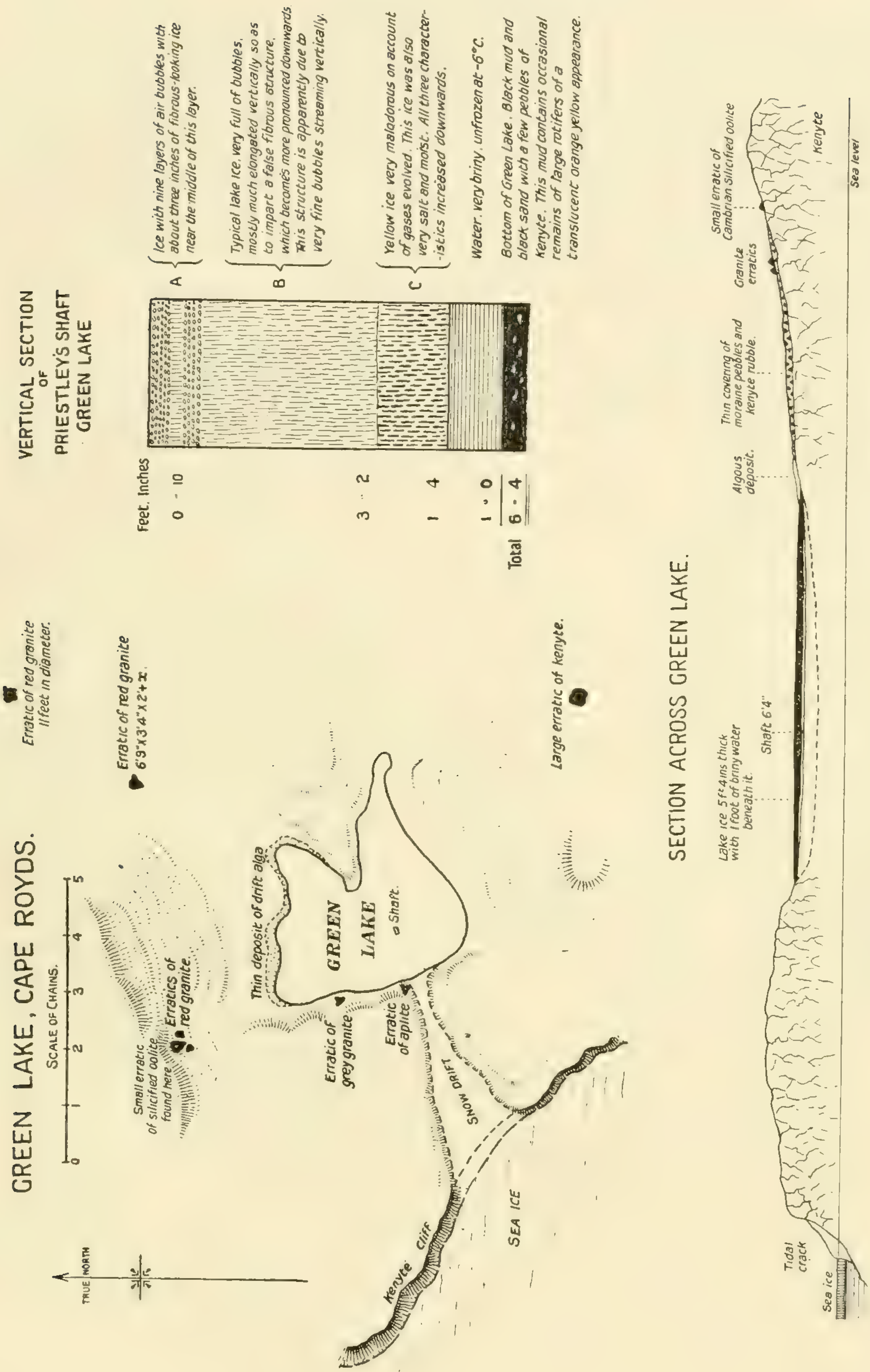
GREEN LAKE, CAPE ROYDS.
SCALE OF CHAINS.
0 1 2 3 4 5
TRUE NORTH
Small erratic of silicified oolite found here.
Erratics of red granite
Erratic of red granite 11 feet in diameter.
Erratic of red granite 6'3"x3'4"x2'+x.
Large erratic of kenyte.
Thin deposit of drift alga
GREEN LAKE
Shaft.
Erratic of grey granite
Erratic of aplite
SNOW DRIFT
SEA ICE
Kenyte Cliff
VERTICAL SECTION OF PRIESTLEY'S SHAFT GREEN LAKE
Feet. Inches
0 - 10
3 - 2
1 - 4
1 - 0
Total 6 - 4
A Ice with nine layers of air bubbles with about three inches of fibrous-looking ice near the middle of this layer.
B Typical lake ice, very full of bubbles, mostly much elongated vertically so as to impart a false fibrous structure, which becomes more pronounced downwards. This structure is apparently due to very fine bubbles streaming vertically.
C Yellow ice very malodorous on account of gases evolved. This ice was also very salt and moist. All three characteristics increased downwards.
Water, very briny, unfrozen at -6°C.
Bottom of Green Lake. Black mud and black sand with a few pebbles of Kenyte. This mud contains occasional remains of large rotifers of a translucent orange yellow appearance.
SECTION ACROSS GREEN LAKE.
Small erratic of Cambrian Silicified oolite
Kenyte
Sea level
Granite erratics
Thin covering of moraine pebbles and kenyte rubble.
Algous deposit.
Shaft 6'4"
Lake ice 5 ft 4 ins thick with 1 foot of briny water beneath it.
Tidal crack
Sea ice
Vertical Scale.
0 50 100 200 300
Feet.
Longitudinal Scale
0 1 2 3
Chains.

Fig. 49

the Hut, and at the foot of the ridges from High Peak in a south-westerly direction. It occupies a fairly shallow basin, completely surrounded, with one exception, by high ground, and must receive the drainings from a relatively considerable area. The one exception is a snow slope towards the sea, which connects with the lake itself, and would serve as an emergency outlet if the thaw-water in summer caused any sudden rise of the waters of the lake.

To the north-east and north it is bounded by ridges which run back to a knotting point near the top of the High Peak, whilst to the east and south-east the ridges and small hills stand some way back from the lake, being separated from it by a very gradually shelving slope, 100 yards broad, of morainic gravel of small sub-angular kenyte fragments with a sprinkling of larger boulders of kenyte and foreign erratics, such as the silicified oolites which we suppose to have analogy with some of the sedimentary rocks at the head of the Beardmore Glacier.

A very slight accession of water or ice to the lake would, if the outlet on the seaward side were blocked up, cause the addition to the lake bed of a considerable area of the shelving plain.

To the south the lake is bordered by ridges running east and west, which end near the sea in a hill of some size, which is marked on the map as Red Flag Hill. On the shore side of this hill is a fairly large snow slope which, being sheltered from the southerlies by the hill itself and on the north by High Hill and its ridges, is one of the most permanent snow-drifts on the peninsula.

On the west the lake is bounded by the sea, and is separated from it by the snow slope already mentioned, and by ridges and knobs of kenyte, which again end in a small rounded hill of a very typical shape. On this side of the lake are two large erratics, one of aplite and one of grey granite.

The lake itself is between 90 and 100 yards in greatest length from north to south, whilst its breadth varies from 100 yards to 45 yards. Its surface is smooth, even glassy, and is traversed in winter by numerous contraction cracks due to the great cold. These cracks after a spell of comparatively warm weather have been observed to become appreciably smaller, and in summer many of them closed altogether and were recemented by regelation in some cases, and in other cases, where the expansion of ice did not quite cause them to join up, by thaw-water from the sides of the crack. The space between the sides of the cracks might also be reduced through the addition of thin layers of ice formed by the freezing of aqueous vapour on the walls of the crack.

On one occasion whilst we were working on the lake we were surprised by a series of reports like pistol-shots and by the appearance of cracks, and the cause was explained when we returned home. After inquiring of the meteorologist we found that the temperature had dropped from $-3°$ F. to $-21°$ F. in considerably less than two hours, so that the cracks were obviously contraction cracks.

The state of the surface changed considerably from time to time, for, although generally rendered glassy and smooth by ablation, yet after a heavy blizzard before the sea was frozen over the ice would be rendered very sticky by the sea spray; in fact the resemblance to a smooth sea ice surface was remarkable. Then, again, after heavy blizzards portions of the lake near the shore would become covered with snow. These drifts would persist for long periods before being removed by ablation, and it was apparently on the underside of these drifts that the very macrocrystalline prismatic lake ice was chiefly observed. Indeed the only places on Green Lake where this form of ice was developed were those which were from time to time covered by these drifts, although on other lakes, notably Clear Lake and Blue Lake, the prismatic ice played a much more important part.

By the contour of its basin there was reason to believe that this lake was nowhere deep, and this belief was afterwards upheld by our trenching work. The total depth of the lake at the spot where the shaft was sunk proved to be 6 feet 4 inches.

Algous Deposit. There is practically no deposit on the southern shores of the lake; to the east it is scattered up the gravel slope for some distance, and pieces occur many feet above the present level, but the sprinkling is very sparse except for short distances along within 2 feet of the ice margin, where it is in places fairly common. The principal deposit is at the north end. Here the width decreases from a belt 12 paces wide at the north-east corner to one 6 paces wide at the north-west corner, and three distinct ridges raised sharply 1, 2, or 3 inches high are well marked at 3, 4, and 5½ paces from the lake border. We believe these ridges to be due to a combination of two causes. The presence of sparse fungus along certain levels on the whole of the north and east side and half the west side of the lake seems to indicate that these definite levels mark the surface of the ice at certain definite periods of recession of the lake. On the other hand, the thick algous deposit at the north, and particularly the north-west end of the lake, tends to the presumption that it is due to the influence of the prevalent southerly winds in the summer when the lake is thawed, and that the ridged appearance is due to wave action, and this view was further strengthened by the way in which during a heavy drift-laden gale in February 1909 the slush in the lake water was piled up on the leeward side of the lakes in similar ridges.

Convexity of Lake Surface. On June 22nd it was noted that a main crack running east and west had appeared at the southern end of the lake, and that the ice to the south of this was tilted up towards the crack at quite a perceptible angle. This convexity of the lake surface was, however, better seen and photographed in some small tarns at Cape Barne, and will be dealt with under the Cape Barne section.

Trenches in Green Lake. On June 24th to 26th, 1908, the first trench was sunk in Green Lake, and temperatures were taken by Murray at every 6 inches during the working. The superficial dimensions of the trench were 3 feet by 7 feet, and the ice proved to be 5 feet deep. There was water under the ice, but the supply was limited, as shown by the fact that when tapped it only rose quickly to within 2 feet 6 inches of the top of the ice, subsequently rising another 6 inches in an hour. This rise was probably due to a slight sagging of the ice, and also to the release of some of the water held under pressure in the bottom 6 inches of the ice, and which would only disengage itself slowly. There was scarcely a foot of liquid left under the 5 feet of ice, and from the slowness with which the water rose in the trench it seems probable that we tapped the lake at one of the few places where a little brine solution was left unfrozen. This brine solution was at the remarkably low temperature of 21° F., and some which we bottled we left to stand for some time, when a ring of oily material about $\frac{1}{2}$ inch thick with a greenish fluorescence was formed at the top. This was formed of tiny globules, each about $\frac{1}{800}$ of an inch in diameter, with a refractive index lower than that of water. It was afterwards masked by a brownish-yellow scum, with a thickness of quite an inch in parts, and a quantity of evil-smelling gas was given off. A quantity of the ooze from the bottom of the lake was also collected.

On Fig. 55 is shown the shaft sunk by one of us in this lake ice in June 1908.

Descending Section.

A. Ten inches of ice with numerous air bubbles. (Four inches of fairly clear ice then a layer of bubbles, 3 inches of ice and then a layer of bubbles, then layers from an inch and a half to half an inch separated by regularly arranged rows of bubbles.)

B. Three feet 2 inches of typical lake ice, very bubbly, and with some bubbles drawn out. A falsely fibrous structure becomes more and more apparent as the lower layers are reached, its cause being apparently streams of very fine bubbles in a vertical direction. The bubbles are fairly uniformly distributed.

C. At 4 feet the ice became yellow and discoloured, with a very unpleasant smell, due to gases given off. It was also very salt and moist, and all three characteristics increased as the work proceeded.

Type A. The structure of this ice is very interesting, and appears to be due to atmospheric conditions. In the late summer, when the lake began to freeze over, the layer of ice formed when the sun was low was at first entirely removed when the sun's rays impinged on the lake at a steeper angle. As the winter approached, and the hours when the sun was high enough to affect the lake decreased, the ice became permanent, and apparently the first permanent layer of ice formed was sufficiently thick to leave a layer of 4 inches at the end of the succeeding day's thaw. During the succeeding period of comparative warmth before another frost set in, and when the first layer of ice was being removed (as thaw at the time was dominating freezing), a number of gas bubbles, disengaged by the decay of the organic matter at the bottom of the lake, rose towards the surface, and accumulated under the sheet of ice. The succeeding frost added to the bubbles owing to the air and gas in solution in the water being expelled mostly above or below the new layer of ice formed. This frost was evidently of a sufficient duration and power to add 3 inches of permanent ice to the lake covering. The same process was repeated again and again, with the difference that as the non-conducting layer of ice on top of the lake increased in thickness, and the remaining solution became more saline, the frosts, although becoming more severe as the autumn approached, were unable to effect as much freezing of the water as the earlier frosts, and thus each day's layer of ice decreased in thickness until the daily variation of temperature ceased to have effect, and the second uniform type ice of ice (Type B.) began to form.

Type B. This was the ordinary type of lake ice of uniform and slow growth. The noticeable fact about the ice between 2 and 3 feet below the surface was the gradual inception of the pseudo-fibrous structure and its analogy to sea ice. This is, however, natural, for it is presumably due to the same reason as the fibrous structure in sea ice, namely, to the extrusion of the salt as a highly concentrated brine solution in a series of little globules, forming thermometer-shaped tubules, outlining the ice prisms.

Type C. The discoloured and odoriferous nature of this last ice is due to the ice being saturated under pressure with a strong solution of gases in brine, the most prominent ingredient in which solution is sulphuretted hydrogen, probably produced by the decay of the algous material so common in all the lakes at Cape Royds.

Mawson found that some of this brine solution froze at as low a temperature as 50° F. below freezing point.

Temperatures. A series of temperatures taken in the trench is as follows. Mean air temperature, June 24th, 25th, and 26th, was −7·2° F.

	June 24, 1908.	June 25, 1908.
Surface	−12·5° F.	−10·5° F.
6 inches	−10·5° F.	− 9·0° F.
12 ,,	− 8·0° F.	− 7·0° F.
18 ,,	− 4·0° F.	− 5·0° F.
24 ,,	− 0·0° F.	− 3·5° F.
30 ,,	+ 3·5° F.	− 1·5° F.
36 ,,	+ 6·5 F.	+ 1·5° F.
42 ,,	+ 9·5° F.	+ 6·0° F.
48 ,,	...	+10·0° F.
54 ,,	...	+15·5° F.
60 ,,	...	+19° F.
Brine solution	...	+22° F.

The comparison shows a general but by no means uniform adjustment to the air temperature.

Second Trench in Green Lake, July 31st, 1908. The section was as in the first trench, but the yellow ice started at 2 feet 6 inches and the ice was almost 5 feet 6 inches thick, reaching to within 3 or 4 inches of the lake bottom.

In making this section two master cracks were used to lighten the labour at a place where they crossed at right angles, and incidentally it was proved that they were open right to the bottom of the lake, as the trench was scarcely 3 feet deep when the brine solution oozed up very quickly along both of the cracks, and it was necessary to desist and cut a trench within a trench. The work was much interrupted by other duties, but the bottom 18 inches was taken out on August 6th, when the section exposed was as follows:—

A. Ten inches of laminated ice as in Trench 1.

B. Twenty inches of colourless ice, opaque, with fine bubbles and salt extrusions.

C. Thirty-six inches of ice similar to above, but of yellow colour and very malodorous.

After the ice was broken through the water rose only 24 inches in the trench. Specimens of ice from the sides of the shaft at different depths were examined by Mawson, and bottles of the brine solution were collected. The latter was similar in colour and consistency to that of the former trench, but nothing like as much gas was given off.

It seems likely, therefore, from consideration of this last fact, and the little height to which the water rose in the trench, that this second trench was cut down into the same reservoir of the brine which we tapped last time, that this solution is the last concentrate produced from the water of the whole lake, and that the part of the lake in which we trenched is the deepest.

Temperatures taken on July 1st were—

Surface (1 inch in)	$-23°$ F.
$9\frac{1}{2}$ inches	$-23°$ F.
19 ,,	$-18°$ F.
$28\frac{1}{2}$,,	$-13°$ F.
38 ,,	$-7{\cdot}7°$ F.
$47\frac{1}{2}$,,	$-2°$ F.

The temperature of the brine solution taken immediately we broke through the ice on August 6th was $-17°$ F., probably one of the lowest temperatures ever recorded for so large a body of water under natural conditions.

Clear Lake. Clear Lake is situated to the north-west of Blue Lake, and in the western fork of the northern continuation of the Blue Lake Valley. Its name was given to it because of the remarkable clearness of the upper layers of ice. There were few striking topographical features immediately near the lake, but one was a steeply-rounded kenyte knoll, whose sides sloped rapidly down right underneath the lake, and a few yards out from which, to judge from the contour of the lake basin, the deepest part of the lake should be situated, for everywhere else the slope of the lake shores was quite gentle. This steep rock slope is seen to the extreme left of the lake shore in the photograph, Plate XLII. Fig. 2. It was near this knoll, and with the object of tapping the deepest part of the lake, that our first trench was made.

Another important feature about Clear Lake was the terraced condition of the slopes immediately above the present lake level. At the north-west end especially there were well-marked traces of terraces in the morainic gravel; these terraces were each from 1 to 2 feet high, and may mark periods of rest during the recent recession of the lake.

First Trench, cut on March 30th. This trench was, as mentioned above, near the kenyte knoll, and there proved to be then only 4 feet 3 inches of ice. The top 4 inches of ice is coarsely crystalline, with wide opaque divisions between the more or less hexagonal prisms, and may be the result of the conversion into ice of the lower portions of snow-drifts by the thaw, such conversion having taken place in crystalline continuity with the prismatic ice formed each year by the re-freezing of the water of the lake. The individual crystals are not at all regular in shape, being often most intimately interlocked, and frequently arranged in curious patterns, with a peculiar radial structure, as if they had grown outward from a central prism or group of prisms.

This roughly radial arrangement of prismatic ice seems quite common in the older moraines on the Ferrar Glacier, and there is no doubt about its origin there, for it is formed in almost every case by the freezing of the thaw-water after a boulder has thawed its way down below the surface. The Western Party saw in such cases the process in all stages, from the boulder that is just commencing to sink in, to the rock moraine where not a boulder is to be seen, and their former presence is only indicated by these radial patches of prismatic ice in coarse hexagons. The structure seems here to be distinctly a secondary one, for although in a few cases hexagonal plates of ice were observed on the surface of thaw-water lying in hollows in the ice, it was far more usual for the first layer of ice at any rate to form as small acicular needles radiating from every projection, and the ice sheet newly formed presented to the eye an apparently homogeneous structure.

It seems therefore that in this latter case at any rate some molecular rearrangement takes place, with extrusion of air as minute air bubbles outlining the crystals. It is suggested that this is a secondary structure superinduced upon ordinary thaw-water ice. In the case of the prismatic ice on the lakes it was more difficult to see any preliminary stages. The surface ice was either ordinary thaw-water ice, or the hexagonal prismatic ice was there in its finished condition. It seems probable that in the lakes, where the freezing is undisturbed by the movement of the water, the ice forms in vertical hexagonal prisms, as was undoubtedly the case in the Narrows of Blue Lake, where the separate prisms could be traced right through the ice. The thawing of the snow-drifts then proceeds in crystalline continuity with the lake ice, and the resultant prisms are sharply outlined by air globules forced out between the crystals. Some explanation of this kind is necessary to account for the domed and uneven surface and great thickness of this variety of ice in the southern half of the Blue Lake. This change, of whatever nature it may be, always takes place in the snow of snow-drifts where there is little lateral pressure, and it is quite conceivable that if a molecular change took place, resulting in the formation of well-marked hexagonal prisms, it should be accompanied by the extrusion of the air from the ice, and in this air being forced into position as minute bubbles along the lines of natural weakness, that is, between the boundary faces of the different crystals.

The top layer of prismatic ice, 4 inches in thickness, as just described, was followed by 3 feet 8 inches of ordinary lake ice with some air bubbles. Beneath the ice was 13 feet of slightly brackish water.

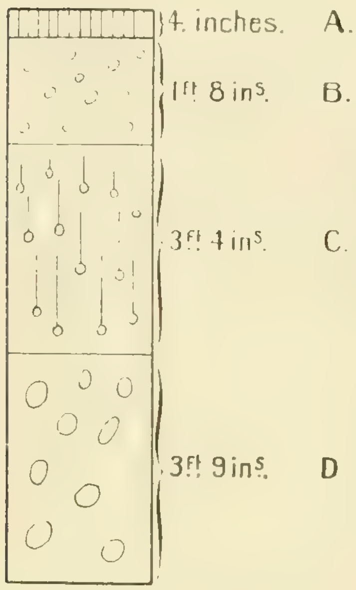

Fig. 50

The bottom material proved to be a deposit of black, evil-smelling mud containing diatoms, some of exceptionally large size, pieces of decayed algæ of small species, several living species of Rotifera and Tardigrada (Water-bears), and some obscure bodies which may possibly be spores, but have not been determined. This deposit was about 6 inches thick, and was succeeded by the typical morainic gravel.

Second Trench in Clear Lake, April 14th, 15th, 16th.

A. 4 inches of prismatic ice.

B. Ice with air and gas bubbles in it 1 foot 8 inches.

C. 3 feet 4 inches ice with drawn-out bubbles giving prismatic structure.

D. 3 feet 9 inches ice with bubbles.

The difference of thickness of the ice in the two trenches is easily accounted for by the presence near the first trench of the large knoll of intensely black kenyte, the influence of which must have been very considerable in regulating the amount of thaw which had taken place during the summer just past.

One other feature of this lake worthy of mention was the occurrence at a depth of 2 or 3 feet of what was apparently a well-defined ablation-rippled surface with the depressions between the ripples still filled with snow, and also at the same level of strings of what we called snow-tabloids, lenticles of air in the ordinary lake ice partially filled with a loose powdery ice.

Temperature at the Second Trench at Clear Lake.

Mean Air Temperatures, April 15th	$-10{\cdot}4°$ F.
„ „ „ 16th	$-16{\cdot}5°$ F.
„ „ „ 17th	$-21{\cdot}0°$ F.

FIG. 1.

FIG. 2. VIEW OF CLEAR LAKE, NEAR CAPE ROYDS, LOOKING TO N.W.
[Photo by T. W. E. David

FIG. 3

FIG. 4. BLUE LAKE, NEAR CAPE ROYDS
Looking north-westerly. In the middle distance is the dyke which almost isolates the northern and southern parts of the lake. The esker mounds are on the near side of the gap in the dyke, "the narrows"

FIG. 5. ESKERS OF BLUE LAKE, CAPE ROYDS
Showing adjacent ice slope formed out of snow-drift by a process of secondary crystallization
[Photo by T. W. E. David

FIG. 6. COAST LAKE, LOOKING SOUTH-EASTERLY
The bottom of this lake is covered with algal peat

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	April 15th.	April 16th.
4 inches	− 6° F.	...
14 ,,	− 2° F.	...
21 ,,	0° F.	...
28 ,,	+ 2·75° F.	...
35 ,,	+ 5·7° F.	...
42 ,,	+ 8·0° F.	...
49 ,,	+ 10·8° F.	...
56 ,,	+ 13·56° F.	...
63 ,,	+ 16·0° F.	...
66 ,,	+ 15·8° F.	...
74 ,,	...	+ 17·7° F.
80 ,,	...	+ 20° F.
90 ,,	...	+ 22·5° F.
96 ,,	...	+ 25·7° F.
102 ,,	...	+ 28·8° F.

Surface temperature on April 16th was	− 12° F.
Water, 1 foot from bottom	+ 35° F.

Below the ice at this point there was 4 feet of water, the lake here being only 13 feet deep. The layer of ice from 2 feet down to 5 feet was quite fresh, but that tested both from above and below these levels was slightly brackish. There is much less alga in this lake than in Green Lake and Coast Lake, and both water and ice are appreciably purer, although there is even here enough decaying organic matter to render the smell of the mud at the bottom very disagreeable.

Blue Lake. This lake is situated in the main glacial valley of the Cape Royds Peninsula, being really part of the boundary between the peninsula and the mainland of Ross Island. Its southern end is partially blocked by a knoll of kenyte with large snow-drifts on either side of it, while on the southern side of this ridge lie slopes of *névé* and drift snow, covered with a layer of frozen spray, which form part of the ice foot of Backdoor Bay.

On the eastern or Erebus side the lake is bounded along its length by the snow slopes of the mountain, which are interrupted at intervals by terrace-like accumulations of morainic matter. To the south-east these snow slopes are broken, and bounded by several strongly marked hills of kenyte, to the largest of which the name of Sentinel Peak was given. South of this peak is a dried-up lake, the bed of which is covered with an accumulation of soil containing diatoms and algæ. The western side of the lake is bordered by the kenyte of Cape Royds, knolls of massive rock standing out between slopes covered more or less thickly with morainic debris, while here and there snow-drifts repose in semicircular hollows between divergent ridges. These drifts are sometimes of sufficient importance to be underlain by considerable *névé* deposits.

The lake is divided into two distinct portions of about equal size by two sharp ridges of kenyte, which traverse it from east to west, and have a gap of only 10 to

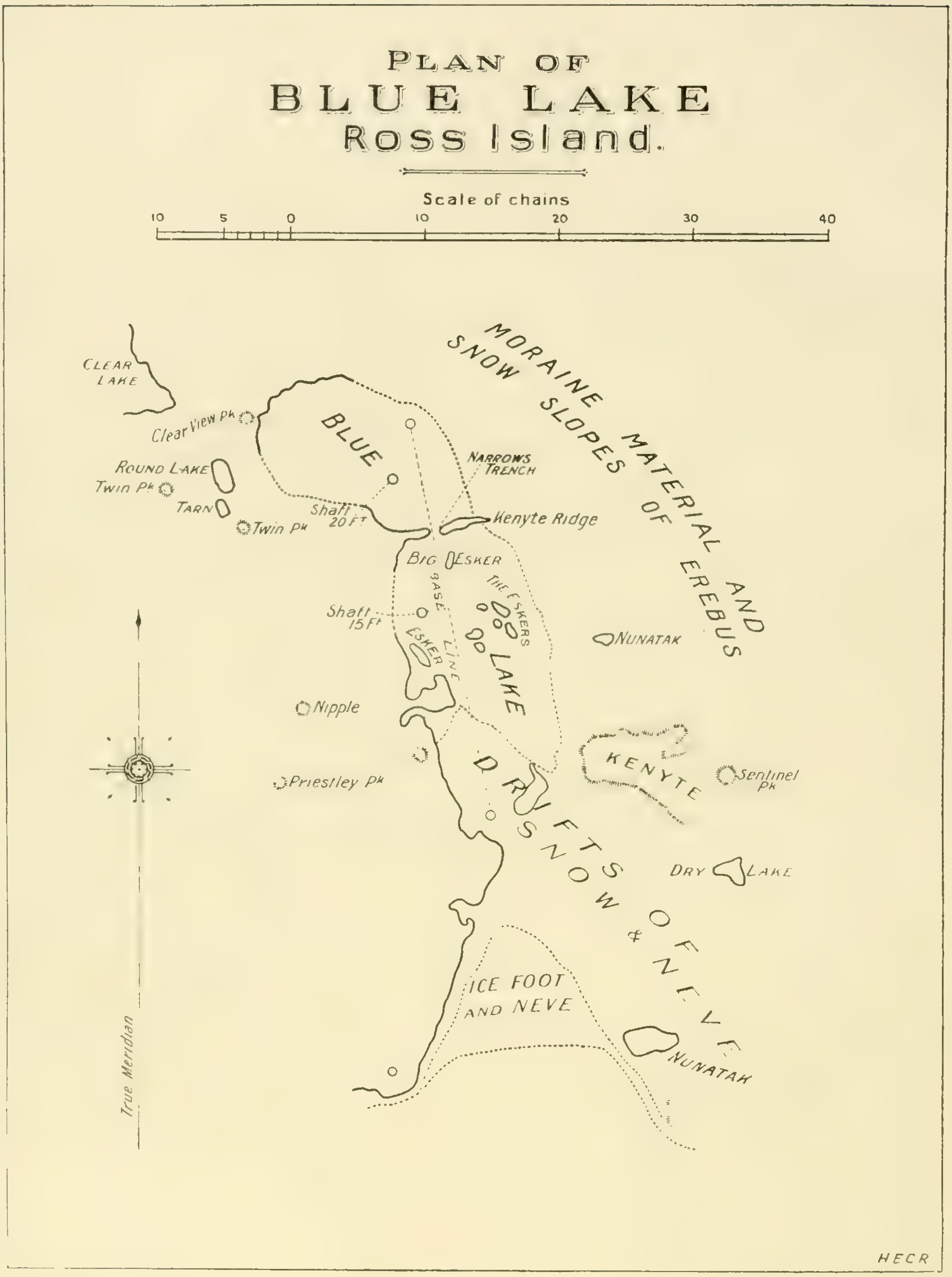

PLAN OF
BLUE LAKE
Ross Island.
Scale of chains
10 5 0 10 20 30 40
CLEAR LAKE
Clear View Pk
Round Lake
Twin Pk
Tarn
Twin Pk
BLUE
Shaft 20 Ft
Narrows Trench
Kenyte Ridge
MORAINE MATERIAL AND SNOW SLOPES OF EREBUS
Big Esker
Base Line
The Eskers
Shaft 15 Ft
Esker
LAKE
Nunatak
Nipple
Priestley Pk
DRIFTS
KENYTE
Sentinel Pk
SNOW & NEVE
Dry Lake
ICE FOOT AND NEVE
Nunatak
True Meridian
HECR

FIG. 51

15 yards between them, and which are probably the remains of a dyke of kenyte more resistant than the other rock from which the valley has been scooped. In the southern half of the lake there are a group of circular eskers of morainic gravel; one or two of them are double eskers, with their long axes directed north and south. (Fig. 45, Chapter VI.)

Plate XLII. Fig. 5 illustrates these small esker mounds, which are from about 5 to 8 feet high. Adjacent to them the surface of the lake ice has been added to by the formation of coralloidal ice out of the lower portions of snow-drifts.

First Trench, July 8th to July 20th. This trench was sunk in the southern half of the lake. There proved to be 15 feet of ice of very uniform character resting on an ice-cemented breccia of kenyte and erratic gravel. The ice was free from salt, and this is remarkable, considering that the lake is swept from end to end by the southerly gales blowing from over McMurdo Sound. During the summer 1907–8 this portion of the lake does not appear to have been melted, and the only effect of the thaw from 1908 to 1909 was to make the hexagonal prismatic ice on top very rotten, and to cause the individual crystals to be separated, as the thaw proceeded with greater speed along the opaque boundaries of the prisms than elsewhere. There are evidences which tend to show that the lake has been partially or wholly melted during exceptionally mild seasons. The following section illustrates the structure of the ice in our main shaft at Blue Lake (Fig. 52):—

A. A layer a few inches thick of clearly crystalline ice, generally showing a hexagonal prismatic habit, but with many of the prisms very much distorted in shape, and with strong white partings between the crystals. This type appears to be separated from the ice beneath it by a brecciated and strained layer, possibly caused by differential horizontal contraction and expansion between the types A. and B.

B. Clear pure ice of remarkably uniform character, though the air bubbles were much more numerous for a foot or two below the prismatic ice than at deeper levels.

The main characteristic of the ice of this lake was its conchoidal fracture, which was very marked, and in the lower portion of the ice the fracture planes of the fragments were generally indicated by fine concentric flutings. A coarse radial ribbing was also common across these same faces.

The ice was also traversed by fracture planes, sometimes several inches in diameter, and generally roughly arc-shaped, which were very strongly recemented, so strongly that when struck against the shaft of the pick the ice showed a marked tendency to break at an angle with the former fracture plane rather than along it. Three or four types of this ice were distinguishable, though only one type could be claimed as being restricted to a particular level.

The first type was a clear ice with numerous bubbles about an eighth of an inch in diameter, which, although met with farther down the shaft, was decidedly more common nearer the surface at a depth of from 1 to 2 feet below the hexagonal prismatic ice.

The second and most common type was a clear ice with very few bubbles, the latter of various sizes; it forms by far the greatest amount of ice present in this portion of the lake, and is frequently traversed by the fracture planes mentioned above.

A third type, occasionally met with, had bubbles of similar size and frequency to the last, but with the bubbles drawn out into tubes, although the direction from

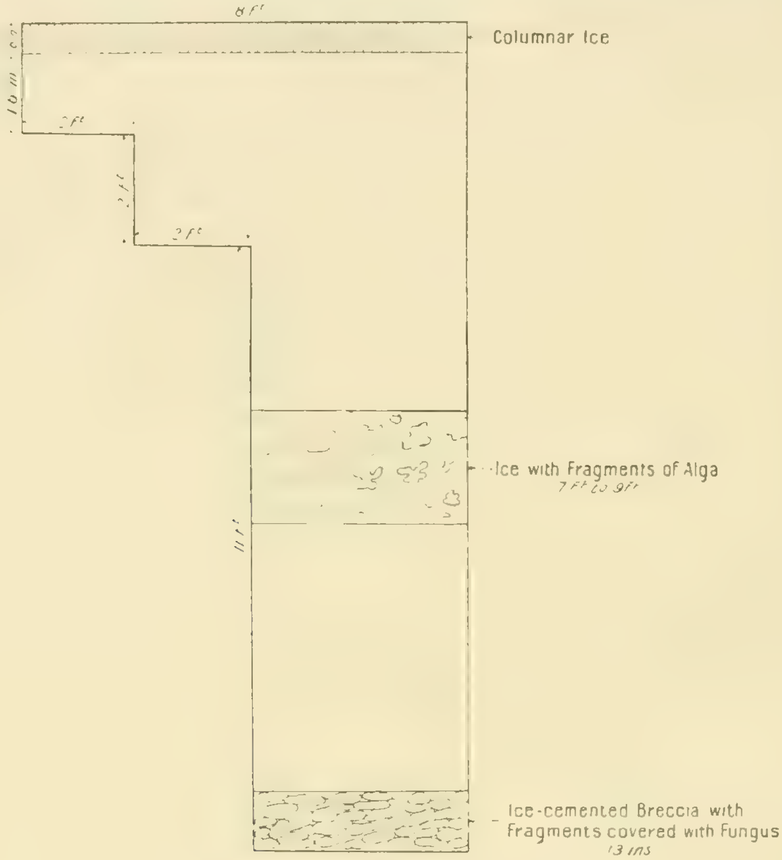


Fig. 52. Section Blue Lake Trench

which they had elongated was sufficiently indicated by a bulging of the tube at the bottom, so that the bubble and tube bore a strong resemblance to a thermometer.

The last type observed was only in local patches about 6 inches square. In it the bubbles appear very similar to those of the last type, but are much smaller and more numerous, giving quite a lined structure to the ice. This type frequently appeared quite suddenly above perfectly clear ice. On examination Mawson found these elongated bubbles to be hexagonal in shape like negative ice crystals. In one or two cases these drawn-out bubbles ended abruptly against one of the fracture planes already noted.

C. From 9 to 11 feet the ice contained a quantity of living alga with living rotifers and water-bears, and frequently around the pieces of alga we could observe a circular patch of ice which was quite opaque, evidently owing to secretion of some substance from the plant.

D. At 15 feet bottom was reached, consisting of a breccia of kenyte and gravel formed from this rock, together with numerous small erratics cemented by ice, and containing a considerable quantity of both living and dead alga. One fragment worthy of note was an angular piece of trachyte, coated on both sides with a layer of growing alga. This alga, when examined by Murray, yielded numerous colonies of a smaller unicellular alga with abundant chlorophyll, several rotifers and water-bears, and a mite.

It seems that the bottom of the layer C. must be the downward limit of the effect of the summer thaw of recent years, and it must be very unusual for the thaw to extend even to that depth, for within the range of our experience there has been very little even of surface thaw at this lake, the removal of the surface of the ice being almost wholly confined to ablation of the nature of evaporation. Unless melting takes place from the bottom upwards, it must be very rare for the whole of the lake ice to be thawed, and the presence of living algæ and microzoa at this depth is therefore very interesting, for the period of suspended animation in both plants and animals must extend over many seasons. A very mild summer indeed would be necessary to cause much of the Blue Lake ice to melt, for this lake is of much greater bulk than the others of the peninsula. A factor still more potent to preserve the ice is the snow-covered nature of the slopes immediately bordering the lake. It is only locally in the shallower parts of the lake, where the insolation of the kenyte is pronounced, that any large amount of ice is thawed.

OTHER TRENCHES IN BLUE LAKE

Trench sunk in the Narrows of Blue Lake, July 20th. The ice was only 3 feet thick, and the section was as follows :—

A. 3 inches of ice, with very coarse gas bubbles partially filled with powdery ice.

B. 6 inches of ice, in which the bubbles were drawn out into fine capillary tubes.

C. 2 feet 3 inches of very clear and compact ice, with conchoidal fracture, and apparently very pure and free from bubbles.

Through all three varieties a coarsely prismatic structure was very marked, the ice being crystallised in long hexagonal prisms about half an inch in greatest transverse diameter, the outlines of which could be traced through the two upper types of ice, and the first 6 to 18 inches of the third type. This ice must have been the product of the freezing of last year's thaw-water, for even in the summer 1908–9 (an exceptionally rigorous one) this portion of the lake ice was completely melted. Mawson reports that the ice at this spot is slightly saline.

Temperatures.

Surface	− 26·5° F.
Depth—1 foot	− 21·5° F.
,, 2 feet	− 16·0° F.
,, 3 ,, ... (bottom)	− 12·5° F.

Towards the close of the winter Brocklehurst sank a trench in the northern half of Blue Lake. Few details are to hand about the section, but the chief differences from the ice of the trench in the southern area seems to have been the extension of the markedly prismatic ice to 3 feet 6 inches below the surface. The ice at this spot was 20 feet thick, and underneath it was 2 feet of water.

On April 3rd a small combined trench and bore, put down a short distance to the west of what was later the site of Brocklehurst's trench, gave a thickness of 2 feet 9 inches of ice, and a depth of 7 feet to the lake, which there had a gravelly bottom, that is, at that time there was a depth of 4 feet 3 inches of water under the ice at this part of the lake.

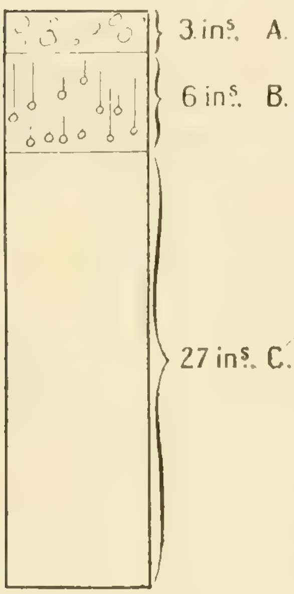


Fig. 53

Thus between April 3rd and October 17th we have almost certain evidence that in this portion of the lake 17 feet 3 inches of ice was formed, as Brocklehurst's shaft, completed at the latter date, was sunk in ice throughout its whole depth of 20 feet, whereas on April 3rd there was probably a thickness there of only 2 feet 9 inches of ice.

Coast Lake. Phenomena due to ablation were very marked at this lake, large quantities of algæ projecting several inches above the surface, as the original surface of the ice which formerly enclosed them had been lowered by evaporation. A peculiar feature induced by the ablation was the production of a secondary rippled surface on the ice. This rippled surface was, during the early summer days, before the melting of the lake, much accentuated, the thaw acting along the bottoms of the ripples far faster than it did along the ridges. A similar phenomenon on a much larger scale was very commonly seen on the Ferrar Glacier.

Trenches sunk in Coast Lake. These trenches brought to light another peculiar feature about Coast Lake. As will be seen from the sections, the whole or most of the lake bottom was covered with a thick deposit of a kind of algous peat, thickest at the centre of the lake, and gradually decreasing as the outside was approached.

Detailed Section of Ice.

A. 18 inches of cloudy looking ice, with regular layers of bubbles at intervals of an inch to half an inch. In most of the lower layers the bubbles tended to become drawn out and thermometer shaped, a tendency that increased with the depth. The layers were less well defined and more numerous in the

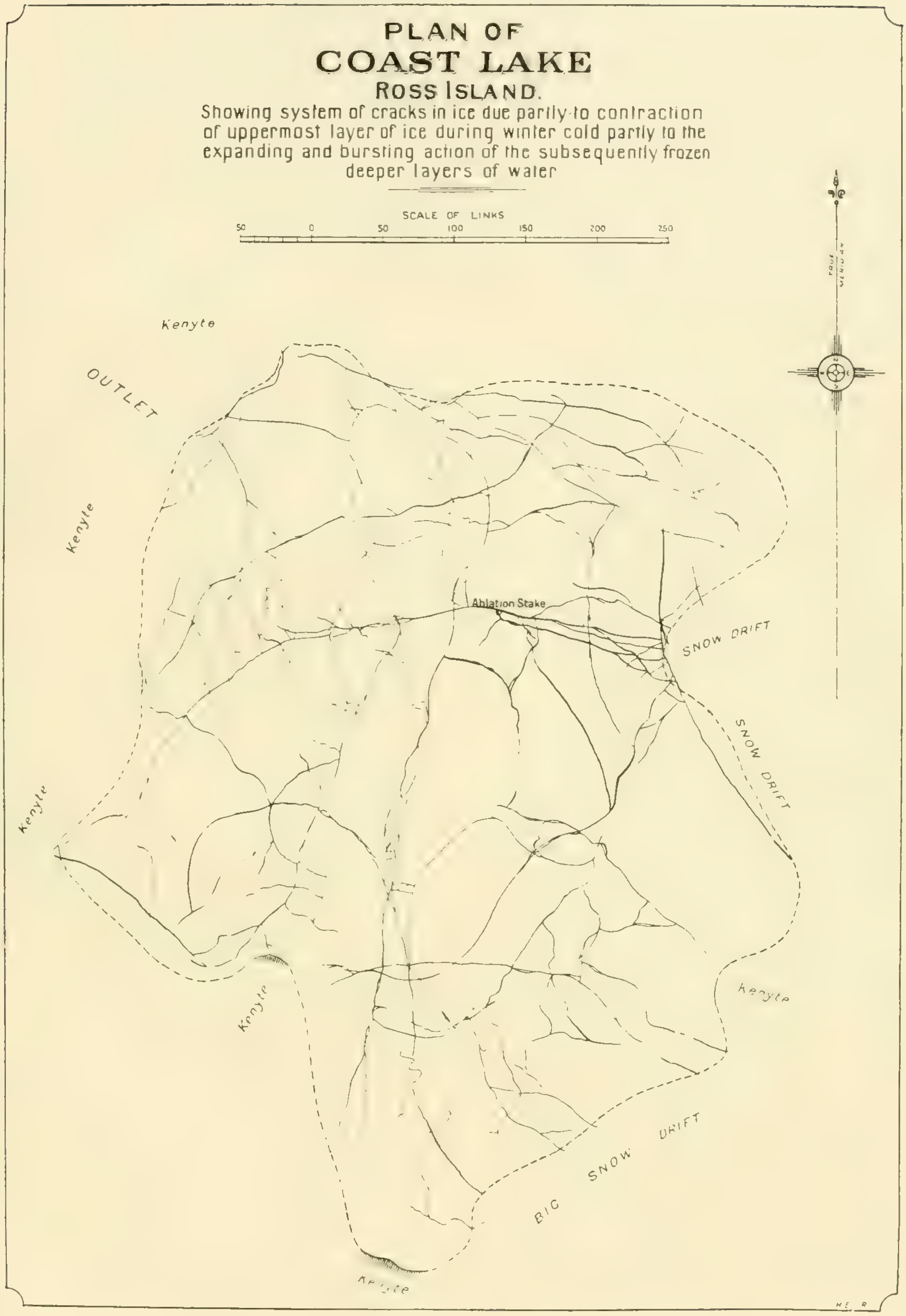

PLAN OF
COAST LAKE
ROSS ISLAND.
Showing system of cracks in ice due partly to contraction of uppermost layer of ice during winter cold partly to the expanding and bursting action of the subsequently frozen deeper layers of water
SCALE OF LINKS
50 0 50 100 150 200 250
Kenyte
OUTLET
Kenyte
Ablation Stake
SNOW DRIFT
SNOW DRIFT
Kenyte
Kenyte
Kenyte
BIG SNOW DRIFT

FIG. 54

lower few inches. This type of ice shows marked resemblance to type A. in Green Lake, and is probably produced in a similar way.

B. From 18 inches to 2 feet the ice was of a similar type, but yellow and malodorous, and again the resemblance to the section of Green Lake is to be remarked.

C. A layer 9 inches thick of a kind of algous peat, which proved on melting to be composed of numerous small fragments of decayed alga.

D. The layer C. was followed by a thin layer of ice fairly free from alga, and containing a series of small snow-tabloids and partially ice-filled gas bubbles. This layer in its turn was succeeded by 1 foot 3 inches of regularly stratified layers of the algous peat, separated by very thin seams of fairly clean ice, and ending in a layer, about 4 inches thick, which contained rather more grit than the upper layers. The presence of this peat was explained by the abundance of living alga scattered through the ice at different levels.

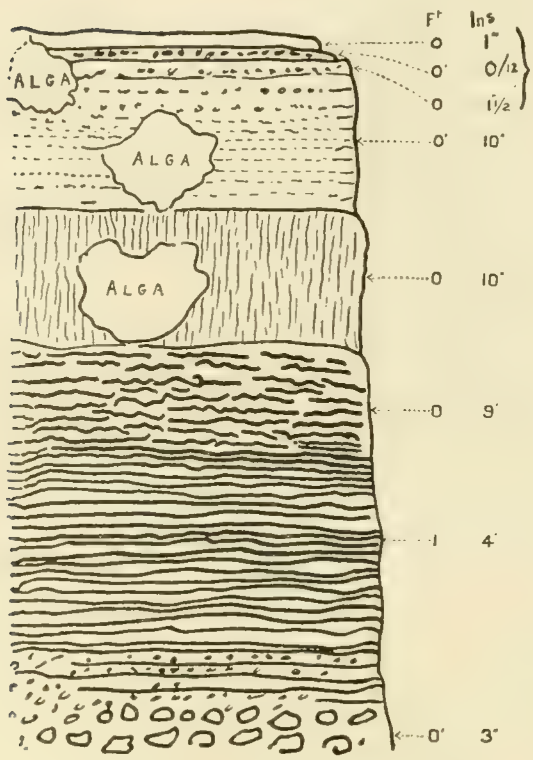


FIG. 55. Section of ice and algous peat at Coast Lake near Cape Royds

When sinking this trench a main crack was used as one side of the trench in order to accelerate the work. This crack had originally been an inch and a half in diameter, but had been filled, with the exception of an eighth of an inch, with ice in extremely thin vertical layers, formed evidently earlier in the autumn by condensation of the vapour from the water and salt ice beneath. The crack only extended, at the time the trench was sunk, to a depth of 18 inches; beyond that depth it had evidently been entirely filled, either by the ice from this vapour, or from the oozing up of the brine along its length.

Temperatures.

Air temperature	− 4·5° F.
Surface	−15·5° F.
1 foot	−16·0° F.
2 feet	−16·0° F.
3 feet	−15·0° F.
3 feet 10 inches	−12·5° F.

PLATE XLIII

Fig. 1. PONY LAKE, CAPE ROYDS, LOOKING EASTERLY

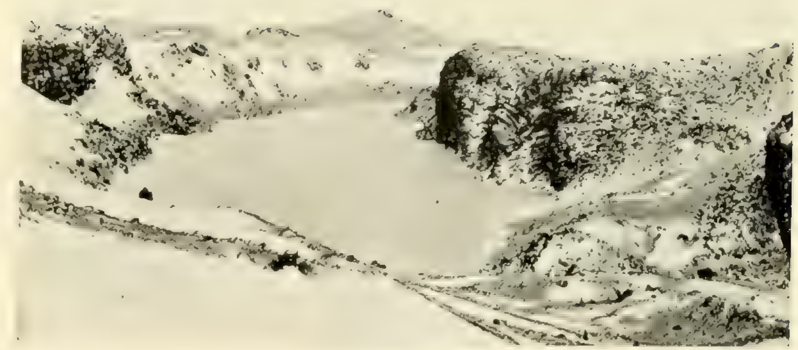


Fig. 3. DEEP LAKE

Fig. 2. SNOW TABLOID, TERRACE LAKE

Fig. 4

[*To face p.* 164

This series of temperatures was taken at a time when there had been a sudden and considerable rise in the air temperature, and the apparent inconsistence in the temperatures respectively at 1 foot and at the surface is due to the gradual adjustment of the ice temperatures to the new air temperature. The slowness of heat conduction in the lake ice is very well seen here.

Other Trenches in Coast Lake. April 1st. A bore was put down in Coast Lake along the main crack which formed one side of the trench already described, but a few yards farther from the sea and as near to the centre of the lake as possible. There was 2 feet 3 inches of ice, and the depth of the lake was nearly 4 feet. Very little bottom material was obtained. It was in this bore that a bamboo was fixed a few days later, by means of which the amount of ablation from the lake surface during the next few months was measured.

August 10th. A second trench was put down in Coast Lake. The section was very similar to the preceding, and the alga was struck at 1 foot 6 inches and proved for a foot.

August 11th. A third trench was sunk in Coast Lake, when the algous peat was reached at 2 feet 3 inches, and again proved to be more than a foot thick.

During the spring powerful ablation exposed large stretches of this algous peat deposit near the edges of the lake, so that there is reason to believe that almost the whole of the lake bottom is covered with it. The ice of Coast Lake was traversed by a series of contraction cracks, and the surface of the ice was distinctly convex in places. These cracks opened on cold nights with a sharp loud tang, something like the sound made by the cracking of a stockwhip. Mawson estimated that on June 20, 1908, the minimum amount of contraction of the ice as shown by the cracks was 10 inches in a horizontal distance of 150 yards. The contraction amount was evidently much more, but was masked by the secondary addition of ice to the walls of the cracks, derived from vapour steaming up from the water below.

Round Lake. This small tarn occupies a depression between Blue Lake and Clear Lake, but is of the Green Lake and Coast Lake type. A trench was sunk in it on April 17th. At about 2 feet 3 inches we reached the bottom, and broke through a thin layer of decayed alga into the gravel beneath; for some time before reaching this layer, however, its presence was advertised by the unpleasant smell of the gases liberated and the yellow colour of the ice. The ice all through was characterised by a streaky appearance, owing apparently to the extrusion of salt solution globules between the crystals.

Temperatures.

Surface	−15° F.
Depth 6 inches	−12° F.
,, 1 foot	− 9° F.
,, 18 inches	− 5° F.
,, 24 ,,	0° F.
Air temperature	−25° F.

Pony Lake. This small lake, close to which our winter quarters were established at Cape Royds, measured about 9 chains by 3 chains. Its surface is about 15 feet above sea-level. The water was somewhat saline, partly through salt spray from the blizzards, partly through mineral matter dissolved out of the surrounding kenyte lava. It occupied a shallow rock basin excavated by the ice of the Great Ice Barrier. The ice of this lake showed about $1\frac{1}{2}$ inches of ablation between April 18, 1908, and June 12 of the same year. The whole of the ice of this lake, which is quite shallow, melted during the summer. At the time of our arrival early in February 1908 the lake surface was recently frozen over.

The general appearance of Pony Lake is shown on Plate XLIII. Fig. 1.

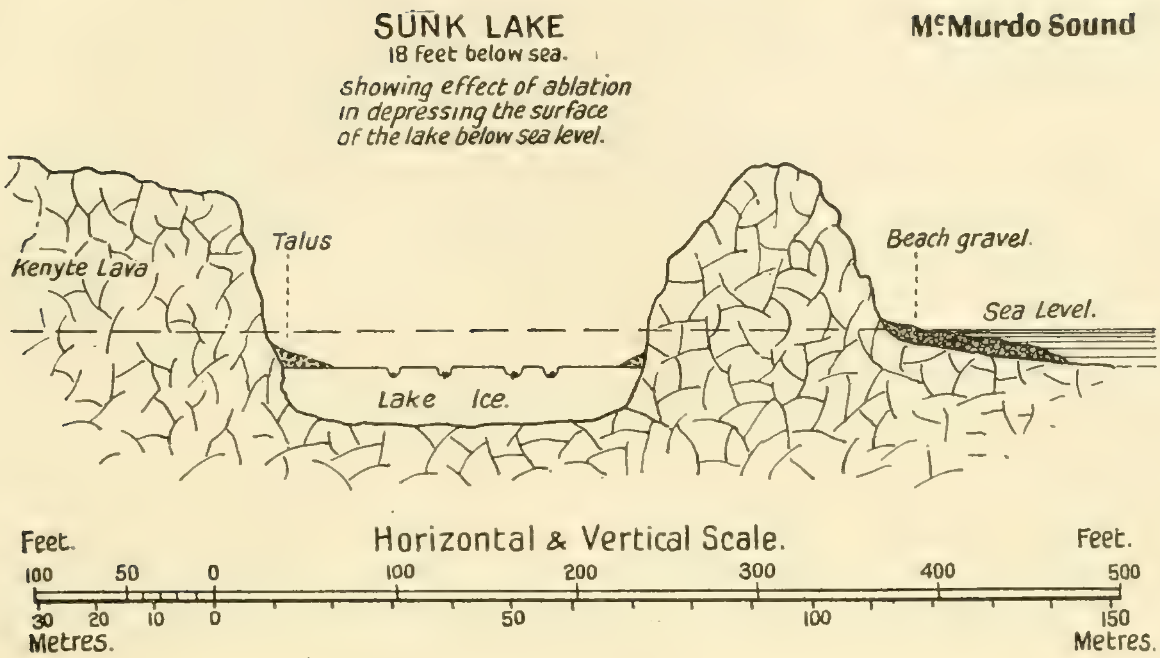
LAKES AT CAPE BARNE

As the Cape Barne lake district was 2 miles or more away from our Hut at Cape Royds, detailed work was impossible during the winter. During the spring and summer also sledging preparations and sledging prevented our spending much time in scientific work near the camp, and consequently the lakes were not examined nearly as carefully as those at Cape Royds. During our few visits to Cape Barne the lakes were roughly surveyed for adding to the Plane Table Map. Most of the notes on the Cape Royds lakes would apply to those at Cape Barne, at any rate as far as superficial characteristics were concerned. The largest of these lakes were situated in roughly parallel grooves running N.N.W. to S.S.E., and were named by us Terrace Lake, Deep Lake, and Sunk Lake; the smaller circular depressions, when ice-filled at all, were occupied by small tarns.

It was in one of these small tarns that our best example of the formation of a convex surface was seen. The method of formation seemed to be here as follows:—

The ice expanding as it was formed was forced upwards in the centre, and thus a convex surface was produced; this was exaggerated by the formation of each successive layer, until at last the pressure on the top layers was sufficient to overcome the cohesion between the molecules, and a crack resulted. As the process continued this crack would become wider and wider, and would affect a greater thickness of ice, until, when finally the water of the lake was all frozen, the lake would be occupied by a bi-convex lens of ice with cracks, wide at the top and tapering away to nothing below. In some cases this process was modified by the cracks traversing the whole depth of the ice and tapping the water, when recementing of the cracks took place. This convex surface would sometimes be partially or completely removed by ablation during the winter, and a level ablation-rippled surface substituted.

Terrace Lake. Terrace Lake occupies the longest valley in the Cape Barne district. It is about 700 yards long, and is almost divided into three lakes by two hard ridges of kenyte. Its surface is about 180 feet above sea-level. It is sur-


SUNK LAKE
18 feet below sea.
showing effect of ablation in depressing the surface of the lake below sea level.
McMurdo Sound
Kenyte Lava
Talus
Beach gravel.
Sea Level.
Lake Ice.
Feet.
Horizontal & Vertical Scale.
Feet.
100 50 0 100 200 300 400 500
30 20 10 0 50 100 150
Metres.
Metres.

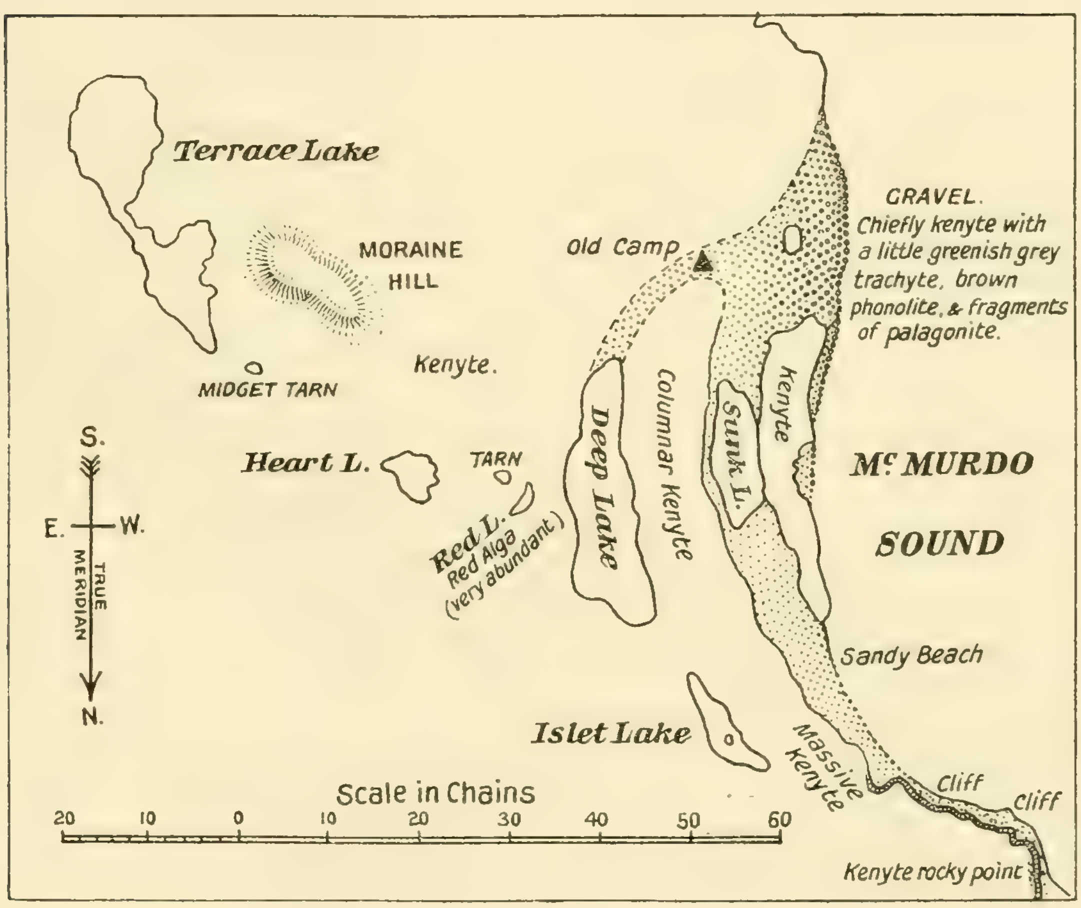

Terrace Lake
MORAINE HILL
MIDGET TARN
Kenyte.
Old Camp
GRAVEL.
Chiefly kenyte with a little greenish grey trachyte, brown phonolite, & fragments of palagonite.
S.
E.
W.
N.
TRUE MERIDIAN
Heart L.
TARN
Red L.
Red Alga (very abundant)
Deep Lake
Columnar Kenyte
Sunk L.
Kenyte
McMURDO SOUND
Sandy Beach
Islet Lake
Massive Kenyte
Cliff
Cliff
Kenyte rocky point
Scale in Chains
20 10 0 10 20 30 40 50 60

FIG. 56

rounded by low debris-covered hills, and receives its name because of the well-marked vestiges of at least three terraces on the slopes of these hills. None of the terraces are very much above the present level of the lake, being only a few feet apart. The lake is fringed with a certain amount of the algous plant so common at Cape Royds, and large bunches of the same plant were weathered out of the surface by reason of the ablation of the lake ice. Before the end of August, at least 3 or 4 inches must have been removed by ablation since the preceding summer.

Parts of this lake were very deep and of very pure and clear ice, and at these places the inclusions in the ice were plainly visible at a great depth. It was here that the photograph of a snow-tabloid half a foot in diameter was secured, and these snow-tabloids were very common. These tabloids were usually cavities formed by gases, in some cases perhaps set free from the algæ, and partly filled with powdery ice. Many pieces of alga were visible enclosed in the ice, and above them generally were streams of small bubbles showing up clearly against the clear lake ice because they contained a quantity of finely-divided ice particles growing like an efflorescence on the inside of their ice-walls. This efflorescence in some of the larger bubbles examined seems to be due to the expulsion at low temperatures of the water-vapour taken up at high temperatures, a process which would have small result at first, but after many repetitions seems quite adequate to produce this small amount of rime.

Another occurrence unusually common here was the interstratification of fairly large stretches of rippled snow between layers of ice. All those seen here seemed to be at the same level, and at 3 or 4 feet below the surface, but the estimation of depth is only approximate, for we dug no trenches in the lakes.

It was near Terrace Lake that a thick deposit of dead alga of the type occupying lakes was found at a height of 40 feet above any present lake surface. It seems probable that this deposit, which was 2 or 3 feet thick, and covered with a layer several feet thick of moraine gravel, was the remains of an old lake-bottom elevated and denuded.

Deep Lake. Deep Lake was bounded on its east and west sides by cliffs of highly-jointed kenyte, with the joints radiating in fan shape. To the north of the lake was the ridge which was capped by mirabilite, and to the south was a gradually shelving plain of moraine matter. The cliffs at the side dipped almost perpendicularly beneath the ice, and it seems probable, since we could see no bottom, although the lake was very clear, that the depth here is at least 15 or 20 feet. Its surface is about 40 feet above sea-level. This lake was one of the earliest of the fresh-water ice lakes to melt, for already before the departure of the Western Party on December 9, 1908, a fringe of water had formed at the foot of the kenyte cliffs. Unfortunately the extent of the thaw was not ascertained.

Sunk Lake. This lake received its name because the present surface of the ice comprising it is 18 feet below sea-level. It measures about 176 yards by 66 yards, and is about 2 acres in extent. Its surface was very rough, and covered by a thick deposit of the prismatic or coralloidal ice, which, from the domed nature of its surface, seems to have undoubtedly been formed from the conversion to ice of the under side of snow-drifts. The presence of this prismatic ice in such large quantities renders the surface of this lake comparable with that of the southern half of Blue Lake, and in both cases it forms strong evidence that both Sunk Lake and southern Blue Lake have not been melted to any large extent for several years.

In the case of Sunk Lake an additional piece of evidence in favour of a long period without melting is afforded by the presence of large blocks of kenyte half imbedded in the lake ice. Similar boulders were observed imbedded in the ice of Blue Lake. It is difficult to account for their occurrence in their present positions.

In conclusion, we are indebted to Murray for a few isolated notes showing the temperatures to which some of the water of these lakes rises during the course of the summer.

TEMPERATURE OF LAKE WATER

Green Lake, 3rd January 1909	+36° F.
2nd February 1909	+35° F.
(It doubtless went higher, but was not visited often.)	
Coast Lake, 4th December 1908	+47° F.
2nd January 1909	+40° F.
18th January 1909	+45° F.
Round Lake, 4th December 1908	+50° F.
10th December 1908	+61° F.
Pond at Cape Barne, December 1908	+54° F.

CHAPTER VIII

ICEBERGS

The first iceberg was sighted on our first voyage south in the *Nimrod* near lat. 63° 59′ S., long. 179° 47′ W., on January 14, 1908. It was not until the *Nimrod* reached the Antarctic Circle that the icebergs became actually very numerous. On this occasion, January 15th, the *Nimrod* encountered an extraordinarily vast fleet of bergs, varying in height from about 20 to 80 feet. These were met with at about 9.15 P.M., and the *Nimrod* continued steaming through them until 3.15 P.M. on the following day. These bergs were met with in approximately lat. 66° 37′ S. and long. 179° 36′ W. It is estimated that they extended for a width of about 80 miles southerly from this latitude. The measurement of the belt in an east and west direction was not ascertained. The following is a description of this vast fleet of bergs written at the time :—

"Singly at first, then in groups of twos and threes, there came into view not pack ice but great icebergs. These were of tabular shape and nearly all rectangular, mostly from 30 to 80 feet in height. Above they showed like the purest alabaster or whitest Carrara marble, shading into exquisite tints of turquoise or sapphire at the water's edge, and changing to a pale emerald-green below the water. Gradually as the *Nimrod* forged her way southwards, and the bergs increased vastly in numbers, we seemed to have entered the great silent city of the Snow King, the Venice of the South. With full steam and all sail we hurried along, now down the wide waterways between the bergs, now along the narrow lanes, with a wall of ice to starboard and a wall of ice to port. The helm had frequently to be put hard up or hard down to avoid colliding with the ice. Now and again the bergs closed in so closely that there seemed no way of escape for our little ship, but always, just as we seemed to have reached a *cul de sac*, a fresh lead opened to our view, and the *Nimrod* was promptly headed into it. There was no darkness that night, and in the grey light the bergs shimmered like ghosts. As the day of the 16th wore on the bergs became lower than before, rising to heights of only from 20 to 40 feet above the water. Most of the bergs were tabular in shape, with flat, even tops, but some, especially the larger bergs, from half a mile to two miles in length, were dome-shaped, sloping gradually right down to the water's edge, or bounded seawards by only very low cliffs. All the bergs were formed of compressed snow or *névé* in the portion visible above the water, and were regularly and perfectly stratified in

PLATE XLIV

Fig. 1

Fig. 2

[To face p. 170

thin layers. Towards noon on the 16th the bergs, which had lately been getting rather fewer in number, thronged thicker than ever, so that it required careful navigation to keep the ship in the leads of open water between them. At last we burst quite suddenly into an open sea, and saw the crystal city fade from our sight below the northern horizon."

These bergs, which were evidently not formed of glacier ice, but were of the nature of snow bergs above, passing into "shelf ice" beneath, were no doubt derived from King Edward VII. Land or the adjacent coast-line. They were mostly too low to have had their origin in the Great Ice Barrier.

The berg in Plate XLIV. Fig. 1 appeared to be about 30 to 40 feet in height, and, as shown by the photograph, possesses long spurs. These project for a distance of from 80 to 100 feet beyond the foot of the cliff of the berg faces. This berg, like all those sighted in this vast fleet, was obviously formed in its upper portion of stratified snow. It seemed probable to us that this rested on old sea ice, and that the great spurs projecting under water from this berg were formed of the latter material. If this surmise is correct, this fleet of bergs must have been formed by the breaking out of a very large area of old sea ice laden with snow. We saw no signs of any true glacier bergs amongst the whole of this vast fleet. No trace was seen of moraine material or erratics on any of the bergs. We thought that they were probably formed for the most part from very old sea ice with many years' accumulation of snowfall. On a larger scale they closely resemble the snow-laden ice floes formed of one season's sea ice with its overburden of snow, which we photographed in the act of breaking out and being drifted out to sea near Cape Royds in 1908.

It is, of course, possible that some of these bergs were formed of thin land ice, instead of sea ice, at the base. Apparently these bergs had been drifted from a point lying to the north of King Edward VII. Land, possibly from its northern shores. According to our present information about King Edward VII. Land, it is a large area of either closely contiguous low-lying islands, or it is a low plateau-shaped portion of the Antarctic continent proper. It is certain, at any rate, in view of the recent discoveries by Amundsen's Expedition and the Japanese Expedition, the latter under Lieutenant Shiraze, that there is a considerable gathering ground for snow in this region. At the same time the snowfall appears to be very light; this would hinder the development of glaciers on a large scale, and would encourage the growth of old sea ice, the aggregation of which might proceed for many seasons for some distance out to sea along its northern and western shores. The old sea ice, weighted down by the burden of snow, might actually sink below sea-level, and the lower layers of snow on the berg or floe might then become saturated with sea water and alternately thawed and frozen, the net result being the growth of a berg, formed of old sea ice at the base, with a layer above that of old snow cemented by salt spray and sea water. Near the top the bergs pass into horizontal and well-stratified layers of snow. The Plate shows one of the larger of these tabular bergs of what may be termed shelf ice capped by snow.

This formed one of the fleet above described.

Plate XLV. Fig. 1 shows the stratified character of the snow in one of these bergs, which had become tilted as the result of differential corrosion in the sea water.

The height of this last berg appeared to be about 60 feet. The older bergs not only exhibited traces of tilting, but also extensive wave-worn grooves at their base. Such a structure is well illustrated in Fig. 2 of an iceberg close to which the *Nimrod* passed in Ross Sea in the third week of January 1908.

While the solvent action of sea water, combined with the mechanical erosive force of the waves, tends to rapidly destroy these bergs, the work of destruction is to a limited extent further accelerated by the collision of the bergs with each other during blizzards. The effect of such collision in crushing up the layers of snow and *névé*, of which the upper portion of the berg is formed, is illustrated in Plate XLVI.

It is very noticeable that the sides of bergs facing the north become strongly etched in the warm beams of the noonday sun. In fact, for a great part of the twenty-four hours during the time of midnight sun, such faces showed evidence of more or less continued thawing. The icicles dependent from this berg are clearly shown in the photograph. At the base of the berg is seen the fringe of icicles formed along the wave-worn grove. If much dust was present on the surface of bergs, the effect of thawing became more pronounced. Such cases were of course most frequent amongst bergs of blue ice derived from land glaciers. An interesting berg of this kind was sighted near Cape Bernacchi by the Northern Party. The berg was about 70 feet in height, and the face directed towards the north was beautifully fluted, the structure having some resemblance to the pipes of an organ. A close examination of this structure revealed the fact that the fluting was the work of comparatively small quantities of rock dust together with fine pebbles. In the first instance these appear to have been distributed with tolerable uniformity in a thin layer over the surface of the berg. In places more heat would be absorbed by this layer of rock material than in others, on account either of difference in the colour of the rock, or in the thickness of the layer of rock debris, and as a result small thaw hollows would be produced into which the rock dust and pebbles would glide. The thaw-water from these conical depressions, if they were situated near the northern face of the berg, would sooner or later overflow in a tiny rill, and cut down for itself a channel in the northern face of the berg, down which it would fall in tiny cascades. It would carry down with it some of the dust and small pebbles, and these, arrested in their downward progress on small projections of the ice-cliff, have further accelerated the process of thaw and completed the grooving process. The surface of this particular berg was, therefore, much pitted with typical "dust wells."

Bergs formed of true blue glacier ice were comparatively uncommon. Altogether only a few were sighted in the journey of 200 miles from Cape Royds to the

PLATE XLV

FIG. 1

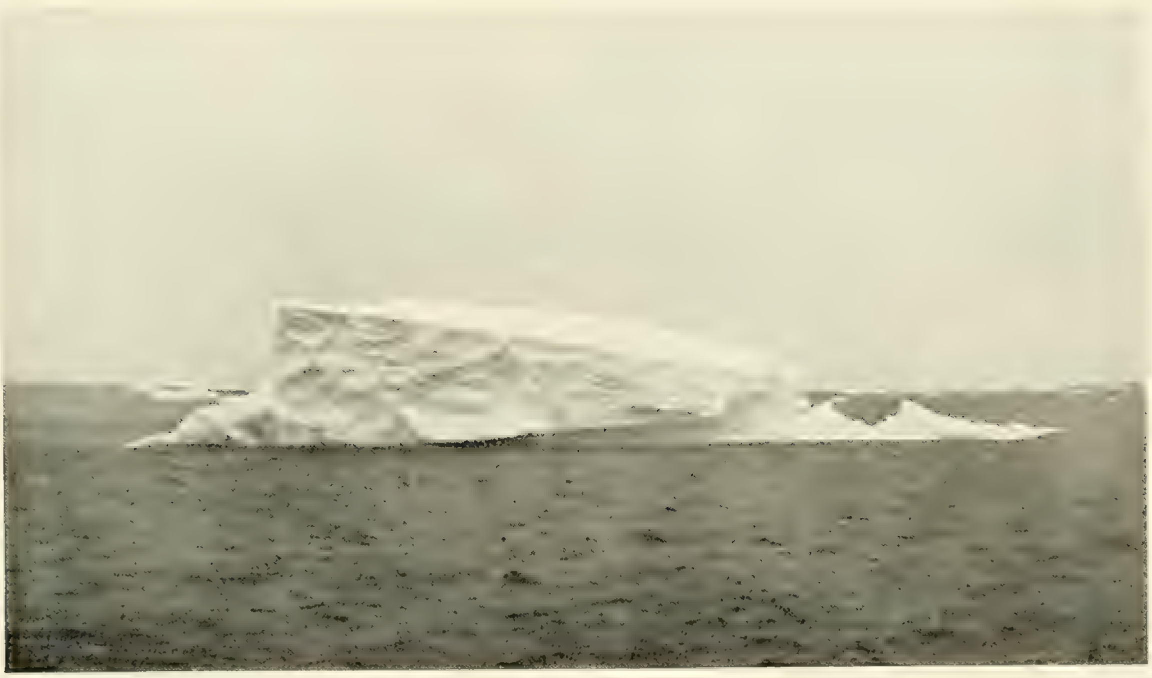


FIG. 2

[*To face p.* 172

Drygalski Ice Barrier as against many snow bergs. This seems strange when one considers that an immense proportion of the west coast of Ross Sea and McMurdo Sound is occupied by piedmont ice. At the same time it must not be forgotten that this piedmont ice or shelf ice closely approximates in places to the structure of the snow bergs formed by accumulations of old snow on sea ice of many seasons' growth. Such bergs as were formed of blue ice, and were more or less charged with rock dust and other rock debris, had probably been derived from the snouts of some of the outlet glaciers of the Antarctic, or from the foot of the piedmont. Near the final stage of their history, before they disappear, the snow bergs with their foundation of old sea ice are gradually eroded away by the mechanical force of the breaking waves, and at the same time become thawed in the rays of the sun, until at last nothing is left but what appears to be a perched block of old snow resting on a small ice island, the buoyancy of the latter being sufficient to keep the old snow of the berg still above the level of high water. Obviously the last part of such a berg to survive would be the substratum of old sea ice on which the snow mass was originally built.

From what has been said, it is apparent that it might be possible to divide the ice bergs of the Antarctic regions into three classes, viz.:—

1. Snow bergs formed on a base of old sea ice.

2. Bergs formed of shelf ice. These may grow as a piedmont resting on a *rock* foundation forming a wide fringe of the Antarctic shore-line, or may develop like the Great Ice Barrier as a mass of glacier ice formed of the expanded fans of numerous outlet and alpine glaciers with the sea ice between them, held fast for a vast number of years, and then added to by many hundreds of years of snowfall. This latter variety of shelf ice presented by the Great Ice Barrier thus unites some of the attributes of the snow berg ice with that of the piedmont ice. Thus the shelf ice may be said to have two types, (*a*) the piedmont, (*b*) the barrier.

3. The third class of bergs are the blue bergs, with their englacial or supra-glacial morainic freight launched from the snouts of outlet or alpine glaciers.

In regard to the flotation of these different types of bergs, the buoyancy of class 3 is already so well known as not to call for comment here.

In regard to class 1, we observed at Cape Royds that when the sea ice was breaking out up to the tidal crack, the rectangular bergs so formed had a covering of from 6 to 8 feet of packed tough snow resting on a substratum of sea ice of one season's growth; the latter originally did not exceed about 7 feet in thickness, and at the time the disruption occurred had been considerably thinned and honey-combed by the thawing action of sea water. As far as we could ascertain, from 3 to 4 feet at the base was formed of honeycombed sea ice, the remaining 6 to 8 feet being hard compressed snow. About 1 mile south of our winter quarters at Cape Royds there were four stranded bergs, but it was not clear as to which of the above classes 1 and 2 they might be referred. The portion of these bergs above sea-level was formed of well-stratified layers of old snow. The bergs were from 78 to 80 feet in height. The interesting observation was made by Captain F. P. Evans, when sounding around these bergs towards the end of 1908, that they were aground in water 14 fathoms in depth. Thus in this case only little more than half of the berg was submerged. This particular berg was of the typical tabular variety, bounded by almost vertical sides, and was about a quarter of a mile in length.

Another and similar berg, evidently broken off from the same mass, is shown on Fig. 2 of Plate XLVI.

It will be noticed that this berg, which has somewhat the shape of a massive castle wall, stands on a wide shelving platform formed by this marine erosion. The wall itself has been somewhat undermined, giving its summit a turreted outline. Icicles can be seen dependent from its overhanging portions. It will be noticed that in the photograph the part of the berg which has been most undercut is naturally that which faces the blizzard wind, that is, the right-hand side of the berg, as shown in the photograph.

PLATE XLVI

Fig. 1

Fig. 2

[*To face p.* 174

CHAPTER IX

ICE-FOOT AND SEA ICE

ICE-FOOT

The term ice-foot as employed by us is applied to the low cliffs formed partly of sea ice, partly of overlying snow-drift consolidated by frozen spray, which fringe the coasts of the Antarctic after the breaking away of the sea ice in summer time. These cliffs of the ice-foot are from a few feet up to as much as 70 to 80 feet in height, their usual altitude not exceeding about 20 feet above sea-level. Their existence makes landing on the Antarctic in summer time often a matter of considerable difficulty. As will be explained in detail presently, they are formed partly by a process of addition, partly by subtraction. As we followed carefully every phase of their development, and took a series of photographs, it is hoped that the observations will make the subject of an Antarctic ice-foot intelligible.

It is proposed to describe the ice-foot, where specially studied by us in the neighbourhood of Cape Royds, in the chronological order in which our observations were made. At the time when we reached Cape Royds, at the end of January 1908, the sea ice was still fast in Backdoor Bay and near Flagstaff Point. Owing to the drifting action of the blizzard winds the surface of the sea ice had been covered with snow, which rose in the form of a gently inclined plane from the surface of the sea ice up to the tops of the low cliffs. The latter were formed of kenyte lava, and at spots where they were completely levelled up by drift were from 15 to 20 feet high. Early in February an exceptionally high tide led to a very sudden break up of the sea ice, together with the overlying snow-drifts next the shore. The general appearance of the breaking up of the fast ice on this occasion is shown in Fig. 57.

The floes in the distance next the *Nimrod* are covered with a thickness of about 6 inches of old snow. In the foreground, where not only the sea ice but the snow-drift as well has been broken through, the floes consist of from 5 to 6 feet of sea ice formed during the winter, capped by 7 or 8 feet of hard compressed snow. This overburden of snow is sufficient to completely submerge the sea ice of the floe. The following sketch indicates the structure of the sea ice at that time at Cape Royds, and shows also the position of the ice-foot.

The detachment of these small rectangular bergs, of sea ice below and compressed snow above, leave behind the vertical wall of the ice-foot. Obviously the tendency is, in rough weather, for nearly all the sea ice to break away right up to the edge of the rocky shore-line, and it is the cliff which is finally left which constitutes the ice-foot. This cliff is attacked by the sea surface below, which mechanically erodes it, as well as by the warm sea water which causes it to thaw, the combined result

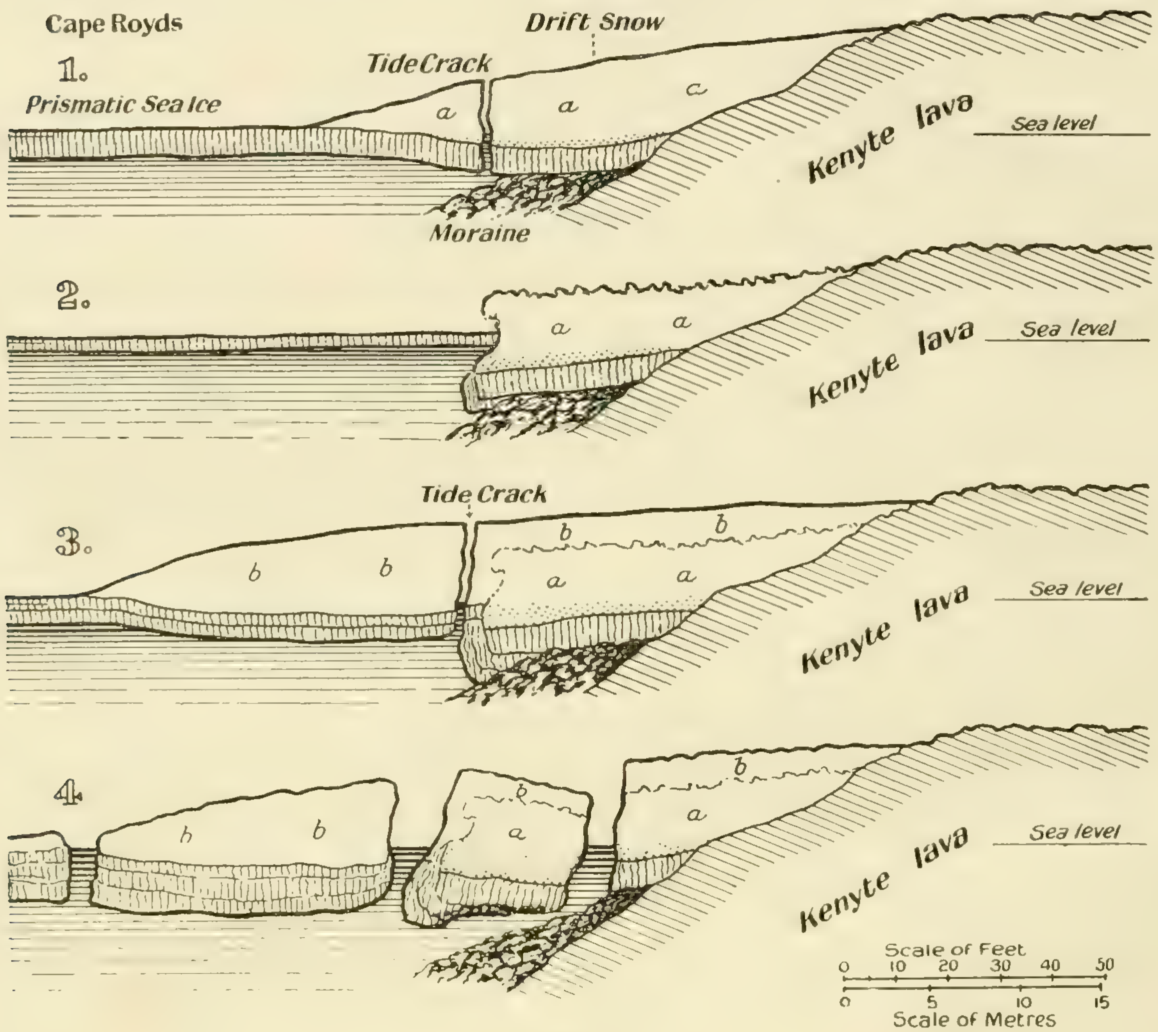


FIG. 57

being that the ice-foot cliff is hollowed out in a series of caves, or is eroded back below right to the rocky cliff face. Meanwhile thaw above removes a great deal of the superincumbent old snow-drifts. Thus, as the summer advances, the ice-foot cliff is constantly dwindling. With the heaving of the waves and rise and fall of the tide the roofs of the caverns of the ice-cliffs are subjected to a constant drip of salt water, and this forms a beautiful set of icicles. The general appearance of the ice-foot, when the thaw has advanced as late in February as the 18th, the time the photograph was taken, is shown on the second sketch.

PLATE XLVII

FIG. 1

FIG. 2

FIG. 3

FIG. 4

[To face p. 176

PLATE XLVIII

Fig. 1

Fig. 2

[To face p. 176

Fig. 1

ICE-FOOT

Fig. 2. KENYTE LAVA FROM MT. EREBUS. SEA ICE WITH ICE FLOWERS

[Armytage

[*To face p.* 176

In this case the whole of the sea ice has been dissolved or eroded away right up to the rocky base of the cape, and all that is left of the ice-foot cliff is a mass of old snow-drift, which, undercut by the waves, and fringed with abundant icicles above, as the result of prolonged thawing of the snow-drift, has been deeply and irregularly carved, leaving an appearance of statuesque figures like those seen on Plate XLVII. Fig. 4.

Plate XLVIII. Fig. 1 shows a slight modification of the previous structure. It is a view of Frontdoor Bay near Flagstaff Point, Cape Royds, taken in February 1908, and shows the overhanging ice-foot, with its surface here further consolidated and added to by incrustations of frozen spray. The particular part of the ice-foot shown has been consolidated and added to by accretions of ice derived from the freezing of sea spray. This headland faces the prevalent blizzard winds, which blow from the direction of the left of the picture, and dense sheets of spray are frequently flung over the ice-foot and across the headland. The portions of it, which escape freezing on the surface, freeze lower down, as dripping takes place, as icicles, and so produce the willow-tree pattern so characteristic of this part of the ice-cliff. From February 15th to 18th, 1908, a fierce blizzard raged, which flung vast volumes of sea spray over the cases of provisions, cloth, and other Antarctic equipment shown in the photograph. In places there was actually as much as 7 feet of tough fibrous ice piled up over our gear.

A different type of ice-foot is shown on Plate XLIX. Fig. 1. This view is taken at Blacksand Beach, about 1 mile north of our winter quarters at Cape Royds. What was originally a shelving beach, formed of kenyte sand, has there been converted into an ice-foot, first, by the freezing of the sea ice, and subsequent drifting of snow by the blizzard wind from inland, in the form of wedge-shaped drifts, across the edge of the sea ice. Storms occurring later broke out the sea ice almost up to the edge of the gravel bank, carrying away much of the snow-drift on the loose floes. At the time when this low cliff was left heavy breakers flung the spray far and wide over this part of the shore, and built up dome-shaped masses closely resembling stalagmites, but formed, of course, of a mixture of old snow-drift and ice derived from infiltrated sea water. Immediately to the right of the two bergs in the photograph may be seen a pressure ridge of blocks of sea ice. This is formed by the pressure of a recent northerly wind on broken-out masses of glacier ice originally met with farther north.

Plate XLIX. Fig. 2 shows a still later development of the ice-foot. This photograph was taken about March 15, 1908. It shows the overhanging ice-foot, there about 15 to 20 feet in height, with its base undercut by the action of the waves, and with icicles hanging from the roof. In the foreground are some slabs of old sea ice with portions cemented together by newer ice, the whole covered by a fine crop of ice flowers. In the background, at the top of the picture, are low cliffs about 50 to 80 feet high of black kenyte lava. Another appearance of the ice-foot taken still later in the year, in April 1908, shows in the foreground heavy snow-drift at Blacksand Beach. Above it are some small dark caverns, from the sloping entrance wall of which there hang a number of club-shaped icicles. It is difficult to understand exactly why these icicles are club-shaped, unless it be that, as sea water is a mixture of several solutions, each having a freezing-point of its own, as the result of progressive freezing the mineral matter contained in the original sea water becomes more and more concentrated in the residual water. As the freezing-point of these concentrated brines is lowered, we observed that the tips of the icicles were nearly always moist and sticky unless the temperature fell below 0° F. Below that temperature they were usually dry and free from any of the brine solution unfrozen. The blizzard winds drove innumerable snowflakes before it, which impinged on the brine-tipped sticky ends of the stalactites and were arrested in their flight, and thus by degrees built up a club-shaped end to the stalactite. A similar phenomenon, but on a still more striking scale, is shown on Plate LII. Fig. 1. This was taken in mid-winter under the overhanging eaves of the ice-foot a few feet above sea-level. It will be noticed that the icicles terminate there in feet-like forms, some resembling the hooves of horses, others human feet. We observed that the toes were always directed against the prevailing wind. Evidently these feet have been built out to windward by the action of the snow-bringing air currents from the south-east. The scale is shown by the height of the two hurricane lamps, by means of which the photograph was obtained after an exposure of 20 minutes with full aperture and special rapid plate.

On Plate L. Fig. 1 some remarkable structures in ice and drift snow are shown resembling the forefeet of horses. The explanation of their origin is similar to that of the human-like feet in the previous figure.

After the formation of the early sea ice in autumn, during March and April, blizzard winds, combined with rise and fall of the tide, served to break off sheets of sea ice formed at the base of the ice-foot, but as the temperature continued to fall, these broken fragments became recemented. Little by little the cliff of the ice-foot, as the winter advanced, became levelled up by snow-drift. In cases where the ice-foot was in the lee of the prevalent wind the drift snow built out a beautiful cornice like that seen in Plate LI. Fig. 1. We observed in several places that, where these snow-drifts were piled up against the ice-foot, where the latter faced the prevalent wind, the tendency of the wind was to scoop out a hollow at the foot of the snow-drift, so as to re-develop the ice-foot cliff. This groove, or fosse, is to be distinguished from the moats formed by actual thawing, where sea ice or snow is brought within the action of radiant heat emanating from dark rocks exposed to the direct rays of the sun. The fosse in this case is due to a strong back eddy of the wind.

Plate LI. Fig. 2 shows the appearance of a large and ancient ice-foot at the northern end of Blacksand Beach. The cliff of the ice-foot is here formed almost entirely of drift snow alternating with a considerable amount of fragments of

FIG. 1. ICE STALACTITES FORMED LIKE HORSES' FEET

FIG. 2. ICE FOOT WITH SEA ICE BREAKING UP

[*To face p.* 178

PLATE LI

Fig. 1

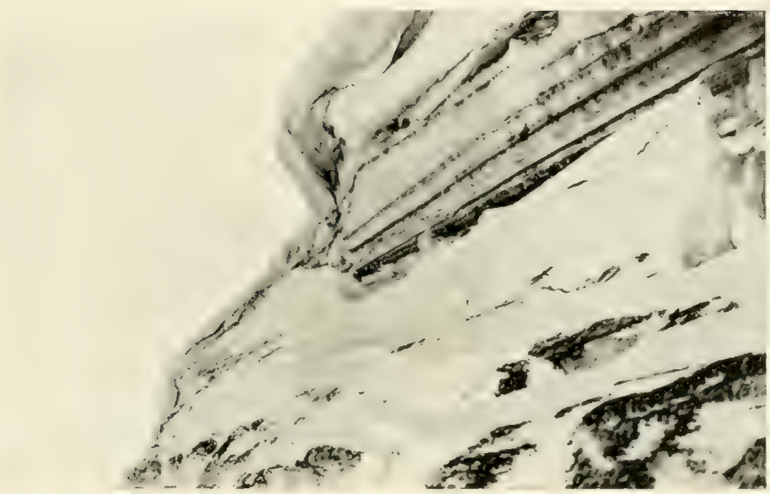


Fig. 2

Fig. 3

[*To face p.* 178

felspar and kenyte lava, forming dark and regularly stratified bands. It will be observed that a fine cornice has formed at the top of this cliff, which was between 70 and 80 feet in height. The dark bands are in part due to the finely divided rock material, which has been drifted over the surface of the snow by the blizzard winds, partly to their concentration from time to time as the result of their settling down under the influence of the thaw. On this latter explanation each dark band represents a prolonged thaw immediately preceding further accumulation of snow-drift. The amount of rock material contained in this part of the ice-foot was very considerable, the layers of broken fragments being from 3 to 4 inches in width, and placed at close intervals to one another, as shown in the sketch. It is clear that already a vast amount of rock material has been removed from this ice-foot by the launching of sea ice with superincumbent old snow and detrital rock material upon it. It is possible that in part this high cliff of the ice-foot is due to the thawing action of the sun's rays, for it faces nearly due north.

Plate LI. Fig. 3 shows the appearance of the ice-foot in spring. At this time the bulk of the sea ice had broken out from McMurdo Sound, and had drifted northwards. This had left behind itself shorewards an indented vertical face of sea ice capped with snow-drift. Above the position in the photo, where the figure is leaning, can be seen a mass of piled up fragments of sea ice, the relic of an old pressure ridge due to the overthrust of the sea ice by a strong northerly wind earlier in the season.

This photograph brings the coast-line with its ice-cliff almost back to the point in the cycle from which we first started to constitute it in Plate XLVII. Fig. 4.

An important feature in the ice-foot is the tidal crack. The average rise and fall of the tide in McMurdo Sound at Cape Royds is about 2 feet 10 inches. This is of course sufficient to fracture the sea ice close to the shore-line adjacent to the ice-foot, but in many cases the position of a tidal crack is not exactly coincident with the base of the cliff of the ice-foot, being often situated slightly on the seaward side of it. In many other instances the two are actually coincident.

SUMMARY

From what has been said, it may be gathered that the ice-foot of the Antarctic regions is mostly a low cliff from 10 to 20 feet in height, occasionally as much as 80 feet high, developed most perfectly in summer time. As the cold of winter approaches the sea becomes frozen over, the ice being detached from the land only by the narrow tidal crack. The snow drifted by the blizzard winds tends to level up with gently-inclined planes of drift the steep angle formed by the meeting of rocky cliff faces or steep slopes with the surface of the sea ice. During the accumulation of the drift snow a certain amount of rock debris becomes intermixed with these snow-drifts at the foot of rocky cliffs. Further, blizzard winds and spring tides, especially in summer time, break out the sea ice with its overburden of snow-drift. Finally, the thick masses of old consolidated drift, partly cemented by frozen sea spray, are broken out at least as far inshore as the tide crack. These large dislodged blocks, containing much finely-divided rock debris, together with coarser lumps of rocks, are floated northwards into Ross Sea, and driven by the south-easterly blizzards towards Cape Adare, or even farther northwards. Sooner or later they part as they thaw with their burden of rock debris, which, as already stated, is largely formed of angular fragments of fresh felspars. Thus such fragments are evidently being scattered far and wide over Ross Sea, where they must become intermixed in the bottom deposits of that sea with diatomaceous and sponge spicule ooze.

In regard to the accumulation of drift snow on the ice-foot at Cape Royds, we observed that a few drifts began to form over the sea ice after its freezing during April, but it was not until the wind and snowfall on June 25, 26, 27, and 28 that these snow-drifts reached any great thickness. By the latter of these dates the drifts had become several feet in depth, and by July 10 were on a level with the top of the ice-foot of the preceding season, and where this ice-foot was lower had even begun to overflow it. Two or three days later the tide cracks had burst right through these drifts.

SEA ICE

If again the chronological order of our experiences be followed, we may pass to the description of Plate XLVII. Fig. 3.

This represents dense screwed pack ice with a large berg frozen into it. We sighted this during our second attempt to reach King Edward VII. Land in January 1908. This pack appeared to be certainly of more than one season's growth, and the interspaces between the crushed masses of ice are filled in with old snow. The pack proved to be far too heavy to admit of its being penetrated by the *Nimrod*. The berg shown has probably broken off from the Great Ice Barrier.

Plate XLVII. Fig. 2 shows the fast ice, against which the *Nimrod* can be seen pressing in the middle distance: to her right are fragments of the drift pack. This photograph was taken in December 1908. The foreground is a hill of kenyte lava, in the neighbourhood of Cape Royds.

Plate XLVIII. Fig. 2 shows the *Nimrod* forcing her way about the same time of the year along the narrow lane in the fast ice. A pressure ridge of sea ice can be seen just in advance of her bows.

Plate LII. Fig. 3 shows the appearance of large masses of floe ice in the neighbourhood of Granite Harbour as seen in December 1908. These floes are covered to a depth of several inches with soft snow. About this time of the year the sea ice was becoming much honeycombed, and the thickness varied from a few feet up to about 5 feet.

Plate LII. Fig. 2 shows brash ice formed from the complete shattering of floe ice after a blizzard in McMurdo Sound. As the summer blizzards often brought

Fig. 1

Fig. 2

Fig. 3

[To face p. 180

with them considerable fall of temperature, they helped to reunite these shattered fragments through freezing the interstitial strips and patches of open water.

Plate LIII. Fig. 2 shows the appearance of the sea in McMurdo Sound near Hut Point at the end of February 1909.

Pancake Ice (*eierkuchen eis*). We observed that ice of this type developed when the surface of the sea was being gently rippled by the wind during a comparatively low temperature. At first the sea presented a soupy appearance. On the first occasion which we saw this (on February 18, 1908) we thought, as it had been immediately preceded by a very heavy three days' blizzard, that this soupy appearance was due to large quantities of partly water-logged drift snow. This idea subsequently proved to be incorrect. The pancake ice shown on Plate LIII. Fig. 2 developed gradually out of countless ice crystals, which on this occasion also imparted a distinct soupy appearance to the sea. It might also be likened to the aspect of melted paraffin wax floating on the water. Little by little these crystals of sea ice felted themselves together into small cakes, which, jostled by the gentle breezes, continually collided along their growing edges. The latter, being very flexible, become gradually turned up so as to form raised rims, and the whole pancake became slightly saucer-shaped.

Plate LIV. Fig. 1, photographed by Brocklehurst, illustrates the growth of pancake ice at about the same period.

Plate LIII. Fig. 3 shows the appearance of the wake of the *Nimrod* as she cut her way through the pancake ice about March 6, 1909. At the time the pancakes were beginning to be more or less firmly cemented at their edges, and thus made a tough surface, which seriously handicapped the *Nimrod*, and for several hours held her up completely. In time the whole of the interstitial water between the pancakes freezes, thus producing a continuous firm surface of ice. If this ice lasts for the whole of the winter and following spring it forms an excellent surface for sledging; the raised rims of original pancakes, by this time rounded off through evaporation, much reduce the friction of the runners of the sledge on the ice.

Plate VII. Fig. 2 shows the appearance presented by the sea ice formed in very calm and quiet water. This photo was taken on March 20, 1908. The temperature at the time these crystals grew was about -10° F. The ice flowers tasted very salt and bitter. A few days later the temperature rose to about $+5^\circ$ to $+8^\circ$ F., and the centres of the ice flowers rapidly disappeared, forming tiny briny pools; these were surrounded with a fringe of the outer ends of the petals of the ice flowers. These outer petals or extremities of the crystal plates of ice were evidently formed of freshwater ice of the nature of hoar frost collected from the moisture in the air. Their thaw point was evidently near to 32° F., whereas that of the crystals containing the strong brines was probably close to 0° F. Evidently the centres of these ice flowers are formed of the residual brines squeezed out of the gradually congealing sea ice when it crystallises in calm cold weather. The appearance of the brine pools formed through the thawing of the centres of the ice flowers surrounded by their fringe of ice plates is shown on the accompanying sketch.

In regard to the history of the curdling over of McMurdo Sound with ice and its final congelation, it may be stated that the surface of the ice first became crusted over during the early days of March. This ice attained a thickness of from 9 to 10 inches when it was broken up and removed by a blizzard. It was on this occasion that the ice flowers just described were formed. The next sheet attained a thickness of 18 inches, when it was broken up by a northerly swell, and removed by a southerly gale at the beginning of April, with the exception of a small patch at the extreme north of Backdoor Bay. On April 2 a fresh sheet of ice began to form, again accompanied by ice flowers. The fragments of ice that had been driven out at the beginning of April now became recemented, as shown in the accompanying photograph, Plate LIV. Fig. 2.

A few days later McMurdo Sound was permanently frozen over for the winter.

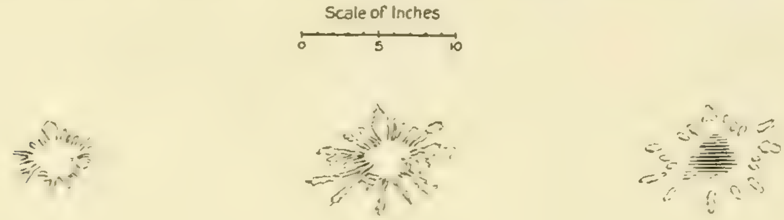


FIG. 58

Nevertheless, from time to time, during blizzards, large areas of ice broke out from near Cape Royds and towards the centre of McMurdo Sound, leaving a long wide tongue of dark open water extending several miles south of Cape Royds towards the "pinnacled ice" in the direction of Mount Discovery. At the beginning of July the thickness of the ice, measured at a crack extending from Flagstaff Point to the stranded berg, and about 400 yards distant from the point, was 4 feet. The thickness of the sea ice at the dredging ground in Backdoor Bay at the end of July was between 4 feet 6 inches and 5 feet.

On August 23 the ice at a spot very near the one just mentioned, 400 yards southerly from Flagstaff Point, was trenched for the purpose of putting down a fish trap, and proved to be 6 feet thick. At the end of September the bay ice in the extreme northern corner of Backdoor Bay proved to be 7 feet thick, the maximum measured by us, but there seems no doubt that this thickness would steadily increase until probably about the end of November. It may be mentioned that we observed that the delicate plate-like crystals, which develop ultimately into pancake if the surface of the sea at the time of their formation is rippled, or into smooth clear ice surmounted by ice flowers if the weather at the time is calm, either form at the surface or possibly at a slight depth below the surface, though there is some doubt as

PLATE LIII

Fig. 1

Fig. 2

Fig. 3

Fig. 4

[*To face p.* 182

to whether the latter phenomenon actually takes place. Certainly plate-like crystals developed considerably below the surface on a dredging line which had been left for some weeks without being used. These fine hexagonal plates were in some cases as much as 6 inches in diameter, and had formed vertically down the dredging line for a distance of several yards. When dredging off the cracks extending westwards from the Penguin Rookery at Cape Royds and southwards through Flagstaff Point numbers of these plate-like crystals were brought up by the dredge, though it is possible that they may have formed in super-cooled water upon the cordage of the dredge coming in contact with it. It should be mentioned that in this case the crystals were not attached to the netting of the dredge in the way that the ice-crystal plates were attached to the dredging line just mentioned. It was observed that if the weather was calm the felted ice crystals, which formed with temperatures falling below 28° F., became firmly adherent to one another, and the ice continually increased in thickness, although still plastic enough to undulate under the influence of a slight swell. If calm weather continued we observed that fibrous sea ice began to form, while the alternations of rise and fall of temperatures gave rise to a banded structure in the first few layers of the ice, as when the temperature rose the ice ceased to form, and when it fell the layer of ice thickened. As the periods of high and low temperature vary in length, so do the bands in the ice vary in thickness, the latter being from half an inch, or less, up to several inches. A similar banded appearance has already been noted as occurring in the ice of some of the lakes, particularly in Green Lake and Coast Lake. A similar reason to that just given has been advanced by us to account for it in the latter instance also. During the formation of the first few inches of sea ice the ice appears transparent, and seems black on account of the deep water seen through it. As the ice becomes thicker it gradually takes on a greenish tinge, and finally becomes opaque. Once the sea ice is thick enough to prevent the under side being seriously affected by changes of air temperature a uniform vertical fibrous structure sets in, without the transverse lamination already described.

It is in this way that all the rest of the ice is formed. During the growth of the fibrous ice salts still in solution are forced out in the form of brines, the mineral matter of which becomes more and more concentrated as the temperature falls. Such brines are partly forced back into the sea water below, partly forced up to the surface of the sea ice, where they form ice flowers, and partly remain entangled between the crystals. It is suggested that this movement of the brines together with that of the air dissolved in sea water which has been expelled on freezing helped to impart a remarkably fibrous structure to the ice. The brines extruded to the surface of the ice obviously freeze as cryohydrates. Such cryohydrates were also observed by us frozen at the tips of stalactites in caverns in the grounded bergs between Cape Royds and Cape Barne. The icicles dependent from the roofs of these caves were slightly sticky from concentrated brine at normal winter temperatures, and had drops of the brine dependent from their lower ends. On the occasion mentioned, the middle of June 1908, when the temperature was about $-30°$ F., the brine had frozen as a white enamel-like cryohydrate.

During the winter we observed that horizontal stratification was imparted to the sea ice in the neighbourhood of the tide cracks by the following process:—with the rise of the tide, at a time when the sea ice was pressed hard against the shore by wind or currents, so that the sea ice was not free to rise with the tide, sea water would overflow the surface of the sea ice for some distance on the seaward side of the tide crack. This layer of water would then freeze. The process being many times repeated, a deposit of laminated ice became superimposed upon the true sea ice. Plate LV. Fig. 3 shows the appearance of such laminated ice from near Flagstaff Point.

A somewhat analogous phenomenon was observed by the Western Party. They observed in summer time that the sea ice at McMurdo Sound was traversed by pressure ridges parallel to the edge of the piedmont ice. Nearest the ice-foot numerous slabs of well-laminated ice were observed, the origin of which was probably similar to that just described. They observed that local depression of the sea ice near the tide crack probably takes place on the western side of McMurdo Sound on a large scale. Along the "pinnacled ice" (perhaps a floating piedmont heavily loaded in places with moraine) is situated a band of ice, which is probably sea ice three or four years old. The junction line between this ice and the new ice of last year was marked by a pronounced ice-foot 2 or 3 feet high. About 1 mile to the E.S.E. of where the Western Party descended there was an area along this ice-foot extending for a distance of 2 or 3 miles of intensely blue, apparently wind-swept, ice with no snow on it whatever. They had hardly advanced more than a few steps on to it when it began to crack and bend in an alarming manner, and they realised that it was merely a thin crust of ice, which had evidently formed during the last two cloudy days over what had before been a pool of open sea water. At first they were inclined to think that they had struck a salt water pool, such as that reported by the *Discovery* off Cape Armitage. The latter was attributed to the thawing of a swift current of relatively warm sea water flowing over a shoal; but in this case, on testing the ice in several places with ice axes, they found that there was a thin upper skin of ice on top followed by a few inches of water below, and then apparently by a solid mass of ice of unknown thickness; at any rate sufficiently thick to resist any efforts to penetrate through it with the point of the ice axe, although they were several yards away from the edge of this belt of clear, freshly-formed ice. The water intervening between the two ice layers was nowhere more than a few inches in depth.

It seems probable that, owing to the pressure from the south-east and north-west, this ice had been thrown into very long gentle undulations, of which the area described was one of the troughs, and that this trough was subsequently floated by

PLATE LIV

Fig. 1

Fig. 2

[*To face p.* 184

sea water coming up through the tide crack.* This theory is rendered the more probable by our further observation, that at the time of the return of the Southern Supporting Party to Hut Point in November 1908 it was observed that the sea ice on which we, together with the Southern Party, had been camped a few days before, had been thrown into a series of broad undulations, with a difference of level of 2 feet between the centre of the trough and that of the centre of the nearest crest. In this case the fold was parallel to the ice-foot at the point, but there were slight evidence of tidal overflow along the ice-foot below Observation Hill. At the same time this overflow was much masked by the fact that the sea ice was for the most part there hidden from view by deep snow-drifts piled against the cliff. It may be added that the old sea ice, possibly three or four years old, forming a zone separating the "pinnacled ice" from the one-year ice, was covered with snow in summer time to a depth of from 1 foot to 18 inches, and its surface was from 3 to 4 feet above sea-level. Less than 2 feet of this, however, appears to be actually ice, and it seems probable that the whole thickness of this old sea ice is not more than from 15 to 16 feet. It would be interesting to ascertain for how long this ice would persist now that it has reached its present thickness, for every year its resistance to disrupting agencies becomes greater, and the exceptionally heavy weather of 1908 had very little effect on it. Its surface was comparable with the type which we found worst for sledging on the Great Ice Barrier itself. The older drifts were not quite sufficiently hard to bear the weight of a man, and at every step one dropped 8 or 9 inches on to a firmer surface. As explained elsewhere, the space between the two crusts was filled with coarse-grained snow powder, due to a selective action of the thaw, the grains which were left having increased in size at the expense of those which had been completely vaporised. The outer crust is evidently due to the formation of fresh drifts on an old and wind-swept surface, with its snow sastrugi a foot or 18 inches high, and also to the subsequent semi-hardening of these drifts by the snow of the previous summer.

After the surface of the sea had become firmly consolidated with ice in early winter, but before the ice had acquired a thickness of more than a few feet, fracture took place along certain definite lines (often approximately parallel to the shore-line) through pressure of wind and tide, and subsequently along these fractured ridges lines of pressure ice were raised. These ridges attained a height of from 10 to 20 feet. They could be seen forming chiefly during northerly winds, which forced the sea ice past Cape Royds, and piled up the ice blocks particularly high between Blacksand Beach and Flagstaff Point. The formation of these pressure ridges was a fine spectacle. While the northerly wind was blowing, as one watched from the shore one saw roll after roll of sea ice forming one behind the other, as the whole mass was steadily pressed against the coast-line by an unseen but irresistible force.

* Later experiences with the Scott Expedition incline me to think that this phenomenon is better explained by a flooding of the sea ice with the thaw-water from the Blue Glacier (R. E. Priestley).

Every now and then the ice would give way with a loud rending noise, and large slabs would be forced over each other across even the summits of the swiftly rising ridges. Every now and then huge slabs of ice would fall over the steep sheer sides of the ridges with a tinkling sound, and would be shattered at its base. The general appearance of one of these pressure ridges, taken by moonlight in midwinter of 1908, is shown on Plate LIII. Fig. 4.

An important line of fracture and pressure extended from Flagstaff Point near Cape Royds to the stranded outermost snow berg, and from there to Cape Barne.

These pressure ridges were mostly not more than from 7 to 8 feet high, except where the pressure was specially centred, as at Blacksand Beach. The individual blocks of ice forming these pressure ridges were usually not more than 2 feet in thickness. After the ice became sufficiently thick to resist buckling and to fracture evenly the belt of pressure from Flagstaff Point to the stranded berg became most prominent. The width of the double pressure ridges, one behind the other, at Blacksand Beach was about 12 yards.

Another type of crack, quite distinct from either tidal crack or pressure cracks due to the wind or ocean currents, was observed by us to form in the sea ice in winter time. Between July 3 and July 6 the temperature fell steadily from $+3°$ F. on July 3 to an average of $-20°$ F., with an occasional drop as low as $-35°$ F. This low temperature led to a considerable contraction of the surface layers of sea ice, and the tensile limit of the ice having finally been exceeded, several cracks opened in succession with a booming noise, like that of artillery. Such cracks may be termed contraction cracks. On the occasion referred to two important cracks of this type formed, one off the Penguin Rookery, and one farther seawards just outside the edge of the pressure belt off Flagstaff Point. The subsequent history of this latter contraction crack, which may be taken as typical of all such contraction cracks, is of some interest. The rise of temperature between July 10 and August 13 led to the expansion of the ice and the closing of the crack for the most part, but on August 14, with another fall of temperature, the crack opened again, until it was several feet wide. The sea water forming an open lane between the sides of the crack froze rapidly, forming delicate rows of crystals, recalling the comby structure of quartz crystals in quartz veins, the long axes of the ridges being at right angles to the general trend of crack, but during the night of the 15th a northerly wind sprang up, bringing with it a rise of temperature; the resulting expansion of the sea ice expended itself on the closing of the cracks, the interspaces between their walls being now crusted over by ice several inches in thickness. This thin ice yielded under pressure, and became ridged up into folds, which were later converted into over-folds, the direction of over-folding being towards the land as one would have expected, the maximum movement of expansion, of course, coming from the direction of McMurdo Sound. The general appearance of this young ice before the buckling and folding due to expansion on rise of temperature is shown on Plate LV. Fig. 1.

Although this tough young ice was fairly plastic, the over-folds eventually cracked open at their summits, as is shown on the accompanying photograph, Plate LV. Fig. 2.

On August 18 and 19 the crack opened wider than ever, and the temperature remained well below $-30°$ F. until the 21st, when it rose suddenly to $-17°$ F. The expansion on this occasion once more closed the crack. Once more the newly formed ice, several inches think, became buckled into folds, which became more and more steeply inclined until they passed into over-folds, which in their turn became fractured and overthrust. Finally, the western side of the crack overthrust the southern by about 30 inches along most of its length. In local patches the opposite occurred, the eastern side being overthrust over the western; in places symmetrical folds were developed. By August 22 the temperature had risen to $+4°$ F., and the overthrust now increased to 5 feet 6 inches. The old ice was now affected by the expansion, and buckled so that the ridges were 4 feet high or more, and large blocks began to fracture and stand on end. This was the last phase in the movement of the ice in this locality until its final break-up in February 1909.

BREAK UP OF THE SEA ICE

The final disappearance of the sea ice in Ross Sea and McMurdo Sound is the result partly of the disrupting forces of tidal movement combined with ocean swell set up by northerly winds, partly of surface friction of the southerly and south-easterly blizzard winds, and partly of thaw. The thaw of the sea ice takes place partly above, but chiefly below. We observed that the surface of the sea ice was soft and sticky when on the northern journey to the Magnetic Pole Plateau at temperatures of about $+20°$ F., and we found that it was extremely difficult to drag the sledges over it. We did not experience an actual thaw on the sea ice until December 15, during a blizzard. On December 16 the temperature on the Drygalski Piedmont rose to $+33°$ F. at about 11.15 A.M. On December 19 the surface of the sea ice was covered with a good deal of slushy snow, with, here and there, shallow pools of water: this was obviously due to thaw. It may be mentioned that, with the exception of sheltered bays, all the sea ice had gone out from the north side of the Drygalski Glacier at least as early as December 10; in fact, the dense cumulus clouds, which we saw rising from the north side of the Drygalski Barrier on December 4, probably indicated that the sea ice had gone out already by that date. On December 20 the temperature about 3 P.M. near sea-level was $+34{\cdot}5°$ F. The surface of the sea would, of course, have been thawing under these circumstances, but there was such a large quantity of thaw-water from the inland snow and ice spreading over the sea ice, that it was hard to say where the salt thaw-water began and the fresh thaw-water ended. For example, at the foot of the Backstairs Passage Glacier there was a shallow lake spreading there over the sea ice for a length of a quarter to half a mile and width of several hundreds of yards. At the same time we could hear torrents of fresh water roaring in subglacial channels in the ice of the piedmont glacier. There can be little doubt that while a certain amount of superficial thaw does take place on the surface of the sea ice in summer, by far the most important thawing takes place beneath the ice as the result of relatively warm convection currents in the sea water circulating beneath it. On our way to Cape Royds, down Ross Sea and McMurdo Sound, we took constant temperatures when on the *Nimrod*, and found the temperature of the sea water at the beginning of January 1908 varied from 34° F. to 28·5° F. alongside the Ross Barrier. We found the general temperature of the sea between January 23 and January 31 was about 32° F. On January 30, after a moderate blizzard, the temperature of the sea water fell to 28·5°, probably as the result of warm surface water being skimmed off by the blizzard and colder water rising from below to take its place. These temperatures are given in detail in the Meteorological Report, and refer only to the surface water. The only deep sea temperatures, those taken at the Drygalski Piedmont at a depth of 668 fathoms, gave such abnormally high results, that we suspected that they were partly in error. It is much to be hoped that future expeditions will obtain complete serial temperatures at various depths in McMurdo Sound. A point of special interest in relation to such work will be its bearing on the direction of ocean currents in the Ross Sea region. The current indicator, which our expedition established off Cape Royds, showed that normally the current there set towards the north-west.

In the direction of King Edward VII. Land it has been thought by some that the current sets in a general southerly or south by west direction underneath the Great Ice Barrier. It is possible, therefore, that it circulates under the Great Ice Barrier, first flowing towards the south-west, then turning westerly, and finally emerging on the west side of Ross Island, where it has a northerly or north-westerly direction. In the neighbourhood of Captain Amundsen's winter quarters at the Bay of Whales the Barrier is fixed, resting on the bottom, so that there can be no current setting under it just at this spot. Immediately to the south of the Bay of Whales Captain Amundsen determined the existence of a high elongated ridge of ice, 1100 feet above sea-level, and stretching 30 miles north and south. This is at the exact spot where Ross reported the appearance of land in 1839–40. In Amundsen's opinion there can be no question that this long ridge of high ice is underlaid by solid rock. Our colleague, Mr. James Murray, is of opinion that there were indications of a permanent current setting south past Cape Bird towards Cape Royds.* He relates that on March 16, 1908, a quantity of fine broken ice, which was being drifted northerly by a strong southerly wind, was checked on its northerly course by what must have been a strong ocean current, which he thinks came from the north-east. This south-easterly current he assumes to be part of a diverted

* Heart of Antarctic, vol. ii. pp. 372–5.

PLATE LV

FIG. 1

FIG. 2

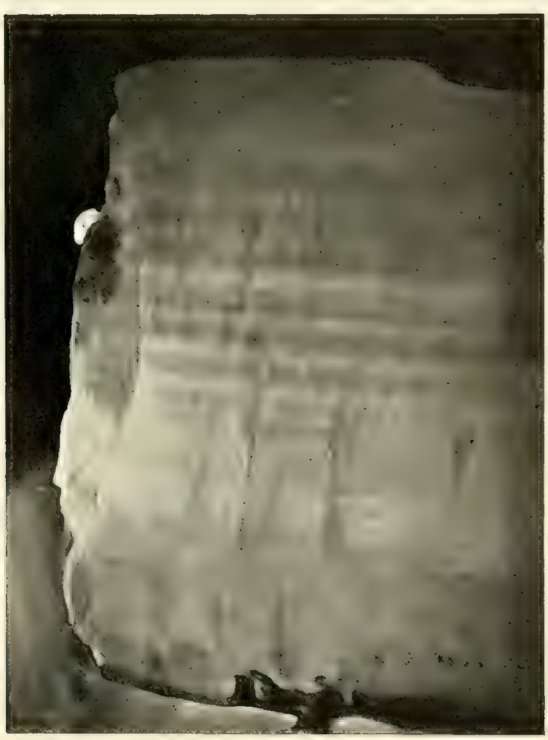


FIG. 3

[*To face p.* 188

current normally setting from Cape Bird towards Cape Royds, that is, setting southwards.

There can be little doubt that the powerful blizzard winds which control the water circulation on the west side of Ross Sea and McMurdo Sound tend to force the water northwards along the shore of South Victoria Land from Cape Royds towards Cape Adare. The easterly winds experienced by Captain Amundsen at the Bay of Whales would obviously tend to drive the water of Ross Sea from the direction of King Edward VII. Land towards Ross Island. One may conclude, therefore, that as the result of the action of these two strong prevalent winds, of which the southerly and south-easterly blizzards characteristic of the Ross Island region are the more powerful, is to cause a clockwise circulation in the waters of Ross Sea.* This satisfactorily accounts for our observed directions of ocean current at Cape Royds, viz. towards the north-west. One would expect from such a circulation, if the deep-seated circulation be similar to the surface, that the warmer water would be drawn down the eastern side of Ross Sea, and that it would exert its greatest influence in thawing the sea ice in that region, and would be somewhat lowered in temperature after passing under the Barrier, and emerging perhaps in part east of Cape Crozier, in part in McMurdo Sound. On its northerly course it would be further chilled by the strong plateau wind blowing from the west off the high plateau on to the western waters of Ross Sea. Thus these western winds contribute another component to control the general surface circulation of Ross Sea. One would expect therefore, theoretically, that the maximum thaw effect exerted by the sea water would be on the eastern side of Ross Sea. The recent observations of Captain Amundsen are not inconsistent with this view. He found that to the north of his winter quarters at the Bay of Whales the sea was constantly open, as indicated by the rising of heavy cumulus clouds and strong water blink actually within about 8 miles of his camp. This open water persisted throughout the whole of the winter. At Cape Royds we were unable during the months of winter darkness to decide whether or not there was open water between us and the mountains of South Victoria Land to the west. Occasional moonlight enabled us to see that apparently the whole of McMurdo Sound during a considerable part of the winter was completely frozen over. This suggests that the sea water temperature here is probably lower than it is near the Bay of Whales. That the greater persistence of sea ice in McMurdo Sound as compared with Ross Sea near the Bay of Whales is due rather to difference of temperature of sea water than to that of surface air temperature is rendered probable by the consideration that Captain Amundsen found that at the Bay of Whales, even with 8 miles of this constant open water, the main air temperature at the surface was often lower than it was for the corresponding period at Cape Evans on Ross Island. So far, therefore, as surface air temperatures are concerned,

* A similar clockwise rotation on the whole dominates the circulation of the water in the Weddell Sea.

this would tend to reverse the actual conditions of the sea ice respectively in McMurdo Sound and near the Bay of Whales.

Obviously what is now urgently needed is a series of current observations at various depths from the surface to the bottom of Ross Sea taken systematically at frequent intervals.

It should be noted that we observed on our ascent of Erebus that the surface of Ross Sea in March froze over earliest under the western mountains, from which one could see from day to day long tongues of ice spreading from the shore far out into McMurdo Sound. After our subsequent experience of the strong cold plateau winds which blow down the gaps in these ranges, especially at night time, we venture to suggest that the very strongly indented shape of the growing ice sheet in this region was due to corresponding tongues of cold air protruded from the outlet glacier valleys allowing these cold air masses to descend from the inland plateau. Obviously this cold plateau wind and the proximity of such high land as the west coast of Ross Sea accounts for this part of the sea freezing over first.

That these ocean currents have a powerful influence in thawing the sea ice was obvious from the slightly honeycombed character of the ice in McMurdo Sound in January and February of 1908. In landing our stores over the bay ice at Cape Royds we frequently came upon what may be termed corrosion hollows, with only a very thin covering of ice over them. These of course were not in any way to be confounded with the seal holes. The fact that the *Nimrod* was able to make some little progress in hammering her way through the ice late in January shows that it must have been immensely weakened as compared with the strength it must have possessed when it was a compact sheet of ice 7 to 8 feet in thickness, as in the autumn. It is not of course certain that the whole of Ross Sea is frozen over during the winter. It is certain that it freezes over, and is continuously covered with ice for many miles eastwards from the coast of South Victoria Land, but no attempt having as yet been made by any ship to penetrate the north-east part of Ross Sea during winter, one cannot predict what its exact state is during that time of the year.

MECHANICAL DISRUPTION OF THE ICE

On September 1 we observed a strong water sky with cumulus cloud over McMurdo Sound, both clear indications of open water. The general appearance of the ice-foot near Blacksand Beach and of the open water is shown on Plate LI. Fig. 3. On the right-hand side is the pressure mound of ice slabs formed in the preceding autumn.

At the time when the Northern Party left Cape Royds on October 5 there was already a long strip of open water in McMurdo Sound extending to within about 5 or 6 miles of the pinnacled ice, so that it was necessary for the party to make a considerable southern detour in order to avoid it. By the time that the party reached the Drygalski Ice Tongue on November 29 long lanes of open sea were spreading shorewards, deeply indenting the sea ice, and threatening to bring about its entire disruption. By the time the party reached the surface of the Larsen Glacier on Christmas Day it was seen that the whole of this sea ice had broken away.

At the time when the Western Party left Cape Royds in November 1908 a slight glazing was noticeable on the northern faces of the snow-drifts on the sea ice, and the sea ice just west of the Penguin Rookery at Cape Royds, particularly where it was discoloured by a large amount of finely powdered guano swept off the rookery by the spring blizzards, showed signs of rottenness. This thawing was further encouraged perhaps by heat radiated from the black cliffs of kenyte rock. From December 1, 1908, to January 24, 1909, we have no complete record of the disintegration of the fast ice. Certainly heavy pack prevented access to Cape Royds early in January, for the *Nimrod* on January 1 was held up in the pack at Beaufort Island, and was unable to reach Cape Royds until January 5. On January 7 she started away again to look for a lost party, and in a few hours she was again jammed in the pack and nearly driven ashore at Horseshoe Bay. She remained fixed in the pack till January 15, and was drifted across the Sound until almost within sight of Granite Harbour. On January 24 the *Nimrod* picked up the Western Party, who noticed that all the sea ice north of a line from the Chinese wall of the Cape Barne Glacier, and passing westwards about a mile north of the north end of Inaccessible Island, had gone out. By January 27 all the ice north of Inaccessible Island had been removed, with the exception of that between Mickle Island, the stranded berg, and Flagstaff Point, as well as a narrow fringe along the coast to Cape Barne. This last was rapidly breaking up. Where facing a large expanse of open water the fast ice usually broke off as long strips with a certain amount of brash ice between.

At Backdoor Bay the first stage of disruption manifested itself as a long crack roughly parallel with the line of open water. The strip of ice between this crack and the open water became later divided by a series of transverse cracks into squarish blocks, and these gradually floated out under the influence of the ebb tide, until they were caught by a surface current and southerly wind and carried round Flagstaff Point northwards to join the main pack. As the thicker and older bay ice was approached the disrupted squares became smaller and smaller, until finally, on February 7, the thickest ice, covered with snow-drifts, broke into almost cubical blocks and was removed, leaving the bare ice-foot. It was remarkable that the blocks of this snow-covered ice frequently had projecting edges 1 or 2 feet wide, either of snow alone or of ice alone. These were due to the fracture being stepped instead of simply vertical, the line of fracture following for a certain distance horizontally the junction line between the snow-drift and the sea ice.

SUMMARY

This completes the cycle in the history of this sea ice. It may be noted that the sea ice is important, both as a geological and meteorological factor, by covering over with a thick, non-conducting layer the relatively warmer surface of the sea itself. The immediate effect of its formation is to greatly lower local temperatures; whenever, as the result of a blizzard wind, the freshly-formed ice was disrupted and driven out temperatures at once rose at Cape Royds. The geological importance of sea ice appeared to us to be generally the following:—

1. During the autumn, winter, and early spring it exerts a protective influence on the shore-line as it checks marine erosion, but when later it becomes broken up, the drifting floes grounding along the coast accomplish a very limited amount of mechanical erosion.

2. Biologically this action is important, as it checks the development of a true shallow water littoral fauna, and accounts for the absence of the shelly beaches so common in temperate and tropical latitudes.

3. It forms a gathering ground for a considerable amount of drift snow, blown off the inland ice fields of the Great Ice Barrier.

4. When broken up the floes bear out with them northwards vast quantities of finely divided wind-blown rock debris, together with occasional larger blocks which have fallen from rock cliffs. By transporting these fragments some distance from the shore seawards, the sea ice, when it melts, sheds a very large quantity of angular rock material, remarkably free from decomposition, on to the marine organic muds of Ross Sea and the adjacent southern ocean.

Fig. 1. FROZEN SEA SPRAY ENCRUSTING BOXES OF STORES

Cape Royds after the blizzard of February 19–21, 1908. In left top corner are the snow bergs aground in 14 fathoms, with Cape Barne in the distance

Fig. 2. DIGGING OUT STORES AFTER THE CASES HAD BEEN BURIED IN ICE DURING A BLIZZARD

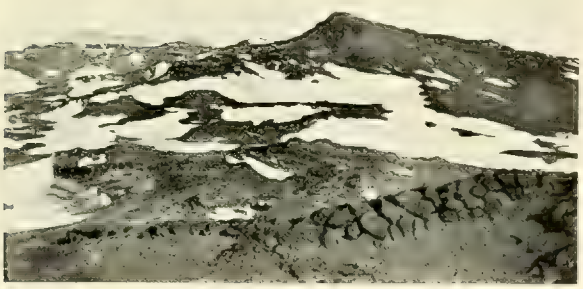


Fig. 3. VIEW OF HIGH HILL, CAPE ROYDS, WITH CAPE BARNE ON THE LEFT IN THE DISTANCE

Showing the effect of insolation in summer in ablating the snow from the surface of the dark kenyte lavas of Mount Erebus

Fig. 4. KENYTE LAVA, SHOWING SPHEROIDAL WEATHERING, NEAR THE PENGUIN ROOKERY, CAPE ROYDS

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CHAPTER X

WEATHERING—DENUDATION—EROSION

WEATHERING

1. *Due to Evaporation.* Ablation, in the sense of loss of volume through evaporation, sublimation, &c., has already been discussed in Chapter II., but some notes may here be given as to the weathering effects which may result from it.

The effect of ablation on salt water ice was well seen in the case of the sea spray which had been heaped over our cases by the great blizzard of February 19–21, 1908. About a month afterwards an attempt was made to recover a case of bottled beer and four volumes of the *Challenger* Reports, and after digging down 3 or 4 feet the search was abandoned. In February 1909 the ice had so far ablated that the site of this trench was only just discernible, and when a trench was sunk for another 18 inches within 2 feet of the former one the *Challenger* volumes were recovered. Thus between 3 and 4 feet of this ice had been removed in the twelve months just past.*

One more effect of the ablation is worthy of comment. The prismatic ice of the southern half of Blue Lake (where it was especially prevalent) evaporated very rapidly, and the evaporation proceeded much more rapidly down the opaque partitions between the crystals than down the crystals themselves, so that they remained standing apart as individual hexagons.

2. *Due to Change of Temperature.* Cape Royds is so littered with morainic debris that it is impossible to tell with any degree of accuracy how important a factor in the breaking up of rock is differential contraction and expansion, the result of sudden changes of temperature. That this agent of weathering is important, however, can be easily seen. After one of the sudden variations of temperature, which were very common at the cape, it was quite a usual thing to find the drifts at the foot of cliffs sparsely covered with flakes of freshly exfoliated rock fragments.

Screes were not nearly as common at Cape Royds as at Cape Barne, but

* Mention should be made of the fact that this ice formed from the freezing of the sea spray was not dense ice, but more or less fibrous, with numerous air spaces. The removal of this 3 to 4 feet from its surface was due no doubt in part to sublimation and in part to thaw. It would of course, by reason of its salinity, thaw more rapidly than fresh water ice.

when these did occur, they gave one some idea of the amount of rock flaked off by the frost-action. Mount Cis, the small parasitic cone on the lower slopes of Erebus, was flanked on one side by such a scree, and the essentially angular nature of the fragments, together with the fact that they were all of the one very local type of rock, precluded the possibility of the debris being of glacial origin.

The highly jointed nature of the lavas at Cape Royds greatly accelerates and facilitates this action, and Flagstaff Point in particular is seamed by huge cracks, and it is always possible, and even probable, that at no very distant date the western half of this cliff may fall into the sea bodily, for there is one crack extending nearly north and south which is in places 3 or 4 inches wide, and in one place it was impossible to touch the bottom of the open part with the end of a 10 feet bamboo pole.

The reason for the disappearance of glacial grooves and striæ at Cape Royds, and indeed from the surfaces of all the land-moraines we visited in Antarctica, is probably largely explained by this frost-weathering. Almost all of the boulders which have their striated surface exposed must have this surface flaked off, owing to differential expansion and contraction resulting in a type of concentric weathering. Many of the holocrystalline boulders at Cape Royds were surrounded with these arc-shaped flakes. Thus the absence of striation on the surfaces of the blocks of the moraines at Cape Royds is amply accounted for, and it is only in places from which the ice has recently retreated, or on the under surfaces of partly embedded blocks, that we are likely to find a large proportion of striated material. The survival of striated roches moutonnées, and of striated blocks, in temperate and tropical regions which have been strongly glaciated in former eras, may perhaps be in part explained by the fact that, once the period of maximum glaciation is over, the region from which the ice has retreated is only subjected to the rapid disintegrating processes of frost-weathering for a comparatively short time.

Another fact which may account for a large number of blocks retaining their striated surface in old glacial deposits is that they are often enclosed in stiff boulder clay, which would exercise a preservative influence on the rocks. It follows from the facts observed, in the region of the Antarctic explored by ourselves, that the only three places where it is likely that striated boulders and rock surfaces should appear in and under the deposits of the present geological period are, (i) on the bed of the Ross Sea, where the material is protected from the action of the frost by the water; (ii) in the deposits at the mouths of the larger glaciers, where the fine sediment brought down by the thaw on the glacier accumulates and protects the boulders; and (iii) in the upper portions of the glacial valleys of the mainland, which are not likely to be exposed to sub-aerial denudation until the very end of the Polar glacial period.

Impressive evidences of the effect of frost-weathering are to be seen in the Ferrar Glacier Valley.

Against all the cliffs bordering the glacier, except those from which the debris

Fig. 1. WEATHERED BOULDER OF KENYTE FROM MORAINE AT CAPE ROYDS

The boulder was originally nearly round and of the full diameter of its base, on part of which it is resting. The rest of the boulder has been removed by weathering

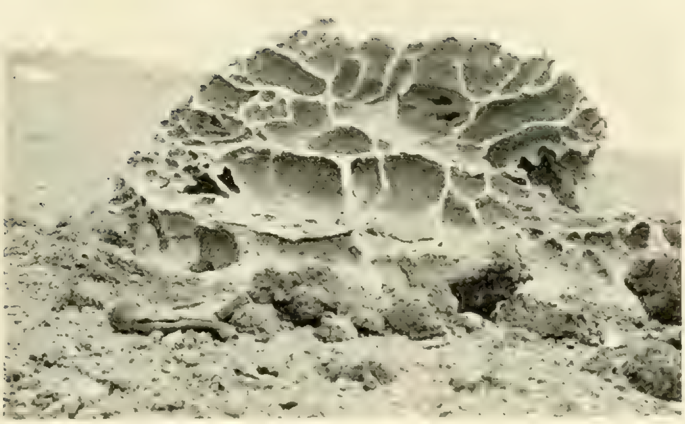

Fig. 2. WEATHERED BOULDER OF KENYTE ON FOOT-HILLS OF MOUNT EREBUS, NEAR CAPE BARNE

Boulder about 7 feet in diameter

Fig. 3. WEATHERED CONCRETIONS OUT OF THE BEACON SANDSTONE, FROM SCREE, KNOB HEAD MOUNTAIN, FERRAR GLACIER VALLEY

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fell directly on the moving ice face, high screes of detritus were piled. These screes in some cases must have reached two or three thousand feet in height, and practically the whole of the material of the upper portion of them must have been derived from the frost-weathering of the cliff faces, for in such situations the action of torrential water must be negligible. The lower portions of these screes contain large quantities of rock which cannot have been derived from the cliffs above them, and must be the material which formed the lateral moraine of the glacier at a former more extensive phase of glaciation.

A phenomenon due to sudden change of temperature was observed during our stay at the Christmas Camp below Knob Head Mountain. During the whole of the stay we met there a very cold breeze, the overflow of the heavy air from the inland plateau, which was blowing over the ice in the neighbourhood of the tent. In the evening we usually lost the sun about half-past nine, and immediately the shadow of the mountain swept across the ice near us the ice was suddenly cooled by the wind, and repeated sounds of sharp cracking would be heard, the cracks taking the form of minute strain lines in the surface of the ice. This action was much more marked in the case of the thin layer of ice covering the boulder holes containing thaw-water, for these layers immediately contracted with reports like a succession of pistol-shots, and sometimes broke up altogether and flew out in all directions, making a noise like breaking glass.

3. *Due to Wind Weathering.* The effect of the sand-blast action on different types of rock was very well seen at Cape Royds, covered as the peninsula was with large and small erratic boulders of almost every description and texture. In the kenyte the porphyritic anorthoclase felspars were more resistant than the ground mass, and stood out all over the rock like iron studs in old-fashioned doors. The wind weathering of the kenyte will be more fully described in the Cape Barne section, for it was at the latter place that the best local boulder was seen and photographed.

Plate LVII. Fig. 1 shows a piece of kenyte, a third of which was embedded in the ground, and protected by the gravel covering it, so that the weathered portion is standing on a natural pedestal. The contrast between this pedestal and the rest of the block gives one a very good idea of the way the felspars stand out in the wind-carved surface, and when it is realised that practically the whole of the exposed kenyte surface is of this description, the roughness of the country can be fairly well gauged.

When there were any lines of weakness in the boulder, for instance, lines of flow in eruptive rocks, or lines of stratification in the Beacon Sandstone, the sand worked much more quickly along these lines, and the rocks were given the appearance shown in the second figure. One specimen of variolitic basalt was reduced to a rim of rock half an inch thick, enclosing a space, about four inches by three, occupied by a series of round balls about three-eights of an inch in diameter, and almost completely weathered out, so that the individual varioles might have been broken off by the hand. One type which was sufficiently common to deserve notice was a basalt with much altered olivines and strongly cleaved augites. Both these minerals, being apparently easily disintegrated, had disappeared almost entirely from the surface of the rock, leaving what was apparently a homogeneous basalt full of small pits.

Lastly, the kenyte tuffs with a soft ground mass had in some cases had this ground mass removed so much that numbers of the kenyte fragments might be seen lying loose around the tuff blocks, and only to be recognised as having been originally part of the block by the presence of a little of the cementing material still adhering to their leeward sides.

The power of this type of sub-aerial denudation must be greatly added to at Cape Royds and Cape Barne—in fact at any place where the country rock is kenyte—by the quantity of small undecomposed fragments of felspar that are lying amongst the debris. The anorthoclase felspars of the kenyte are liberated in immense numbers by the weathering of the rock, and they are liberated in an undecomposed state owing to the excess of mechanical disintegration over chemical alteration. This excess is mainly due to the absence of much water denudation.

These felspars, owing to their perfect cleavage, are easily broken up into small pieces, and are carried by the wind against the face of other rocks, every fragment acting as a small but sharp chisel. When these felspars, for instance, are hurled hard against any obstacle, the resistance does not cause a blunting of the point so much as a splitting into smaller cleavage masses, thus doubling or trebling the number of sharp points.

The presence of these immense numbers of undecomposed felspars, large quantities of which are carried out to sea as fine dust, and similar large quantities removed in larger pieces by the floe-ice and ice-foot bordering the coast, must be having a marked effect on the beds at present forming under the Ross Sea, and partially decomposed sub-angular and angular pieces of felspar will be an important factor in the rocks which these beds will form when finally consolidated.*

Another way in which the winds are playing an important part in the denudation of Ross Island is presented when we consider the quantity of fine material which must annually be deposited in the Ross Sea, having been removed by winds from the peninsula. We have already mentioned in our notes on ablation how, towards the end of October, the whole of the sea ice beyond Cape Barne became dirty with sediment; and all that material must have been deposited in the sea when the ice melted. The fine dust from Cape Royds, and a good deal of fairly coarse material too, must be removed straight into the sea to the north. It is necessary that we should not give the idea that the size of the individual grains removed in this way are all microscopic. By far the greater proportion of the grains are very

* It is well known that undecomposed felspar fragments are very characteristic in the glacial sandstones of Cambrian age in South Australia, as well as in the Permo-Carboniferous glacial sandstones and tillites of India and Australia.

small it is true, but many of them, on the contrary, are quite large. Several members of the Expedition were struck quite heavy blows by the gravel carried from the ridge behind the Hut during some of the blizzards, and pieces up to an inch or more in diameter have been found on the fast ice at distances from the cliffs, which they could have traversed in no other way.

A local effect, but one which must have an appreciable effect off the great rookeries, is the removal of the fine guano dust by the powerful blizzards of the spring. The long ablation during the winter and autumn had caused the accumulation of a lot of loose dust on the Cape Royds Rookery by the end of the winter of 1908, and the first spring blizzard removed the majority of this. There may have been some slight difference in the direction of this wind, which might account for its removing so much of the material which had apparently been almost untouched by previous blizzards, but whatever the cause, the effect was very obvious. The whole of the drifts to the north of the rookery were coloured a deep brown, the fast ice of the Sound was discoloured until it came to an end at Blacksand Beach, large quantities of the dust must have been carried right out to sea, while behind every projection along the coast the snow-drifts were discoloured, and it was impossible to get away from the unpleasant, penetrating smell of the guano anywhere to the north or north-west of the rookery.

In the Ferrar Glacier Valley denudation by wind was not so common as at Cape Royds, but locally it was very active, owing to the influence of the plateau winds. The reason for its influence being less in this valley is not so much that the winds are less, as that the amount of fine gravel which would be used as an agent of friction is insignificant. Such material as is carried on to the surface of the glacier by the winds is either removed by the thaw into the streams, which in their turn carry it to the entrance of the valleys, or is swept by the wind into the channels of the super-glacial streams and lodges there, or perhaps, if left long on the surface of the ice, becomes embedded there, and finally disappears beneath the surface. A limited amount of wind-weathering shows in some of the boulders of the moraines, and where it does occur the weathered surfaces all point up the glacier, so that evidently the strongest and most common winds here met with are those which are caused by the downward overflow of the cold air from the plateau.

It was in the gully between Knob Head and Terracotta Mountain that the most striking instances of weathering of the sand-blast type were to be seen. One was the occurrence of numerous cups of sandstone beautifully polished and concentrically striated on the outside and hollowed out more or less perfectly inside, ranging in size from that of a cocoanut to that of an ordinary glass marble. (See Plate LVII. Fig. 3.) We were for some time puzzled to account for the origin of these "potholes," as we named them, but the mystery was cleared up when a block of weathered sandstone was found which proved to be full of rounded patches, anything up to ½ a foot in diameter, which were of a different colour and consistency to the rest of the rock. Several of these round nodules had weathered out and were lying at different distances from the parent rock, and when one or two of them were collected, and broken across the middle with a hammer, they were seen to consist of a very hard and indurated outer shell from an $\frac{1}{8}$ to a $\frac{1}{2}$ inch thick, enclosing a dark-green ferruginous-looking sandstone of larger grain, and with less cohesion between the grains. The mode of origin of these pot-holes was now clear, for they were to be seen in all stages of formation, from the nodule which was left intact and only polished on the outside, through the various intermediate stages, to the perfect cup, where the inside had been completely cleaned out, and only the outer polished shell was left, containing many of the quartz grains which had been used by the wind as files to get rid of the less resistant portion of the stone. Even a further stage was to be seen, for in time the outer shell itself began to wear away, and the cup became sufficiently light to be moved by the wind, and many had been lifted up and smashed to pieces.

One other testimony to the power of the plateau wind as a denuding agent was well shown, at a height of 6000 feet, on the Terracotta Mountain, where the talus became sufficiently thin to allow the Beacon Sandstone to be seen *in situ*. One of the beds of sandstone was a fine-grained white rock, and this stood out in ledges 18 or 20 inches wide, and the underside of these ledges had been weathered into a series of thin, roughly hexagonal columns from 1 to 9 inches long, and from $\frac{1}{4}$ to $\frac{1}{2}$ an inch thick.

Where these columns hung close together their original structure seemed, as before mentioned, to be hexagonal, and it appears probable that the weathering has been assisted in producing this particular result by some secondary structure due to alteration and secondary crystallisation in the rock itself. When the columns hung farther apart, owing to the gaps made by the entire removal of some, they had lost all definite shape, and resembled nothing so much as stone icicles or stalactites.

4. *Due to Chemical Action.* Chemical weathering plays a very subordinate part at Cape Royds, although the water around some of the large boulders in summer tasted quite strongly of magnesium. This type of weathering is much more developed in the western mountains, and it seems probable from the small part it plays here that the kenyte is not so easily decomposed as other rocks of the region. One phenomenon, which would lead one to an erroneous view of the importance of this agency, is the presence of an efflorescence of salts all over Cape Royds, but these salts are mostly sodium sulphate and chloride, and their common occurrence, when the removal of snow-drifts has caused concentration of the salts contained in the drift, seems to point to their having been brought originally as sodium chloride from the surface of the sea ice, so that the main chemical change that seems to be taking place in the rock material is the filching of the sulphates and their replacement by chlorides. The minerals most probably taking part in this

reaction are compounds containing ferrous iron, and the most probable products will be limonite or hæmatite, causing the rocks to weather brown and red. It is a curious coincidence (if it is not a result of the process) that the removal of snow-drifts by ablation generally exposes a browner soil than the neighbouring permanently-exposed soil.

Although there appears to be very little chemical weathering at Cape Royds, this is by no means the case in the districts examined by the Western Party, who explored the Ferrar Glacier Valley, where this type of weathering seems to play a much more prominent part in the denudation of present land-forms. In the moraines its effect was especially important, and was brought before our notice in three ways. The water of lakes of the Stranded Moraines, and that surrounding the boulders in the moraines of the Ferrar Glacier, tasted very strongly of magnesium, and indeed had a strong medicinal effect. The amount of salt it contained was especially noticeable in the case of many dried-up lake beds in the New Harbour Dry Valley. Where lakes had dried up owing to strong evaporation, their beds were covered with a strong efflorescence of white salt.

Many boulders of the more resistant types of rock represented in these moraines were coated with a crust, in some cases an eighth of an inch thick, of carbonate of lime, and the less resistant rocks, such as many of the softer varieties of Beacon Sandstone, had had all their cement removed, and had become reduced in many cases to heaps of individual quartz grains, whilst many blocks, although retaining some semblance of their original form, crumbled to powder when struck with the haft of a hammer.*

Plate LVI. Fig. 3 illustrates the effect of insolation in dissipating the ice and snow from the surface of the dark kenyte rocks of Cape Royds, and Fig. 4 of the same plate shows the general aspect of kenyte weathered spheroidally at Cape Royds.

DENUDATION AND EROSION

A. *By Avalanches.* The descent of avalanches from the steep rock slopes of the Antarctic Horst was observed by the Northern Party for a few days before Christmas in the neighbourhood of Mount Crummer. At frequent intervals daily great masses of snow would rush down with a deep thunderous roar on to the piedmont ice at the base of the mountain. Such avalanches must of course move with them a certain amount of rock material, but on the whole the denudation accomplished by this factor is probably insignificant as compared with the erosion effected by ice, running water, changes of temperature, and wind action.

B. *By Ice.* Abundant evidence has already been quoted in support of the vast amount of erosion accomplished by ice in this region of the Antarctic. This is proved, both by the subtraction of material from the rocks of the horst, and the addition of sediments to the floor of McMurdo Sound and Ross Sea.

* Frost-weathering of course contributed to make these lumps of sandstone so friable.

Negative forms due to erosion are valleys, both of the wide U, or alb* valley type, and of the trogtal type, hanging valleys, cirques, steps, treads, terraces, and rock basins. In the physiography of South Victoria Land the great feature above all others which arrests the eye of the observer is the extraordinarily long, straight valleys occupied by the outlet glaciers. They resemble nothing so much as vast railway cuttings 50 to 100 miles in length and 5 to 20 miles in width, their smooth sides rising from 3000 to 5000 and 6000 feet above the present level of the glaciers.

Plate LVIII. illustrates a typical glacier-sculptured valley, the Ferrar Glacier Valley, showing the remarkably smooth spurless walls.

Evidence has already been quoted to show the existence of alb and trogtal valleys at Granite Harbour, at the Mawson Glacier, and at the Beardmore Glacier, while there is probable evidence of a similar structure at the Ferrar Glacier. On a larger scale than typical alb valleys are the ancient spillways, through which, during the maximum glaciation, the inland ice overflowed across the great horst to Ross Sea. These are as much as 40 miles in diameter near the Drygalski Ice Barrier Tongue. The great horst has sagged downwards between Mount Nansen and the Ferrar Glacier Valley, thus allowing a vast sea of ice to overflow it bodily during the maximum glaciation.

The rocks of the horst being capped by an almost horizontally bedded formation (the Beacon Sandstone) to a thickness of at least 2000 feet, facilities for observing the amount of erosion are particularly good.

The lowest portions of these gaps are still occupied by glaciers which have now sunk into their *trogtäler*. The erosion of the rocks of the horst has been carried on to far below sea-level, at all events in the neighbourhood of the Drygalski Ice Barrier Tongue. It is of course possible to argue that the ice there, which is some 2000 feet in thickness, has simply occupied a pre-existing deep bay in the sea coast formed by tectonic subsidence. Until far more soundings than are at present available have been taken, one must admit that actual scientific measurement on this subject is somewhat lacking, but as far as the evidence goes, it shows that in the neighbourhood of the present glacier snouts the sea floor is over-deepened, shallower soundings being obtained farther out to sea than close inshore. (See sections illustrating Chapter III.) Obviously this fact is in favour of the rocks of the horst having been cut down far below sea-level by ice erosion.

Another possible view of this phenomenon is that under the weight of ice, during the maximum glaciation, the whole of the land surface, including the shore-line, sank from 2000 to 3000 feet, and that the land glaciers were gradually submerged as the result of this subsidence. At present there is no proof whatever of such a subsidence having taken place, whereas there is evidence of the great horst having risen vertically, probably for fully 50 feet, in recent geological time.

* Mr. T. Griffith Taylor uses the term kar terrace for the flattish floor of what we have termed the alb valley.

MOUNT FERRAR

A TYPICAL GLACIER SCULPTURED

The Ferrar Glacier Valley, showing the remarkably smooth spurless walls. This valley is as dee

A TYPICAL GLACIER SCULPTURED VALLEY

The Ferrar Glacier Valley, showing the remarkably smooth spurless walls. This valley is as deep as the Grand Cañon of the Colorado, possibly deeper

[*To face p.* 200

PLATE LVIII

KUKRI HILLS

VALLEY
p as the Grand Cañon of the Colorado, possibly deeper

[To face p. 200

Cirque structure was not studied in detail, but many fine examples of cirques exist, as near Mount Chetwynd, and in the neighbourhood of the north-west side of the entrance to the Beardmore Glacier, also at the north side of the Mawson Glacier.*

Hanging valleys have already been described in the Ferrar Glacier Valley in this Memoir, and fine examples could be seen in the valleys to the north of Terra Nova Bay.

Steps or treads are well marked in the course of several of the outlet glaciers. Their presence can only be inferred from the existence of numerous large ice-falls, like that to the north of the Suess Nunatak in the Mackay Glacier Valley, where a great rock-bar of quartz-dolerite crosses the valley almost at right angles. These would seem to be developed, in the outlet glaciers, chiefly at the point where the glacier ice, in course of its erosion, has reached the base of the Beacon Sandstone formation, and is recessing itself into that formation, so that it brings down its channel eventually on to the hard resistant rocks of granite, gneiss, &c. Such ice-falls were met with by Captain Scott near the head of the Ferrar Glacier Valley, above Depot Nunatak; by Sir Ernest Shackleton near the great coal-measure and limestone nunataks, Mounts Buckley, Bartlett, and Darwin. The Northern Party also observed from a distance with field-glasses that there were immense ice-falls some 30 to 40 miles inland at the head of the David Glacier, at the point where it was recessing into the Beacon Sandstone of the plateau. Terraces were observed at Ross Island, near Cape Bird, and at Backdoor Bay, as well as on the coast of Victoria Land. They are very strongly marked at Mount Crummer, and much has already been said about the shelf on which the great piedmont of the eastern side of the horst rests. The question as to what extent these terraces are due to marine erosion, glacial erosion, or the effect of running water has already been discussed.

The subject of the glacial erosion of lakes has already been described in detail in the section of this work dealing with lakes, where it has been pointed out that in the neighbourhood of Cape Royds there is good evidence of rock basins having been scooped by ice action to some distance below sea-level. This is notably the case with Sunk Lake near Cape Barne. Deep Lake, Blue Lake, Clear Lake, and Coast Lake are obviously rock basins scooped out of the solid rock by glacier ice.

* A special study of cirque structure has been made by Mr. T. Griffith Taylor, of Captain R. F. Scott's recent Antarctic Expedition, between the Mackay and Koettlitz Glacier regions, and by one of us (R. E. P.) to the north of the Reeves Piedmont. These results have partly been published in "Scott's Last Expedition," vol. ii., partly in the *Geographical Journal* for 1914. In the latter paper Mr. Taylor argues for the formation of outlet glacier valleys by cirque (cwm) erosion, obviously a possible origin. The facts should not be lost sight of (1) that the outlet valleys may be partly tectonic in origin; (2) that even if the Antarctic Horst post-dates Lower Miocene time when river erosion dominated Antarctic relief, the strip of the earth's crust occupied by the horst may already have been somewhat notched by river valleys previous to the faulting which produced the horst.

C. *By Weathering.*—The vast importance of the denudation effected by weathering, brought about chiefly by evaporation, by diurnal ranges of temperature, and by wind, have already been described at the beginning of this chapter. We would here specially emphasize the enormous importance of wind in removing snow from inland seawards. The heavy cold air over the Antarctic Continent, as from time to time it rushes seawards into the great trough of the atmosphere near 62° S. (*Der Rinne*, or *Die Luftfurche* of Hann), not only bears seawards most of the new-fallen snow, but tears out deep furrows in the old snow, thus forming the sastrugi. Near the Magnetic Pole area these sastrugi are fully 3 feet in height.*

This wind erosion may very likely remove at least as much snow annually as is annually added as the result of precipitation.

D. *By Thaw and by Running Water.*—We may now pass on to consider the phenomena of thaw and the erosion accomplished by running water.

It was on November 13, at our winter quarters at Cape Royds, that the thaw was first noticed to be taking effect, when many boulders of black kenyte, which had snow in their crevices, showed large wet patches owing to the heat from the sun raising the temperature of the dark rock and melting the snow. Several large erratics of the same rock, resting on ice, or surrounded by snow-drifts, developed shallow pools around themselves the next few days, and the thaw might be said to have commenced.

By the end of November the thaw had fully set in, and those drifts which had withstood the ablation of the winter and spring were fast disappearing. The thaw seemed to strike along parallel lines in the drift, resulting in sharp knife-edges of coarse-grained *névé* with deep depressions between, the ridges being parallel and striking upwards at a slight angle of 10° to 20° measured from the horizontal, in the one or two cases particularly noticed, towards that direction where the sun would have most power on the particular portion of the drift. Thus, a drift sheltered on the southern side, as they usually were, would have these ridges with their edges pointing towards east on the eastern side of the drift, north on the northern side, and west on the western side; probably the depressions and ridges were caused by the sun working back quicker along the bedding planes of snow charged with dust particles produced annually, or perhaps, after each blizzard season, by the concentration of the sediment in the drift.

One curious feature in the thaw, partly caused by the intense blackness of the rock at Cape Royds, was that in many cases the thaw proceeded much more quickly from below the snow-drift than from above. We have trenched through a small drift, 3 or 4 feet thick, in midwinter, and found it to be snow right through to the rock, yet when it was trenched again a month after the return of the sun in the spring

* Bage, Webb, and Hurley, of Dr. Mawson's Expedition, report that in 1912–13, in their journey towards the South Magnetic Pole area, they encountered sastrugi, to the south-east of Adélie Land, quite 5 feet in height.

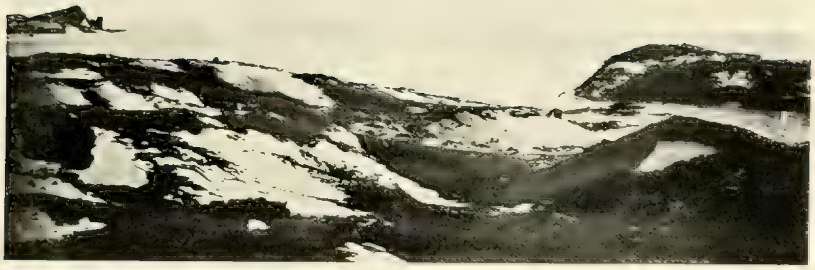


Fig. 1. LOOKING S.S.W. FROM CAPE ROYDS ACROSS THE NOW NEARLY SNOW-FREE SURFACE OF KENYTE

The heaviest snow-drifts are on the north-west sides of the slopes. To the right is a broad U-shaped hollow eroded by an ancestor of the Ross Barrier. To left of centre on horizon is Inaccessible Island, with Tent Island at the back of it; then to the left, more distant, is Razorback Island, then Cape Barne and Cape Barne Pillar

Fig. 2. SURFACE OF FERRAR GLACIER

Showing the remarkable etching effect of the sun on the surface snow-drifts in producing shallow sharp-edged basins, like those of siliceous sinter terraces

[Photo by Sir Philip Brocklehurst.

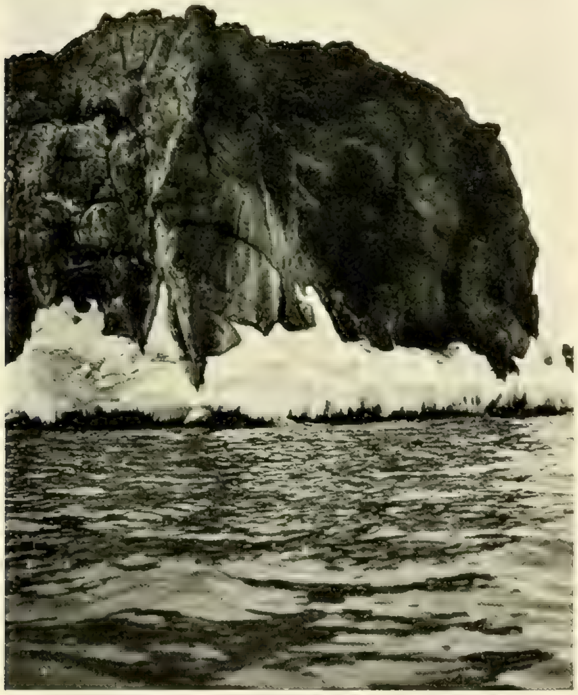


Fig. 3. FLAGSTAFF POINT

Cape Royds, a bluff of kenyte lava about 80 feet high, showing results of marine erosion

[Photo by David

Fig. 4. COAST AT CAPE BARNE

Showing cliffs (of basalt) 300 feet high, the result of marine erosion

[*To face p.* 202

of 1908, the snow, 2 feet from the rock, was converted into a coarse-grained *névé*, graduating into ice as the rock was approached, and before the end of November a small rivulet was seen flowing from underneath the drift, whilst the surface, except near the edges, seemed to have remained comparatively unaffected.

At Cape Royds, as observed at the Stranded Moraines later on, there was a periodicity in the thaw which was not governed by the amount of sun's heat so much as by the complete, or almost complete, removal of the smaller snow-drifts, and the necessary lull until the snow-drifts had been renewed by a drift-laden blizzard or a snowstorm. Our observations of thaw at Cape Royds are naturally somewhat incomplete, as after December 1, 1908, there was no geologist left at the winter quarters.

It is quite a common thing for snow-drifts to melt quite quickly on slopes exposed to the summer sun, and for the thaw-water to become frozen when it reaches a hollow where the sun has no direct effect.

A well-marked example of this, much exaggerated by circumstances, was seen when the snow-drift on the ridge at the back of the Hut commenced to melt in December 1908. The thaw-water which ran below the house, where the sunshine could not penetrate, and the air temperature never rose above 32° F., froze at once, and never again thawed. Each day's thaw added another layer, until the snow-drift had disappeared entirely from the hill, and there was a pool of ice 18 inches to 2 feet deep below the Hut.

We are indebted to our biological colleague, Mr. James Murray, for the following information in regard to the summer thaw of the lakes at Cape Royds :—

SUMMER THAW OF THE LAKES, CAPE ROYDS

Accounts have already been given, in Chapter V., of the thaw observed by the Western Party in the Ferrar Glacier Valley, and the thaw-water streams are illustrated in Plate XVIII. Fig. 1 and Plate XIX. Fig. 2.

1908.

Oct. 13. No open water in any lake.

Nov. 4. Clear Lake. A few inches of water lying on the ice in narrow zone along the black rocky ridge.

Nov. 14. No open water at any lake.

Nov. 28. Blue Lake, pool at the Narrows (never thawed further), Pony Lake, several small pools.

Nov. 29. Green Lake, thawing at edge.

Nov. 30. Blue Lake. Pools on the ice at margin formed by thaw-water running down from drifts.
Coast Lake, melted at edge.

Dec. 11. Clear Lake. No melting except narrow band round the island which you could step across. (This lake never thawed more.)

Dec. 13. Pony Lake, three ponds formed, the largest at hut; overflow by two streams, one going to the Rookery and the other to Arrival Bay.

Dec. 29. Green Lake and Coast Lake, about half melted.

1909.

Jan. 2. Coast Lake all melted but a small patch. (In Blue and Clear Lakes found pools frozen.)

Jan. 18. Coast Lake and Green Lake all melted.

Feb. 2. Green Lake all frozen except hole 2 yards across in centre.

Feb. 24. All lakes frozen, ice thick (1 foot or more in Coast Lake).

Dec. 1 to 4. Maximum thaw on land. Snow gone from all Cape Royds District except little drifts at north side of peaks and ridges. Thaw-water from drift behind hut, flooded beneath hut (2nd December). Small streams running in all valleys, and their channels green all over with algæ.

Drygalski-Nansen Region. Little evidence of much work being accomplished by thaw-water was observed by us in this area. On December 22, 1908, we found a pool of thaw-water on the surface of the ice, fed by a subglacial stream coming from an old rock moraine on the piedmont about 2 miles off the coast. On December 22, 23, and 24 a thaw-water stream could be heard roaring along under the snow and glacier ice of Backstairs Passage, next to the northern granite cliff of Mount Crummer. This was evidently flowing at the bottom of the snow-filled fosse at the base of the cliff. This thaw-water formed a shallow lake about half a mile by a quarter of a mile over the surface of the old sea ice at the foot of the glacier. At this time avalanches were descending from time to time from Mount Crummer. At the south side of the Drygalski Ice Barrier Tongue, at the point where our route reached its farthest point east, we observed a glacial torrent channel entering a kind of estuary, or inlet, in the Barrier. The inlet was about half a mile in length, and then passed into a narrow torrent channel 10 to 20 yards wide and about 20 to 30 feet deep. The channel was cut chiefly out of drift snow, partly out of ice. The following is a sketch plan of this thaw-water channel (Fig. 59).

A curious and very beautiful etching effect was observed on the Larsen Glacier portion of the Drygalski-Reeves Piedmont on January 31 and February 1, 1909. The surface of the piedmont was found to be covered with curved anastomosing plates of thin ice, dipping at angles of approximately 30° or so, and on the whole, while the direction of dip varied, showing a general tendency to dip away from the north towards the south.

Sledging over these inclined thin sheets of ice might be compared to tramping over a wilderness of cucumber frames inclined at the above angle, the ice plates sometimes supporting one's weight, sometimes giving way with a crash, and letting one through up to one's thighs on to the surface of the solid ice below. Our colleague Murray's explanation of a somewhat similar structure probably applies to this region also: *—

"In the height of summer the combined action of the sun and air on compacted

* Heart of the Antarctic, vol. ii. p. 341.

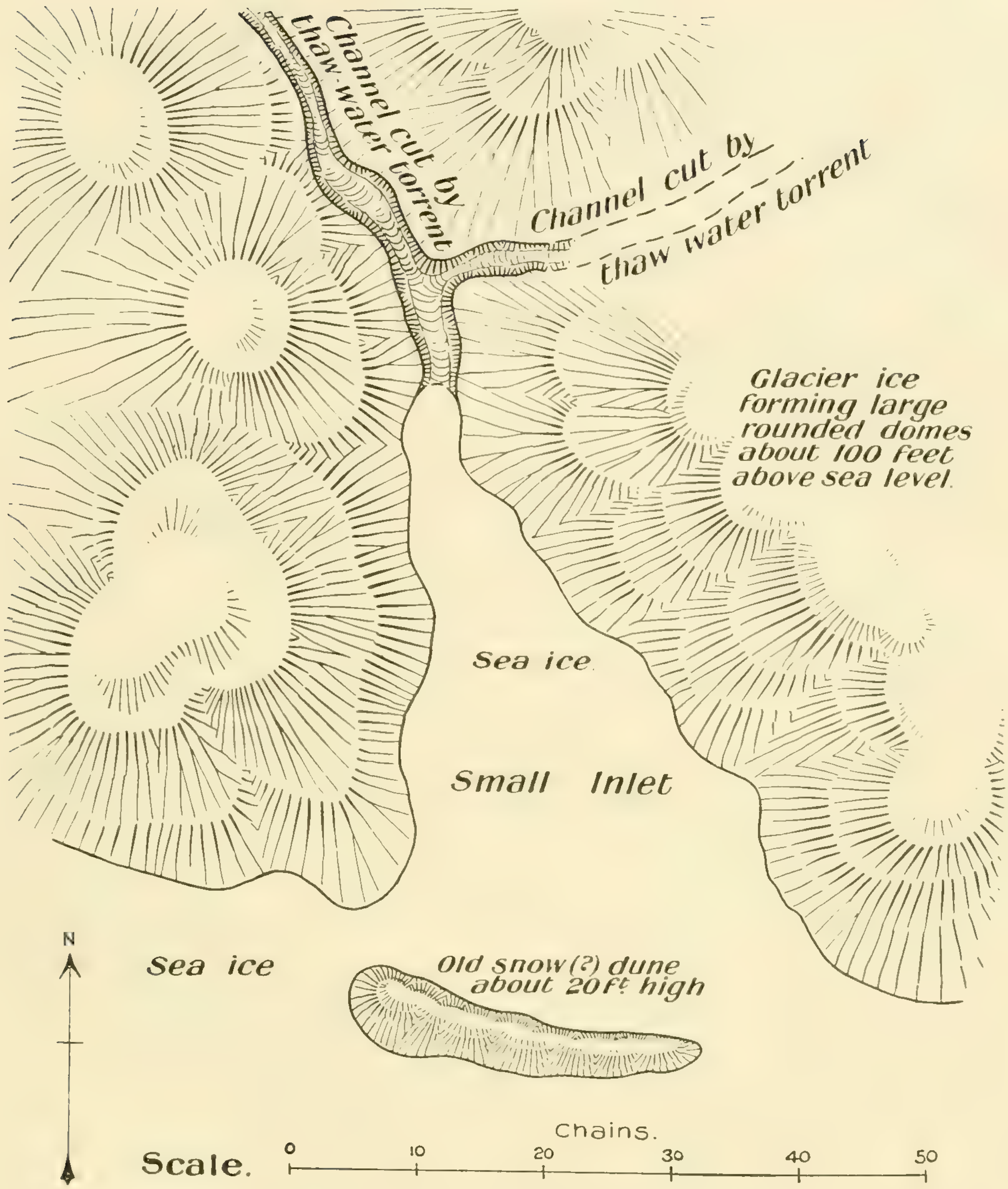


Fig. 59. Sketch plan showing small inlet receiving the drainage of a surface glacial stream on the southern side of the Drygalski Ice Barrier Tongue at a point 20 miles west of its seaward end

snow-drifts caused deep erosion of the snow. A kind of stratification resulted, which appeared to have no relation to any original stratification of the snow. Thin flat layers of ice were formed, separated by cavities. These dipped at a gentle angle to the south, that is to say, their edges were directed towards the sun at the time of day when it is highest. These ice plates were so fragile that they collapsed in multitudes as we walked over the drifts, and a slight breeze whirled quantities of them along, often rolling them on their edges."

In the Drygalski-Reeves Piedmont area these plates were much thicker, frequently quite strong enough to support the weight of a man.

There can be little doubt that this remarkable and beautiful structure is the result of etching of old snow-drifts by the heat rays of the sun. The thawing of the surface snow sets free thaw-water, which under gravity creeps down the planes of bedding of the snow, being arrested by the less pervious layers, and there during the cold of night it freezes, and the process being repeated from day to day, the remarkable inclined plates of ice result.*

This is not a complete explanation of the phenomenon, for, as Murray remarks, "a stratification resulted which appeared to have no relation to any original stratification of the snow."

Transportation. The glacier itself is still a very important agent of transportation, but the amount of this work it does to-day is nothing to what it must have done at or near its maximum period of glaciation. All along the length, wherever the slope of the sides of the valley is gradual enough to support debris, they are strewn with a miscellaneous collection of rock which, for many hundreds of feet above the present level of the ice, can only have been carried and deposited there by the glacier. In many places the rock is mingled with angular fragments, obviously derived by frost-weathering from the neighbouring cliffs, but the presence of the old lateral moraine is still indicated by the number of subangular and rounded blocks of rock in the lower portion of the screes.

Another important agent in removing the light material is the wind, and its power is shown by the amount of small sediment which is scattered over and in the surface ice of the glacier.

Lastly, the agents which are having most effect at the present day are the many streams of thaw-water which seam the glacier in every direction during the thaw-season. Immense quantities of fine sediment must be annually removed in this manner in spite of the shortness of the thaw-season, for all these streams that we saw had a good deal of small gravel in them, and those pouring into the lake near the Solitary Rocks were thick with sediment. The result of this transportation is well seen in the New Harbour Dry Valley, from which the ice has retreated, leaving a vast hummocky sheet of the ice- and water-transported debris exposed to view.

* Unfortunately we had exhausted the last of our photographic plates before we descended from the Magnetic Pole Plateau on to this unique type of glacial surface, and so are unable to figure it.

MARINE EROSION

There is evidence of a considerable amount of marine erosion having taken place in the Ross Sea and McMurdo Sound areas since the close of the phase of maximum glaciation. At Cape Barne, for example, there is a sheer cliff about 200 feet in height which has obviously been cut out by the sapping action of stormy seas in summer time. During the colder periods of the year obviously no marine erosion can take place on account of the surface of the sea being crusted over with ice. Flagstaff Point, near our winter quarters, exhibits a sheer cliff of marine erosion about 80 feet in height. (Plate LIX. Fig. 3.*) The denuding force of the sea also expends itself of course on piedmont ice, ice barriers, and glacier ice tongues. In the case of the Nordenskjöld and Drygalski Ice Tongues the combined effect of sea and wind erosion had been to round off and level off the weather side of the ice tongue. The same feature was noticeable at Glacier Tongue.

Throughout its whole length the Ross Barrier exhibited a deep wave-worn groove at its base. All icebergs, excepting those quite freshly calved, showed the same feature. The terraces, which were conspicuous near Cape Bird and above Backdoor Bay near Cape Royds, may be due to marine erosion, or possibly may mark former levels of fresh water lakes at the margin of the great lobe of the Ice Barrier when it completely filled McMurdo Sound. In this case these terraces are comparable with the parallel roads of Glen Roy or the seter of Scandinavia and Greenland. Even when high waves are raised in the open sea by the action of blizzards, like the great blizzard of February 16, 17, and 18 in 1908, their effect on the coast is not entirely destructive, but in the long run is protective, for towards the end of that blizzard we observed that the coast-line for some distance inland was coated with a thick crust of ice formed from the freezing of the spindrift and spray. This effectually protected the rocks fringing the coast from further marine erosion. The protective character of sea spray in strengthening and consolidating the snow-drifts of the ice-foot has already been explained in Chapter VIII. At the same time, it is obvious that the wetting of extensive cliff faces with sea spray by the blizzard winds, followed by a quick freezing of the films of sea water, which have penetrated the joints and cleavage planes of the rocks, must have a very strong destructive influence, owing to each film of ice thus formed wedging off flakes of rock. In this way marine erosion considerably aids normal frost weathering in the work of rock destruction.

* See also Plate II. Fig. 2 illustrating the great wave-worn cliff at Cape Washington.

CHAPTER XI

VULCANISM

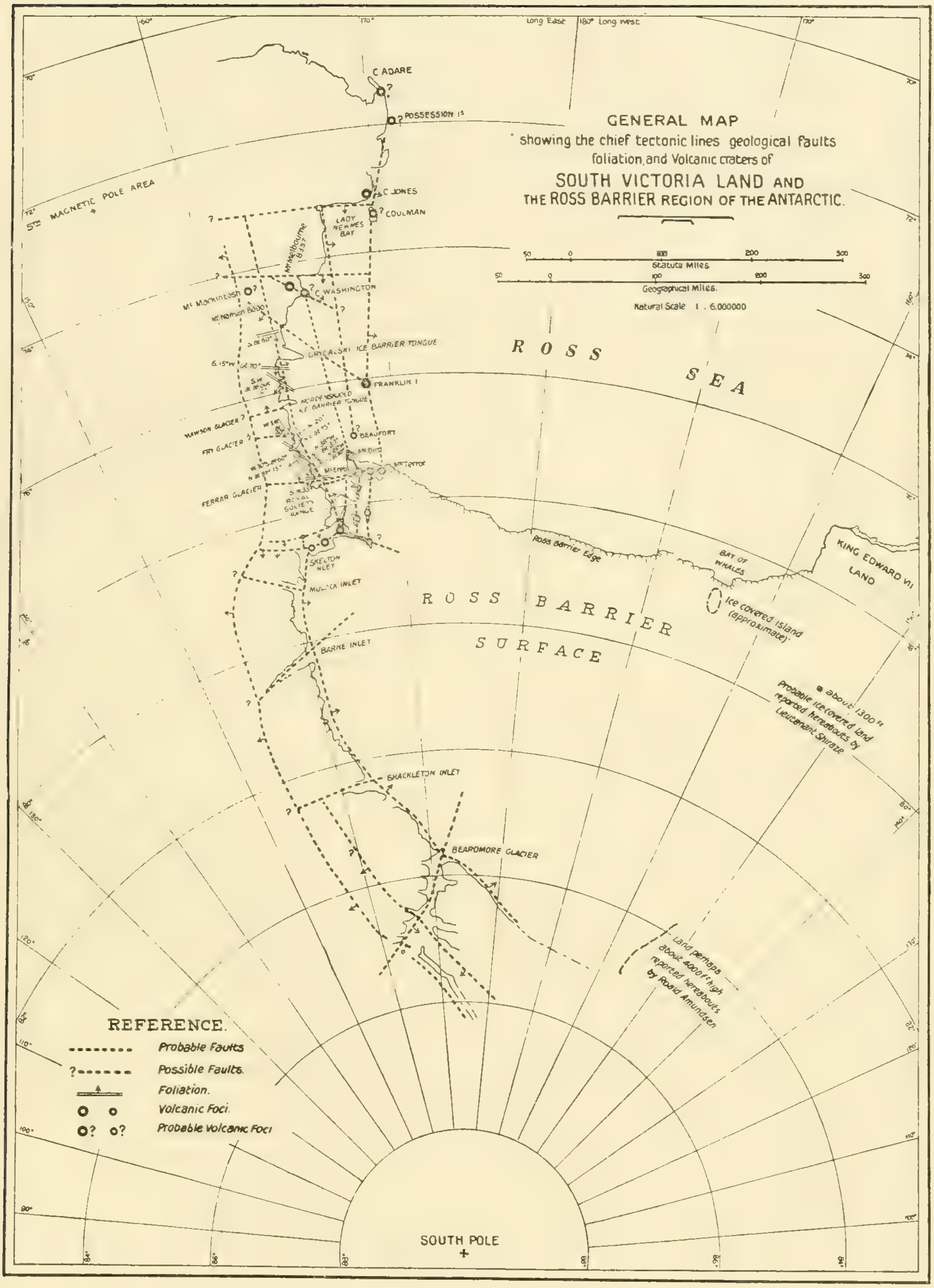
The chief volcanic trend lines have already been described in Chapter I., dealing with the physiography of the region. In this chapter it has been explained that the chief volcanic centres are situated at the ends of a network of faults running partly parallel to the great horst, partly more or less rectangular to it, as shown on the accompanying Plate LX. The volcanoes may probably be grouped in two main zones.

Firstly, the zone to the east of the horst; secondly, that which lies to the west. The latter has not yet been definitely proved to be volcanic, but the shape of many of the hills on the western side of this horst, such as Mount Judd, Mount Bowen, Mount Priestley, Mount Mackintosh, suggest that they are probably volcanic, and the rocks of which they are composed appear to be very black. The existence of this western zone may be looked upon at present as problematical, and our attention may now be directed to describing the volcanoes on this belt to the east of the great horst. This zone, having a general north and south trend, is crossed by strong tectonic lines running either due east and west, or from about E.S.E. to W.N.W. One of the strongest of these cross lines is that upon which Mounts Terror, Terra Nova, and Erebus are situated. This great fracture zone runs through Cape Royds, and, according to the discovery just reported by Mr. F. Debenham, undoubted traces of it are met with at New Harbour in the form of very recent craters of basic lava.* These occur near New Harbour. Thus this strong transverse line has a length of nearly 100 miles in an east and west direction measured from Cape Crozier to Dry Valley.

Our description will commence with Erebus and its parasitic cones, touching next on Cape Royds, the Dellbridge Islands, Hut Point, and finally Mount Bird, all these localities being situated on Ross Island, which is itself entirely composed of lavas and tuffs of Cainozoic age, except for some insignificant inclosures of what appears to be Beacon Sandstone in the lavas.

Mount Erebus. The general appearance of Mount Erebus is well shown in the photograph by Dr. D. Mawson forming the frontispiece to this Memoir, as well as in Plate II. It will be noticed that, if one looks across the ice in the foreground at Backdoor Bay, one sees a wide belt of mounds of moraine gravel, amongst which occur at intervals patches of raised marine muds, together with shallow ice-filled

* Press account of scientific results of the Scott Expedition.


GENERAL MAP
showing the chief tectonic lines geological faults
foliation, and Volcanic craters of
SOUTH VICTORIA LAND AND
THE ROSS BARRIER REGION OF THE ANTARCTIC.
Statute Miles
Geographical Miles.
Natural Scale 1 . 6.000000
Long East
180° Long West
C ADARE
POSSESSION Is
C JONES
COULMAN
LADY NEWNES BAY
C WASHINGTON
FRANKLIN I
BEAUFORT
ROSS SEA
5TH MAGNETIC POLE AREA
FERRAR GLACIER
SKELTON INLET
BARNE INLET
SHACKLETON INLET
BEARDMORE GLACIER
Ross Barrier Edge
BAY OF WHALES
KING EDWARD VII LAND
ROSS BARRIER SURFACE
Ice covered island (approximate)
about 1300 ft
Probable ice covered land reported hereabouts by Lieutenant Shiraze
Land perhaps about 4000 ft high reported hereabouts by Roald Amundsen
SOUTH POLE
REFERENCE.
Probable Faults
Possible Faults.
Foliation.
Volcanic Foci.
Probable Volcanic Foci

lakes or dried-up lakes, the floors of which are strewn with remains of algæ and diatoms. These moraines ascend to a height of from 1000 to 1100 feet above sea-level. In the description of the raised marine deposits attention is called to the fact that the one near Cape Barne, at an altitude of about 160 feet above the sea, is actually resting on a foundation of ice. It is very probably the case that there is still a considerable amount of ice, perhaps a relic of the ice of the former Great Ice Barrier, still preserved under this moraine debris.

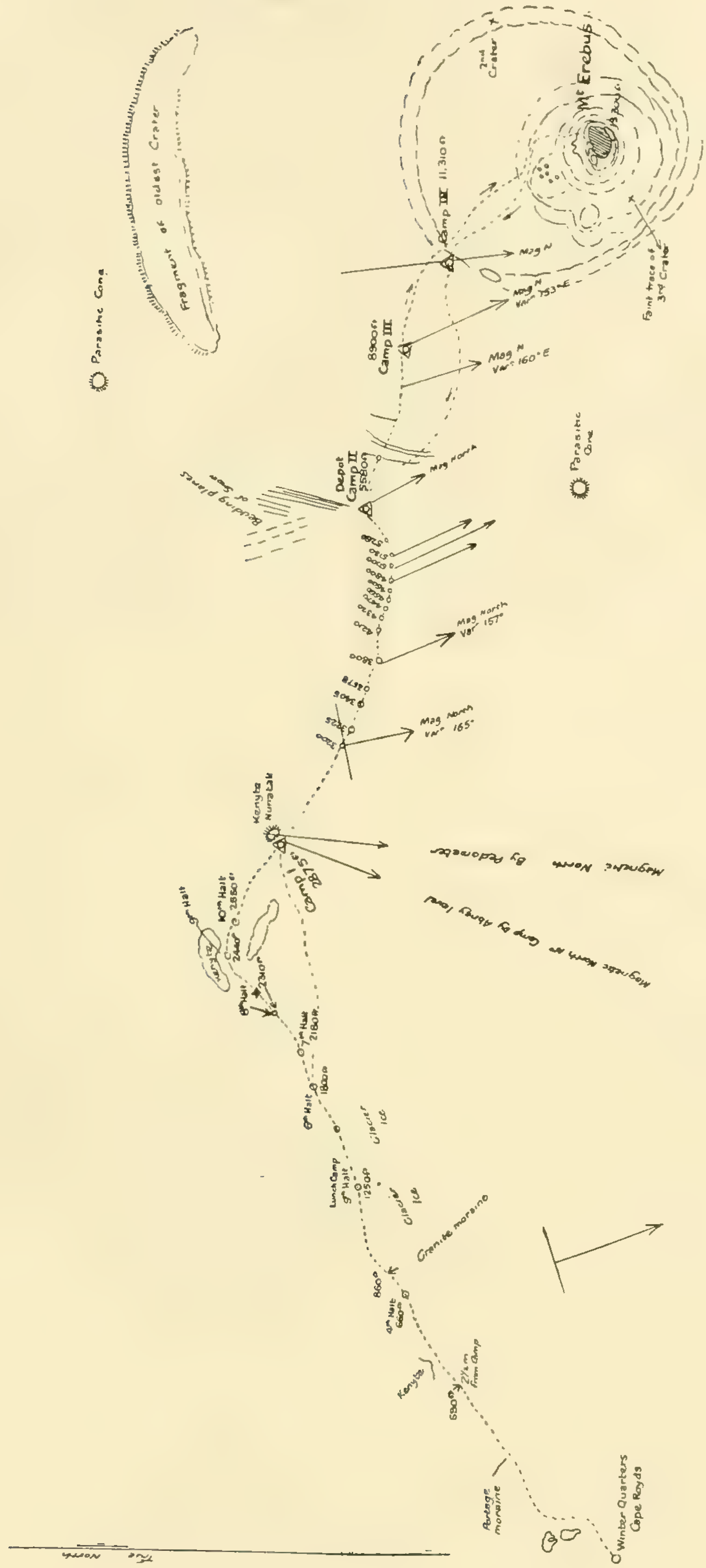
A little to the right of the centre of the photograph above the termination of the moraines two parasitic cones are visible. Of these, the one described in detail, Mount Cis, is the one which lies to the right of the other.

In the centre of the picture, and in the middle distance at the foot of the steep cone proper, is a large and very conspicuous black parasitic cone surrounded by a very deep snow fosse. This is probably on the line of fracture trending from the centre of the second crater towards Cape Royds. On the extreme left of the great cone there is just visible the rugged outline of the great cliff forming part of the first and oldest crater of Erebus. This oldest crater is now largely in ruins, with only small portions of the crater wall preserved at intervals. Its diameter is about 8 miles, as estimated by Mr. H. T. Ferrar,* which agrees closely with our own measurements.

Unfortunately on our ascent of Mount Erebus in March 1908 we were unable to visit this first and oldest crater. Its general appearance, as viewed from the summit of the active crater, is shown on the accompanying Plate LXI. Fig. 2. The greatest altitude attained by the rim of this oldest crater was not accurately measured, but appears to be of the order of about 8000 feet.† On its inner edge is a stupendous cliff, almost vertical, apparently over 2000 feet in height. Thus the oldest crater was a gigantic explosion crater somewhat analogous to that of Teneriffe. Within this rises the second crater, with its steep outward slope showing that concavo-convex outline so characteristic of cones formed of volcanic ejectamenta. It is buttressed by gigantic arêtes of black kenyte lava. At the foot of the steep slope of this second crater we observed some smoothed surfaces of ice, evidently representing frozen lakes. These have probably been formed by the thaw-water resulting from the melting of ice and snow in contact with the black kenyte lavas, which in summer absorb so much of the sun's heat that they become quite warm to the touch. This second crater terminates in a magnificent perpendicular—in places overhanging—wall of black kenyte lava. The second crater itself is fully 3 miles in diameter from north to south, and about 2¾ miles from east to west. The great cliff forming its inner boundary wall is in places at least 80 feet in height. The crater itself is piled up higher towards its southern end by the material of the third and fourth craters, the

* National Antarctic Expedition, 1901–4, Geology.

† According to the estimate of a party which examined this old crater in 1912 on their way to the summit of the mountain, it reaches a height of about 10,000 feet (R. E. P.).



Scale 1 mile to an inch

Fig. 60. Plan showing route of party which made the first ascent of Mount Erebus, March 5 to March 11, 1908, together with position of craters and local magnetic variations

last being still active. Its central portion is filled largely with bands of felspar crystals with pumice and a little sulphur alternating with bands of drifted snow. All around the northern, western, and eastern portions of the inner wall of the crater there runs a deep fosse, the appearance of which is shown on the accompanying sketch. This fosse is formed in two ways. In the first place, the absorption of solar heat by the black rocks so warms them that the snow and ice in contact with them melts away, often for some distance back from the rock face. In the second place, the blizzard winds are blowing here from the S.S.E. or S.E., and impinging against the sharp summit of the crater rim produce a very violent back eddy. This helps to further excavate the snow filling the old crater, leaving a clean vertical wall of snow with an overhanging snow cornice. We were at a loss for some time to find a crossing place over the fosse, until at last we reached the snow-drift shown on the sketch (Fig. 2).

This second crater is formed of kenyte lava, like the third and fourth craters. Its altitude as determined by aneroid is about 11,300 feet. The extraordinary ice structures due to the freezing of the vapour from numerous fumaroles and solfataras are illustrated in the photo by Dr. Mawson (Plate LXIII. Fig. 1). It may be mentioned that for about a couple of miles before reaching the foot of the slope of the great cone, to which this crater belongs, we observed several fragments of very fresh and somewhat glassy kenyte lava. This occurred in the form of lapilli and bombs, varying in size from that of a hazel nut to that of a man's head. These had an extremely fresh appearance, which makes it probable that Erebus has been in a state of eruption in very recent time. These bombs were met with at a distance of about 4½ to 5 miles from the present active crater. They must have been carried to between W.N.W. and N.W. from the active crater by a strong south-easterly blizzard. That such blizzards actually crossed right over the summit of Mount Erebus on occasions was proved by us as the result of our experience in the terrific blizzard of March 8–9, 1908, which we encountered when at an altitude of 9000 feet on the north-west slope of Erebus. The floor of the second crater, deeply filled with snow and ice, was very strongly grooved by the blizzard wind in a general south-east and north-west direction, leaving hard sastrugi in high relief. The angle of slope of this second great cone of Erebus is gentle at first, but rapidly increases until it reaches an angle of 34°. Its sides are formed of arêtes of jagged lava, with smooth, hard marble-like *névé* slopes between.

In regard to the fumaroles on the floor of this crater we observed that approximately one hundred were visible, out of which some twenty were sufficiently near for us to observe them carefully, and we saw that nearly all were emitting vapour from chimney-like openings at their sides or summits. These openings were mostly situated to leeward of the prevalent winds. The fumaroles appear to be joined together underground by tortuous channels and irregular crevasse-like openings in the ice. The temperature of the vapour, though obviously above that of the surrounding air, was not sensibly warm. It must be explained that none of these

PLATE LXI

Fig. 1. PANORAMIC VIEW OF MOUNT EREBUS, LOOKING EAST
with the heavily glaciated region of Cape Royds in the foreground. Cape Barne is on the extreme right

[Photo by D. Mawson

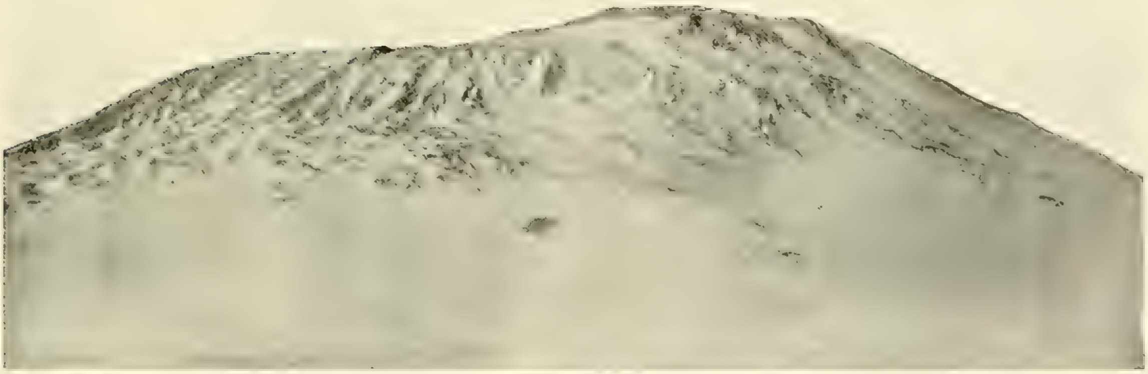


Fig. 2. TELEPHOTO VIEW OF MOUNT EREBUS TAKEN FROM CAPE ROYDS, 15 MILES DISTANT

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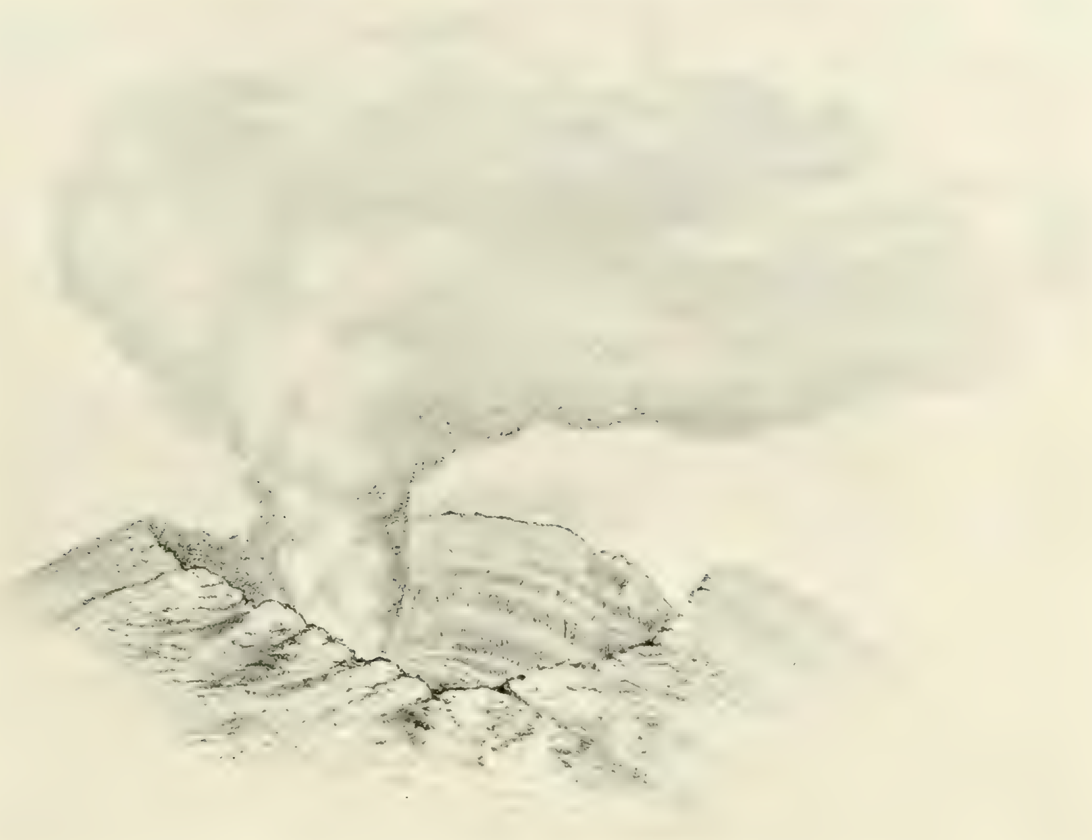

FIG. 1. ERUPTION OF EREBUS ON MARCH 10, 1908, LOOKING SOUTHERLY

FIG. 2. VIEW OF EREBUS LOOKING ABOUT E.S.E.
[Photo by E. S. Marshall

FIG. 3. LOOKING ABOUT N. BY W. FROM SUMMIT OF ACTIVE CRATER OF EREBUS across the floor of the second crater to the dark cliff of the fragment of the first and oldest crater. Cape Bird, about 30 miles distant, is just visible to the left of this oldest crater
[Photo by D. Mawson

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fumaroles were in active eruption at the time of our visit on March 9, 10, 1908, and merely a very gentle current of air was issuing from them. At times, when the steam cloud over Erebus was developed on a larger scale than usual, it seemed to us that an outburst took place from some of these fumaroles, and no doubt at such a time hot steam and various vapours, especially sulphurous, would be given off. The shapes of the raised mounds around the mouths of the fumaroles was most weird and fantastic, some resembling pinnacles or minarets, others being dome-shaped like gigantic beehives. Many recalled the shape of the ventilating cowls used on the decks of ships. Their height was mostly from 10 to 20 feet.

In ascending the gently-inclined filled-up floor of this second crater we reached, at an altitude of about 12,000 feet, what appeared to be a small parasitic cone within the old crater. Fragments of lava and felspar crystals in its vicinity were covered in places with sulphur. The ice, too, in patches near here was of a lemon-yellow hue, owing to the admixture with it of sulphur. Here we saw that the covering of snow became thinner, until it almost entirely disappeared, being replaced by a surface formed of crystals of anorthoclase felspar from half an inch to 4 inches in length. These were mostly very perfectly formed, but many showed signs of their angles and edges having been considerably abraded through attrition. Here and there one noticed a small quantity of volcanic glass adhering to the crystals, and amongst them were numerous fragments of pumice, with the large porphyritic anorthoclase crystals entangled in it. Evidently these crystals had formed at a considerable depth below the surface in the volcanic chimney, or reservoir, beneath it, and when the magma, charged with these porphyritic crystals and steam, reached the surface, the glassy magma had been blown, through the force of the steam explosions, into the form of impalpable dust, thus setting free the porphyritic crystals, which must thus, during an eruption of Erebus, form a continuous hail-storm for some distance around the crater. The direction in which the maximum fall of these crystals takes place is controlled by that of the prevalent winds at the time.

The character and shape of these crystals, as well as of the pumice in which some of them are included, is shown on the accompanying plates (Plates LXIV. and LXV.).

It may be mentioned that on the evening of March 9, at 8.30 P.M., at the rim of the second crater of Erebus, at an altitude of about 11,350 feet, light snow fell. The sky at the time was quite thickly overcast. The fact that snow actually falls over the summit of Erebus is obviously of some meteorological interest. Just previous to the snowfall a perfect sea of dense cumulus cloud had been seen by us rolling inland from Cape Bird to at least as far south as Cape Royds, and was surging against the foothills of the great cone of this second crater, at an altitude of about 6000 feet above sea-level. It is possible that this northerly wind, bringing in with it the cumulus snow-clouds from off Ross Sea, climbed the slopes of this second crater, parting with more moisture as it became chilled in its ascent, and so produced the snowfall. On other occasions we observed that the summit of Erebus was capped by snow-cloud which gathered on top of the mountain at a time when the lower slopes were entirely free from cloud. This development of high-level snow-cloud was often the precursor of a southerly or south-easterly blizzard.

A reference has already been made in Chapter II., dealing with meteorology, especially in regard to snowfall, to the direction of the sastrugi on the floor of this second crater. They were found on March 9 to follow the direction of the blizzard wind experienced on March 8.

If now we continue the section across the second crater of Erebus at an altitude of about 12,000 feet the base of the third crater is reached. This lies a little to the west of the present active crater. This third crater rises to about 12,600 feet above sea-level.

A little to the east of the third crater, which is extinct, is the present active crater. The fourth and active crater of Erebus rises as a moderately steep cone largely free from snow and formed mainly of pumice. The latter is grey to yellowish on the outside, and of a resinous brown appearance on freshly fractured surfaces. The lumps were from about 1 inch up to about 3 feet in diameter.

The spectacle afforded by the active crater is truly magnificent and inspiring. The summit as determined by our hypsometer was about 13,300 feet above sea-level.* The crater itself is a vast abyss fully half a mile in diameter and about 900 feet in depth. Its walls are nearly vertical, with a suggestion of terracing due to the presence of layers of unequal hardness. Plate LXIV. Fig. 2 shows about 200 feet of this crater wall. The dip of the beds of pumice and lava away from the crater can be seen in the photograph.

The view was taken looking towards the west through a great breach in the crater rim. Evidently the latest flow of lava has descended in that direction. The highest parts of the crater rim appear to be on the south and east. For the greater part of the time of our visit a vast column of steam and sulphurous gas obscured everything at the bottom of the crater. This rose many hundreds of feet into broad, mushroom-shaped masses in the air above us. When the wind drifted the clouds towards us the smell of sulphur was strong and almost overpowering. Every now and then could be heard a roaring noise, like that of a huge engine blowing off steam, coming from beneath the crater, and this was immediately followed by a greatly increased uprush of steam. As we watched, a gentle northerly breeze drove the steam cloud to the south, and enabled us to see across the crater and down to the very bottom. We then made out that there were three well-like openings giving off steam at the bottom of the great cauldron. The approximate position of these is shown on the plan, Fig. 66.

* The exact correction factors for hypsometers in such latitudes being uncertain, the deduced levels are obviously also uncertain.

FIG. 1. ICE MOUND AROUND FUMAROLE ON FLOOR OF SECOND CRATER OF EREBUS

[Photo by D. Mawson

FIG. 2. SNOW FOSSE AT N.W. SIDE OF RIM OF SECOND CRATER OF EREBUS

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PLATE LXIV

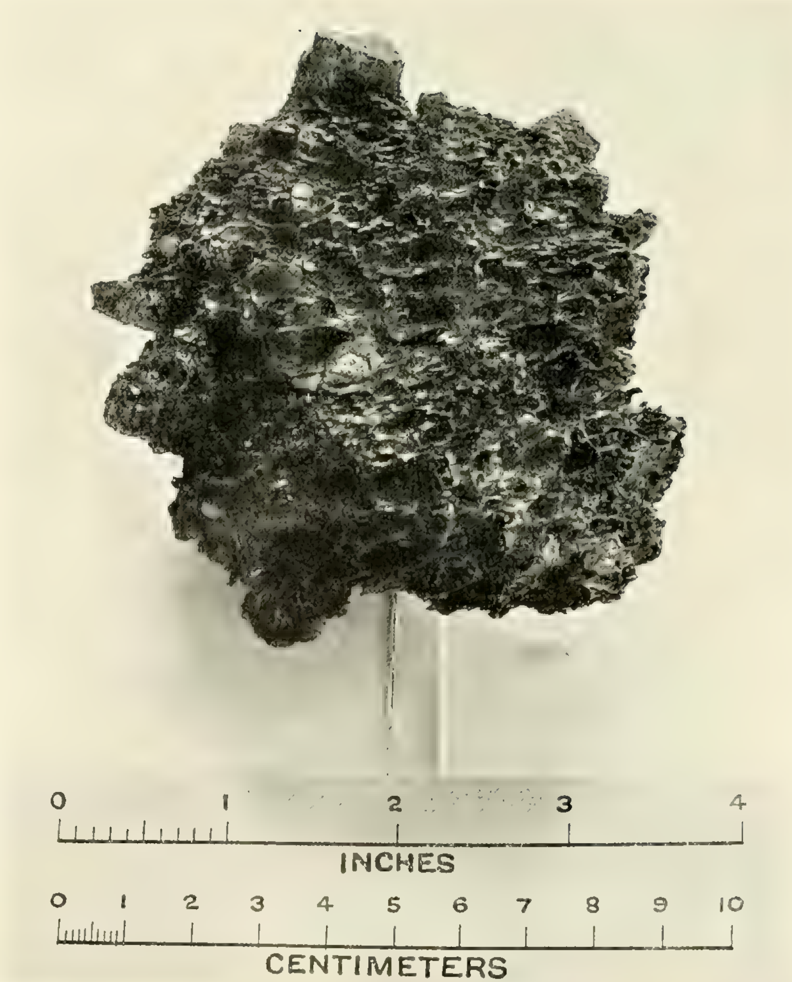

Fig. 1. PUMICE FROM SUMMIT OF ACTIVE CRATER OF EREBUS
showing large porphyritic crystals of anorthocase imbedded in it

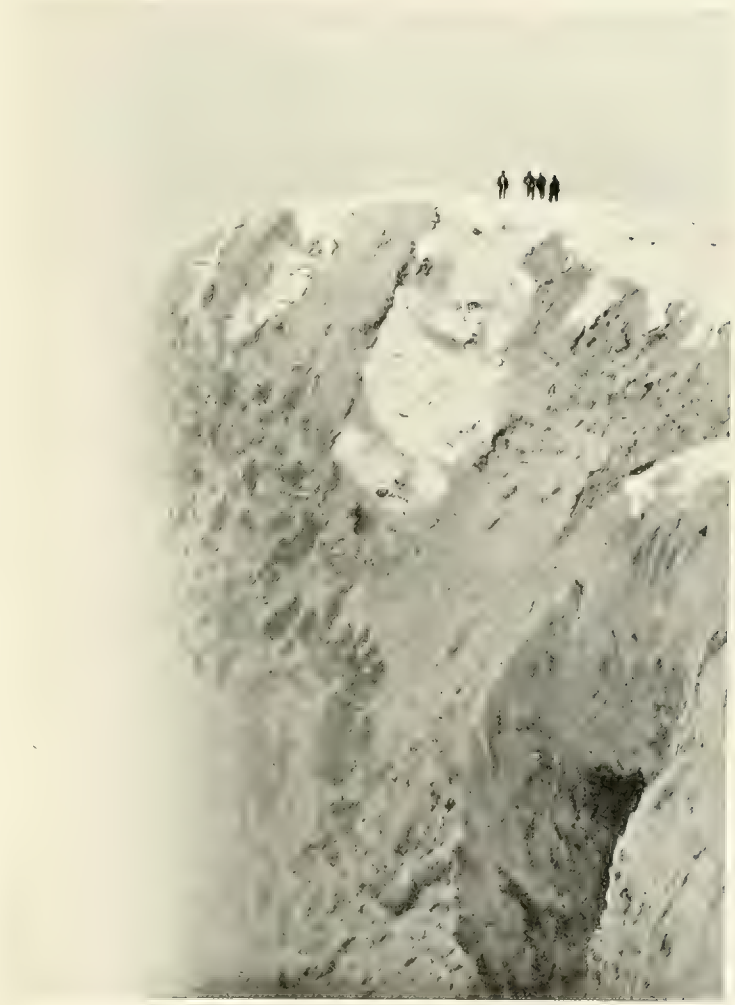

Fig. 2. THE ACTIVE CRATER OF EREBUS
900 feet deep and half a mile wide. Steam is seen rising on the left

[Photo by D. Mawson

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PLATE LXV

FELSPAR CRYSTALS FROM SUMMIT OF MOUNT EREBUS (NATURAL SIZE)

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The walls of the crater itself were of special interest. They were formed, as far as superficial appearance went, of belts of dark pumiceous lava and bands of white snow. The latter were not necessarily interbedded, though it is quite possible that some of them were so, as for a considerable distance before reaching the edge of the crater we had observed, as already stated, that the floor of the older crater had been levelled up by alternate beds of snow and pumice with felspar crystals. The two last had obviously been produced from the present active crater, and had been deposited in their present position by the action of strong winds coming from a southerly direction. A specially thick bed of dark-brown pumiceous lava occurred at perhaps about 300 feet below the lip of the crater, and when the main steam cloud was blown aside we noticed many scores of small steam jets rising from the line of contact of its upper surface with the snow. It is unlikely that these were all fumaroles, and the phenomenon seems to suggest that this thick brown layer of rock possibly marks the highest flood-level of the latest eruption of lava within the crater. On this view this incrustation of lava within the crater still retains sufficient of its original volcanic heat to vaporise the snow in contact with it.

As regards the height of Mount Erebus, our aneroid levels alone made it about 13,270 feet. This result combined with that of the hypsometer gave the height as 13,330 feet. Sir James Clark Ross determined its altitude in 1841 to be 12,400 feet; Captain Scott in the National Antarctic Expedition of 1901–4 originally estimates its height at 12,922 feet. This last estimate was based on trigonometrical measurements, which of course should be more accurate than measurements dependent on atmospheric pressure, as are those made with aneroids or hypsometers.

These sections below show the four craters of Erebus, together with the order of superposition of the various lavas and tuffs and material infilling the second crater.

These sections show that the bottom of the oldest crater of Erebus must have been close to sea-level. It also shows the progressive shifting of the volcanic chimney from north to south. The active fumaroles on the south side of the crater suggest that this shifting is still in progress.

We observed that the eruptions of Erebus, like those of Stromboli, were most frequent during a low barometer. The chief eruption of Erebus seen by us was that which took place on June 14, 1908. On that morning, about 8.45, just as the small blizzard of the preceding night was subsiding, we noticed that Erebus was more than usually active. The steam cloud over its summit was exceptionally broad and tall, and there were frequent strong outbursts of steam. At 11.30 A.M. it became obvious that an eruption of altogether unprecedented vigour, so far as our experience of Erebus went, was now in progress. Immense masses of steam rushed upwards to at least 2000 feet about the summit of the volcano in about half a minute, and then spread out to form a vast mushroom-shaped cloud. It was observed that the explosions did not assume a perfectly vertical direction, but deviated a few degrees from the vertical towards the south, as shown on the accompanying photograph, Plate LXVII. Fig. 1.

We inferred from this that the funnel of the active crater of Erebus dips slightly to the north, that is, towards the centre of the second crater. It is obvious that in quite recent time the centre of activity of Erebus has travelled from north to south. As the eruption of June 14, 1908, progressed, the steam cloud rapidly became asymmetrical, while the main steam column was bent over towards the E.N.E. by the wind blowing from off the high plateau of Victoria Land from a W.S.W. direction. We observed that the higher and still ascending portion when at about 2500 to 3000 feet above the top of the crater was swayed over by the cyclonic high-level air-current into a S.E. or S.S.E. direction. At about 2.30 P.M. there was a specially grand outburst of steam; it rushed upwards, still slightly bent away towards the south, and dashed its head with great violence through the mushroom-shaped cloud canopy, which it swiftly penetrated, emerging on the upper side, and then rushing upwards once more to a height of at least 5000 feet above the summit of the mountain. At 3.15 P.M. the steam cloud was lit up with a bright glow, forming a magnificent spectacle in the blackness of the Antarctic night during midwinter. At 3.25 P.M. another remarkable bright glow lit up the whole of the lower part of the steam column above the crater. By 3.45 P.M. the steam cloud had become much more extensive, and had also risen higher, the earlier formed portions of the cloud being now trailed away in long streamers towards the south-east, while lower branches bent towards the E.N.E. and were dragged out in that direction by the plateau wind. At 3.50 P.M. there was another bright glow. No doubt each of these bright glows indicated a separate eruption, and was caused by the breaking open of the cooled scum of the lava within the crater by fresh masses of steam and incandescent lava arising from beneath. We estimated that the uprushes of steam took place at intervals of between four and five minutes, though this was not absolutely constant. Towards 6 P.M. the steam column gradually swayed around towards the N.N.W., and finally to the N.W. By this time the earliest-formed part of the steam cloud had formed a surface of thin cirrus cloud about 20,000 to 30,000 feet above sea-level. At 6.40 P.M. there was another very bright glow. At 8 P.M. the eruption appeared to be subsiding, and the steam cloud meanwhile stretched across the sky in a direction from E.S.E. to W.N.W. (the surface wind at the time was about N.N.E.). It now resembled the sinuous thin folds of some delicate drapery. Evidently the wind direction had by this time changed above the summit of Erebus, so as to blow from E.S.E. to W.N.W.

During the whole of this eruption we were unable to observe, although we constantly watched with good night-glasses, any trace of lava actually flowing down the sides of the cone. Apparently on this occasion the crater was only partly filled with molten lava.


NORTH
NORTH

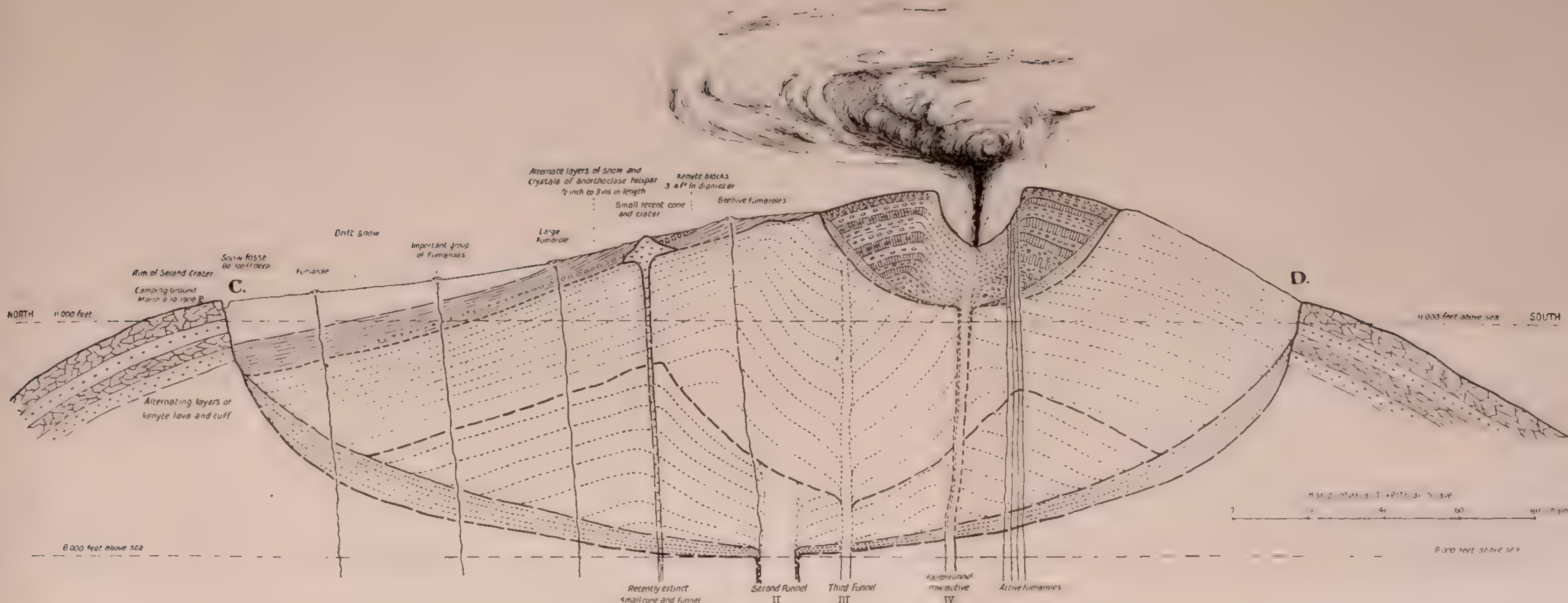

FIG. 1

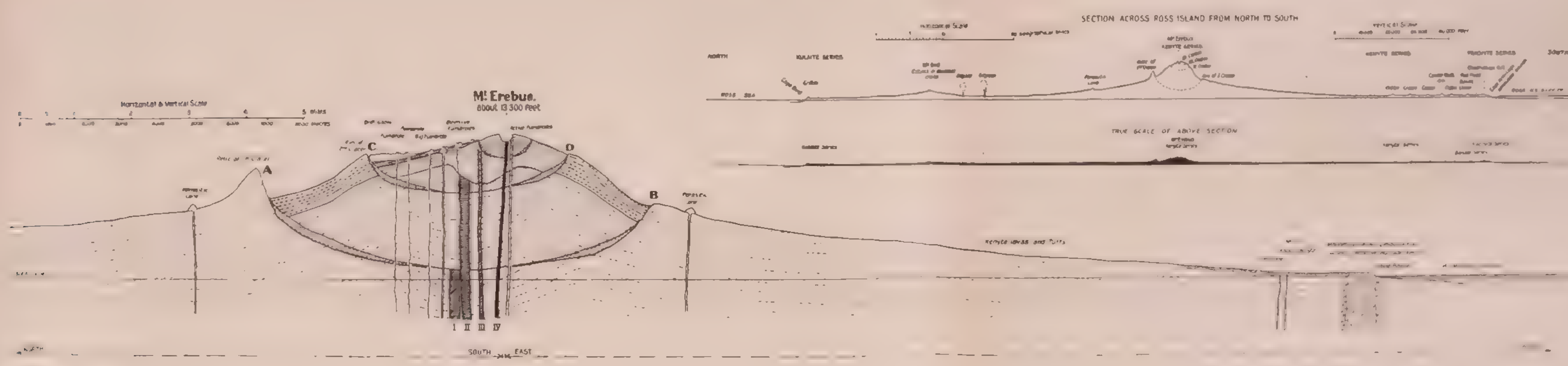

FIG. 2

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FIG. 1. ERUPTION OF EREBUS, 1908
Showing slight northerly dips of the steam column immediately over the crater looking east

FIG. 2. ERUPTION OF EREBUS, JUNE 14, 1908, LOOKING EAST
[Photo by moonlight by David

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The final phase of this eruption of Erebus is shown on Plate LXVIII., taken by moonlight.

It may be mentioned that during this eruption the barometer fell from 29·098 at 10 A.M. to 28·87 at 10 P.M. The glow on the steam column over Erebus was observed more or less continuously from June until September. Soon after this there was so much light in the sky at night that the glow, even if it had been there, would scarcely have been visible. On November 27, 1908, Mr. James Murray has recorded another strong eruption of Erebus, of which he gives a sketch in "The Heart of the Antarctic," vol. ii. p. 312.

Mount Bird Geyser. It is of interest to note that between Erebus and Cape Bird, apparently a few miles to the south of the latter extinct volcano, there is an enormous geyser which spouts fitfully, but at long intervals of time. Judging by the height to which the steam column ascends during an eruption it is by far the largest geyser known in the world. The chief eruption was witnessed on June 17 at 8 P.M., when a remarkably dense white mass of what seemed to be cumulus cloud was observed to the N.N.E. of our hut at a distance of perhaps 20 miles. At 11 P.M. Mawson observed from the top of the anemometer ridge a tremendous outburst of steam in the direction of Cape Bird. This mass rose rapidly from its starting point at about 2000 feet above sea-level to probably at least 5000 feet above the sea. We rushed for our cameras, but by the time we were able to get them to work the great steam column had sunk down so as to look once more like a low isolated dense cumulus cloud. The existence of this immense geyser, if it can be called such, or possibly a parasitic cone of Mount Bird, is of considerable interest, as showing that the line of crack along which volcanic energy is now active in the Erebus region is not so much the east and west line of fracture, which extends from Cape Crozier through Mount Terror, Terra Nova, and Erebus to Dry Valley, but rather the north and south line of fracture extending from Erebus through Cape Bird.

Other occasions when distinct eruptions of Erebus were observed were June 18, 1908, when at 12.20 P.M. a steam cloud was projected in an incredibly short space of time for about 3000 feet above the summit of the mountain. At this time there was a phenomenally low atmospheric pressure, slightly below 28·3.

On the 21st Erebus was again very active, the steam cloud being carried southwards on this occasion for a distance of at least 9 or 10 miles. On June 25, 1908, at 4 A.M., Mawson observed two bright flashes, of what he described as flame, at the summit of Erebus; the first had the appearance as though a big bubble had burst, releasing a lot of glowing gas. Black smoke rushed up to a height of about 2000 feet above the rim of the crater in about 1½ minutes. The black cloud did not appear until about 10 seconds after the bright flash.

On June 30th, constant strong glows were observed over the summit of Erebus. On July 6, 1908, at 11.30 A.M., we observed what appeared to be a fumarole eruption from near the centre of the second crater of Erebus, but we could not be absolutely certain as to whether this steam was coming exactly from that spot. It did not appear to be connected with the active crater.

On July 15, 1908, there was again a very strong glow over Erebus, and again on the 16th and 17th, also on the 19th and 27th July.

On August 1, 1908, there were signs of a strong steam eruption at Erebus. On August 25th there was a remarkably bright glow over Erebus from about 10 P.M. till past midnight. On September 8th, at 8.5 P.M., a remarkable outburst of the Cape Bird fumarole was witnessed by Murray and Marshall. According to Murray's estimate, this eruption must have carried the steam up several thousands of feet, as, measuring to the point indicated as its summit level, its angle of elevation was fully $5\frac{1}{2}$ degrees as seen from Cape Royds. This would probably give a minimum height of about 11,000 feet.

Cape Bird. A landing was effected here by Lieutenant Macintosh and McGillan on January 3, 1909, after their adventurous journey, during which they had to abandon their tent and the mail bags. The *Nimrod* put in here on February 11, 1909, when Mawson landed and obtained a number of geological specimens, mostly loose pieces of rock, and we obtained the photographs reproduced on Plate LXIX.

These show at least one well-marked volcanic cone at the spot on the coast shown on the plan.

In his description of the specimens from this locality Dr. Jensen describes these rocks as being intimately related to those of Erebus, being alkaline in facies. "Their distinguishing feature in all varieties," Dr. Jensen reports, "is the abundance of brown basaltic hornblende, and alteration products after this mineral." The chief rocks he describes as strongly alkaline trachytes, kulaites, and sub-alkaline basalts and dolerites, amongst which latter he distinguishes olivine basanites, alkaline dolerite, and limburgitic dolerite.

We can now pass on to the parasitic cones and other evidences of vulcanism in the neighbourhood of Cape Royds and Cape Barne.

Cape Royds. Cape Royds is probably situated near an independent point of eruption of the nature of a parasitic cone, but as the result of a long period of denudation, chiefly effected during the maximum glaciation, its true structure is largely obscured by extensive patches of morainic material. It is obvious, nevertheless, that Cape Royds is traversed by a network of volcanic dykes intersecting some of the older kenyte lavas. At Flagstaff Point, at the landing place on its south side, distinct stratification is noticeable in the volcanic rocks, the dip being somewhat steeply seawards. Here and there some resistant dykes stand out prominently, such as the one at the Penguin Rookery, and that which divides up Blue Lake. The principal type of rock at Cape Royds is a highly-jointed alkaline basic lava, rendered porphyritic by anorthoclase, which Dr. G. T. Prior identifies as a kenyte identical in character and composition with that of Mount Kenya in Central Africa. The kenyte is black, and in places has a very glassy base. The felspars are

FINAL PHASE OF THE ERUPTION OF MOUNT EREBUS ON JUNE 14, 1908, LOOKING EAST BY SOUTH

[Photo at moonlight by David

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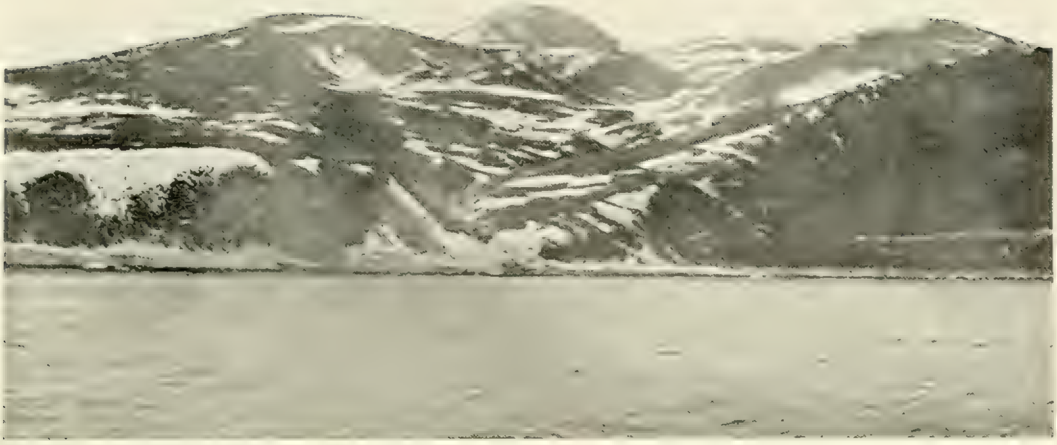

Fig. 1. PARASITIC VOLCANIC CONE AT CAPE BIRD, LOOKING EASTERLY

Fig. 2. CAPE BIRD, ROSS ISLAND, LOOKING SOUTHERLY

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very glassy, and, besides these, other phenocrysts are met with in the form of leucite in small rounded isotropic crystals, and of olivine of a yellow variety in small rounded grains.

Cape Barne. As shown on the detailed geological map of the Cape Royds to Cape Barne area we found developed at Cape Barne an elongated mass of basalt and basalt agglomerate. Its general trend is east and west, inclining to north-west at its western extremity on the coast. As shown on the section on line A to C this basaltic belt is strongly intrusive into the older kenyte lavas, large blocks of kenyte with reddened crystals of anorthoclase being enclosed in the scoriaceous basalt of Cape Barne. A section of this is shown on the detailed geological map of this area.

Notes on Cape Barne Lavas. The Cape Barne area is bounded on the west by the sea, to the south by the Cape Barne Glacier, to the east by the foothills and snow slopes of Erebus, and to the north by a shrunken glacier to the east of Back-door Bay, Cape Royds.

The most westerly point of the Cape is Cape Barne Pillar, a rounded plug of basaltic agglomerate 150 feet high. Evidently this mass formed originally part of the material choking the neck of a small volcano. Across the middle of this plug, striking almost north and south, runs a dyke of a very highly-jointed basalt, the strengthening influence of which probably played a great part in enabling the Pillar to resist the denudation which has already worn down and removed the greater part of the volcano.

To the east of the Pillar is a steep sugarloaf-shaped hill, representing apparently all that is left of the volcano. This hill is composed mainly of steeply-sloping tuffs, generally fairly coarse and agglomeratic, but with bands of finer material. Intercalated amongst the tuffs are one or two thin flows of highly-jointed basalt. So highly jointed were they, that on our earlier visits we failed to distinguish them from the agglomeratic beds above and below them.

The larger materials of the agglomerates were mostly fragments of basalt or of basaltic agglomerate, but several burnt and reddened fragments of kenyte were lying at the foot of the hill amongst the debris, and on one occasion one of these kenyte fragments was found in place cemented in the agglomerate. The ice-foot below the sugarloaf-shaped hill after a southerly wind would be strewed with debris dislodged from the hill sides, and it was from amongst this debris that two or three pieces of vesicular basalt were picked, with vesicles up to three-eighths of an inch in diameter filled with very pure sulphur.

Farther inland from the Cape are dome-shaped, obviously glaciated, hills, composed, as far as could be seen through the mask of debris, mainly of beds of basaltic tuffs and agglomerates, whose outcrop was in some cases well marked by the lines of kenyte boulders. The regularity of position of these boulders renders it practically certain that they have been weathered out from the basalt, and have not been deposited on the beds by glacial action. Many of these kenyte boulders were burnt a brick red and coloured with sulphur, as if they had been part of the lining of the vent by which the basalt was poured out, and had been torn off by the explosive action of the steam and gases accompanying the eruption.

There are, therefore, two pieces of evidence which combine to show that the basalts of Cape Barne were forced through a series of pipes drilled through the older beds of kenyte. First, there is the occurrence of the kenyte boulders weathered out from the basaltic agglomerates, and secondly, the occurrence of baked and sulphur-covered fragments of kenyte in the tuffs of the sugarloaf hill.

There is also little doubt that the kenyte of the newest of the Erebus craters is more recent than the basalt of Cape Barne, so it seems probable that at or about the time that the volcano at Cape Barne was erupting basalt the main crater of Erebus was erupting kenyte, and therefore that the lava of Cape Barne is the product of a subsidiary reservoir which was, at any rate at the time of eruption, cut off in some way from the main Erebus reservoir.

The evidence of glacial action all points to the Cape Barne lavas being either preglacial or interglacial.

The basaltic rocks of Cape Barne are reported by Dr. H. I. Jensen to contain an extraordinarily high percentage of magnetite (in one or two cases as much as 50 per cent.), and that the magnetite, contrary to its usual habit, is amongst the latest products of crystallisation.

EREBUS

PARASITIC CONES AT LOW LEVELS

Mount Cis. On October 8th the nearest of a number of small conical hills about a mile back from the coast, and near the 700 feet contour line, was examined, and proved to be the remains of a small parasitic cone of a very peculiar type of rock. The only part of the cone now remaining is a plug of lava, which evidently formed the neck of the volcano. It is of course quite possible that there never were any liquid extrusions, and that this plug was solidified beneath the surface. On the southern and western side the hill is flanked by a scree of angular debris, all of it clearly derived from the hill itself. The scree probably is continuous right round the hill, but on the other side it is hidden by a snow-drift.

The hill looks decidedly top-heavy, its diameter being less a few feet down than at the top, for it is strongly undercut on its southern side. It was this appearance that caused its close examination, for the only way for accounting for this shape was by presuming that it was composed of rock *in situ*, and would not prove to be an esker, composed of miscellaneous rubble. The rock is highly jointed, and undoubtedly *in situ*. Its small extent, and the fact that few fragments would be identifiable, has probably prevented its recognition amongst the moraine

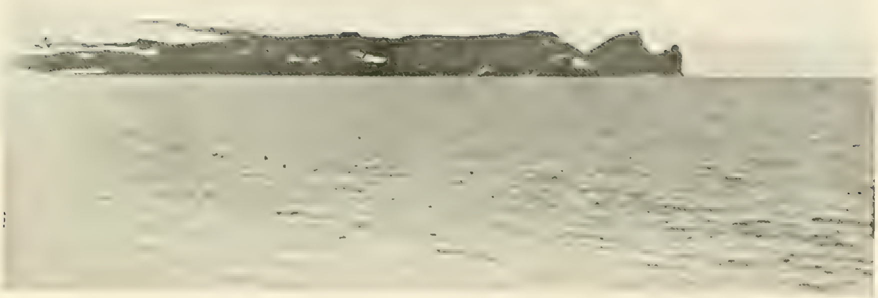

Fig. 1. CAPE BARNE
Seen from distance of about 1 mile, looking southerly. The Cape is about 300 feet high

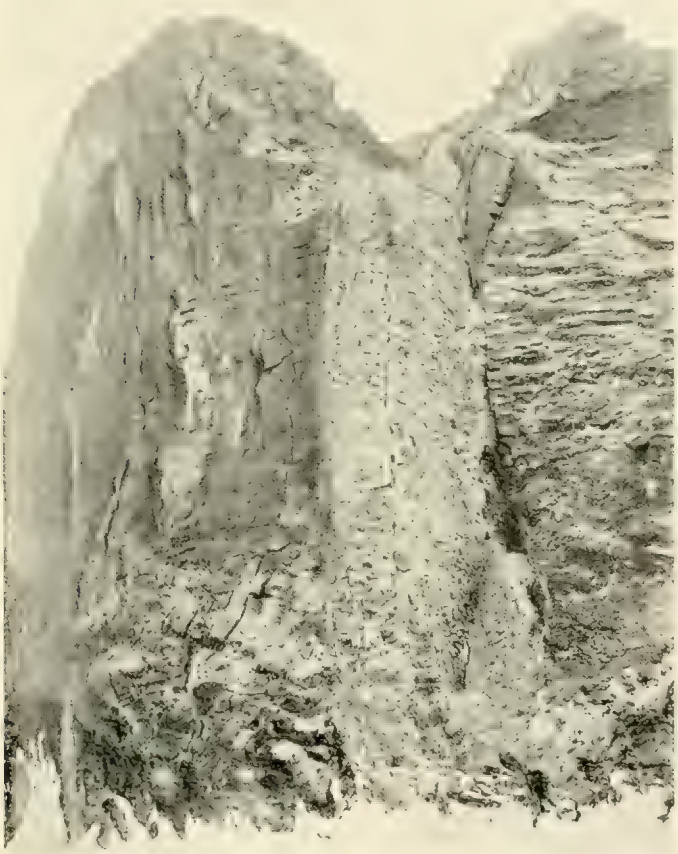

Fig. 2. BASIC DYKE INTERSECTING AGGLOMERATES AT CAPE BARNE PILLAR

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debris of Cape Royds by any members of the scientific staff of the expedition. Erratic specimens, described by Mr. J. Allan Thomson in his notes on the "Inclusions in the Lavas of Ross Island," in the second part of this volume, seem undoubtedly to have come from this source, or from a similar cone.

The main mass of the rock composing this plug is a homogeneous grey trachytic lava with long drawn-out vesicles with, however, numerous inclusions of sanidinites, consisting of felspar (sanidine or anorthoclase) and a little olivine. The olivine is of very secondary importance, and appears in hand specimens as a few small grains of a very clear gem olivine of a yellowish colour, mostly grouped about the exterior of the sanidinites. In some cases ground mass is not excluded from these sanidinites, but is only much more sparsely distributed, and it seems probable that these particular specimens are formed by the segregations of porphyritic felspars.

Besides the coarse-grained sanidinites, there are a number of fine-grained inclusions which may be referred to two main types :—

1. Microsanidinites, very similar to the sanidinites in composition and structure, but aphanitic in grain.

2. Enallogenous inclusions of the rocks through which the lava has burst. These are especially important, since they include fragments of altered sandstone and dolerite, which may be referred without doubt to the Beacon Sandstone Formation.

This is exceptionally interesting, as confirming the theory that the Ross Sea is a *sunkungsfeld*, due to a north and south fault along the Victoria Land Coast.

TUFF CONE

On October 20th, when collecting specimens from Mount Cis, we noticed another conical-looking hill about 400 yards to the N.N.E. On examination this proved to be also a portion of a parasitic cone, and the rock was a very beautiful agglomerate of angular fragments of variously-coloured volcanic rocks.

Several types of kenyte and kenyte tuffs were represented, some of the fragments of kenyte being of a far more acid type than any hitherto found at Cape Royds. Basalts also appear to be represented by occasional fragments, and yellow lapilli were common, and the whole is cemented together very firmly by fine material of a dark grey colour. This was by far the most compact kenyte tuff found.

On the southern side of the cone the rock was strongly weathered, the weathering having worked along the cement much faster than along the fragments, and in many cases this weathering had gone so far as to completely chisel out large fragments of lava, which could only be known to have belonged to the cone by the adhesion of a little of the cement. The only place where erratics of this rock were found was on some hills a little to the south of west from the cone.

OTHER PARASITIC CONES

A few hundred yards up the slopes of Erebus, due east from Tuff Cone, were a bunch of three or four conical hills, with one or two more scattered within a short radius. One or two of these proved to be eskers, but the majority were plugs of massive kenyte which had either occupied the necks of parasitic cones which have since been denuded, or had been intruded near the surface and since weathered out.

On February 13th, on the way back from Cape Barne with a load of mirabilite, we stumbled on the remains of another parasitic cone, just above the terrace at the east of Backdoor Bay. The remains at present consist of a much denuded sugar-loaf, only a few feet high, and formed of a very fine-grained and finely laminated brown tuff, containing large blocks of a pumice so much altered, and so very friable, that blocks 18 inches thick could be crushed to powder by the pressure of the hand.

HUT POINT

Lavas. The peninsula, of which Cape Armitage is the extremity, and on which Hut Point is situated, is built up of a series of lavas and tuffs which are the product of subsidiary volcanoes situated on what may be termed the Erebus fracture zone. Castle Rock, a plug of palagonite tuff, and the highest point on the peninsula (1300 feet), is the denuded remains of such a volcano. Others are the Sulphur Cones (basalt), Crater Hill (scoriaceous red basalt glass), Harbour Heights (olivine basalts), and Observation Hill (trachyte with a horizontally bedded tongue of basalt on its south-west side). This district has been described in fair detail by Ferrar in the Geological Memoir of the National Antarctic Expedition, 1901–4. During our short stays at the Hut a few observations were made.

Small foreign erratics were very numerous, and were found at the top of Crater Hill, a few being picked up inside the crater itself, and at a small scoria cone just a short distance north-east of Crater Hill. They were also found in great numbers on Cape Armitage, and to within 100 feet of the top of Observation Hill. There was a quite obvious reason why they were not found any higher than this, for the leeward slopes of the hill were covered with snow, and the top of the hill had been carved into a sharp ridge which was almost unencumbered with small debris, and which had been weathered by the wind into a series of fantastic shapes. These small foreign erratics were also very common in that portion of the Gap moraines which we saw free from snow.

A very interesting question is suggested by the occurrence of these small erratics at the top of Crater Hill. The edge of Crater Hill is remarkably sharp, and it is inconceivable to believe that the summit of the hill has ever been heavily glaciated. The sharpness of the rim of the crater and the fresh appearance of the scoriaceous lava is suggestive of the crater being post-glacial in age, and yet how are we to

Fig. 1. PARASITIC TUFF CONE, CHIEFLY FORMED OF KENYTE TUFF, NEAR CAPE BARNE

Fig. 2. PARASITIC CONE ON THE SLOPES OF MOUNT EREBUS

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account for the presence of these numerous small erratics in the crater? The height of Crater Hill above sea-level is a little over 1000 feet. It has been described by H. T. Ferrar (*op. cit.*, p. 12), where he mentions that the hill is formed of black vesicular basalt and red scoriaceous basalt glass. As we have seen from the evidence at Cape Royds, the basalts are amongst the newest of the lavas of Ross Island. The following explanations may be offered of this apparently contradictory phenomena of the unglaciated state of the crater rim combined with the presence of glacial erratics within the crater:—

1. The crater is post-glacial in the sense of its post-dating a maximum glaciation, and the presence of the glacier erratics in the crater may be explained by the erratics having been brought into their present position by floating ice during a period of submergence. This would demand a far greater submergence than that which has already been assumed for Ross Island, for obviously in order to carry erratics into this crater a submergence of at least 800 feet would be required, possibly 1000 feet. It is conceivable that the crater was formed at the edge of the retreating ice sheet, and therefore only just subsequent to the culmination of the glaciation. In this case flood waters during the season of thaw may have washed down erratics into the crater from the retreating ice front.

2. A second alternative is to suppose that the crater preceded the maximum glaciation. As we have seen, the height of the moraines left by the Great Ice Barrier during the maximum glaciation is near about the level of 1000 feet above the sea. Possibly, then, the rim of crater may have been just high enough to have been above the level of the great ice sheet, or if it was ever covered by ice, the ice over it must have been very thin. If this second hypothesis could be adopted, the presence of glacial erratics dropped by the retreating ice sheet into the crater can of course be readily explained. It is noteworthy that all the erratics seen at Hut Point were uniformly small. No single specimen was more than about 1 cubic inch in size. These are in marked contrast to the erratics at Cape Royds, many of which are several cubic yards in volume.*

A point worthy of attention in the vulcanism of this region is the approximately uniform height of the volcanoes in the main volcanic zones. On the American side of the Antarctic the highest volcano yet found is Mount Haddington, which rises about 8000 feet above the sea. We do not know the altitudes of any possible volcanic cones of any considerable dimensions between that and Mount Morning. Mount Morning, according to Scott's determinations, is 5778 feet in height; Mount

* As already stated, subsequent to our expedition, Mr. F. Debenham, B.Sc., of the British Antarctic Expedition of 1910–13, has discovered craters of basic lava and tuff at Dry Valley near New Harbour, which he considers to be probably post-glacial, that is, later than the maximum glaciation in date. If this determination is correct, the east and west fault fracture running from Cape Crozier to Dry Valley must have been active subsequent to the climax of recent Antarctic glaciation, though, for reasons already stated, the Cape Bird to Erebus line may undoubtedly be considered the most recent active volcanic zone.

Discovery, adjacent to it, 9085 feet; Mount Erebus, over 13,000 feet; Mount Terror, 10,755 feet; and Mount Melbourne, 8000 feet. It is evident from these altitudes that if this volcanic chain is a continuation of that of the South American Andes the extrusive terrestrial forces have here in the Antarctic less elevating power than they have in the South American Andes, where several volcanic cones exceed 20,000 feet in altitude.

DELLBRIDGE ISLANDS

These four islands lie 3 or 4 miles from the nearest point of Ross Island, with their longest axes directed nearly east and west. They rise steeply out of deep water, and the steepness of their slopes continues above water, so that they are all of the razor-back type. They consist of volcanic rock of a number of types, but on the whole allied to those of the adjoining mainland of Ross Island.

Inaccessible Island. Inaccessible Island is about 450 feet high, very steep towards the south, but sloping sufficiently on its northern side to allow of the weathered material lying on its slopes, which are therefore covered by a mantle of angular debris. Our information about the island is very meagre, as it was mainly gathered during the initial or final stages of different sledge-journeys, when time and food considerations did not allow of any length of stay.

Its name, Inaccessible Island, given by Captain Scott of the National Antarctic Expedition, 1901–4, is very appropriate, for the first effect of the summer thaw is to melt the sea ice immediately round its ice-foot, and thus cut off the island in summer, so that it was only during spring and early summer that it was accessible for our sledge parties. Mr. Hodgson, biologist on the *Discovery*, collected specimens which proved to be red vesicular trachyte, porphyritic basalts, yellow trachytes, and a trachy-dolerite of intermediate character.

On August 23, 1908, Sir Ernest Shackleton walked from our winter quarters at Cape Royds to the island, and brought back specimens which were identified from their microscopic characteristics as trachytes and tuffs. The trachytes he obtained *in situ*, and reported it as occurring as a flow beneath the basalt, thus adding one more link to the chain of evidence regarding the relative ages of trachytes, basalts, and kenytes.

The eastern portion of the island was examined by a Hut Point sledge-party on September 4th, and proved to be formed of a sheet of massive basalt overlying a red basaltic agglomerate with many pockets of yellow ochreous dust. Farther to the north were several blocks of a reddish kenyte with platy felspars, which appears to be intermediate in character between the rocks of the Turk's Head and those of Cape Royds, but inclined to be rather more like the Turk's Head kenyte (1797). One specimen secured contained a nodule or segregation of kenyte of a more acid type with numerous felspars (1787). These blocks were lying on the ice-foot, and

FIG. 1. INACCESSIBLE ISLAND ON LEFT, PART OF TENT ISLAND ON RIGHT, LOOKING NORTH. TENT ISLAND IS ABOUT 400 FEET HIGH

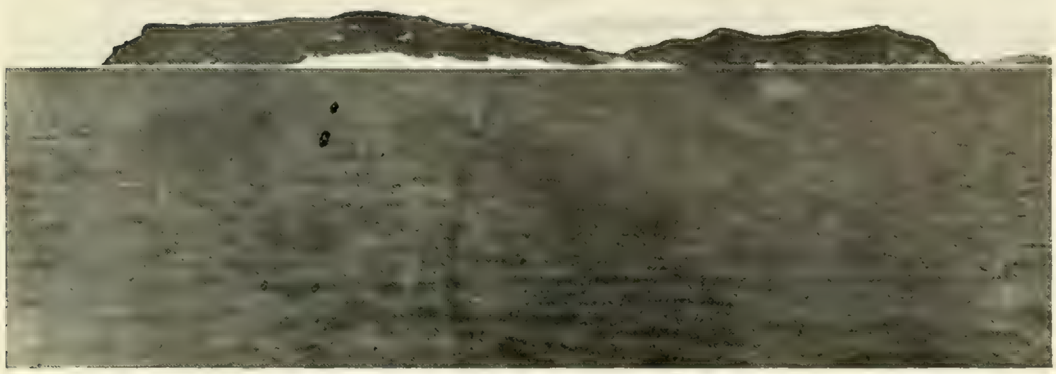

FIG. 2. TENT ISLAND ON LEFT, INACCESSIBE ISLAND ON RIGHT, LOOKING N.N.W.

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were much weathered. From their shattered condition it seems probable that they had fallen from the higher slopes of the island, where there may be kenyte *in situ*, or where they may have been part of a mantle of moraine debris.

On November 14th the north-western point of the island was visited by a seal-killing party *en route* for Tent Island in the motor car, and this portion of the island consists entirely of a massive flow of basalt with small porphyritic felspars, which appears to be dipping to the south.

Tent Island. Tent Island is nearly rectangular in shape, and is nowhere more than 400 feet high. It was visited on November 14th by a motoring party sent out after specimens of young seals. Ferrar describes its geology in the Geological Memoir of the National Antarctic Expedition, 1901–4, as follows :—

"The lowest rock exposed is a basalt agglomerate, which occupies the lowest 100 feet of the north-west cliff. It is covered by sheets of a vesicular glassy kenyte with lenticular porphyritic crystals of felspar, like the rock of Cape Royds. These rocks have a dip of about 20 degrees, are parallel, and are each almost 20 feet thick."

Our cursory examination of the island confirmed this description, and there is very little that can be added to it. The beds dip about south-east, and the slope of the top of the island agrees with this dip in general direction. On the top of the island is a very beautifully weathered kenyte boulder, which Murray photographed.

The northern side of the island is deeply cut by a gully worn by water and frost, down which, at the time of our visit, a stream of thaw-water was flowing. All the drifts on the island had a very dirty appearance, owing to the concentration of the dust by the past two or three days' thaw. Quite a quantity of the lighter portion of this sediment was being removed by the water and deposited as a small delta in the ice-foot. The work of the thaw was also evidenced by the quantity of jagged pieces of rock which were lying about the ice-foot, and which had evidently been broken off by the frost action, and loosened by the heat of the sun.

Both Tent Island and Inaccessible Island are surrounded by a very typical ice-foot of frozen spray.

Razor-back and Little Razor-back. These islands were not visited by members of the expedition, and the only known specimens from them are a few fragments of olivine basalt and trachyte, collected by the National Antarctic Expedition, 1901–4.

TURK'S HEAD

On November 15th the motor took a party down to the Turk's Head to secure the skins of some young Weddell seals, and advantage was taken of this trip to make a geological reconnaissance of this nunatak. Here the rock is exposed as a bare cliff, in places over 300 feet high. Screes rest against the cliff at most places, and the weathered material is lying just at the angle of repose, thus not only masking the face of the cliff, but also making the upper portions of the exposures very difficult of access.

The section of the cliff is roughly as follows :—

A. The northern part of the exposure consists of a kenyte flow or series of flows of considerable thickness. The kenyte is of a very different appearance from that which forms Cape Royds and the Skuary, but one which is quite common amongst the erratics at Cape Royds. The felspars are in shape very flattened and plate-like, arranged with an orientation usually parallel to the direction of the dip of the flows, but occasionally arranged in a way which gives a very beautiful curvilinear flow structure to the rock. The ground mass is stony and reddish. It is impossible to gauge the thickness of the flow, as to the north the whole of the surface is covered by a magnificent ice-cascade, so that the next exposure north of the Turk's Head is the Skuary, consisting of a different type of kenyte altogether. This kenyte of the Turk's Head and all the other rocks of the exposure dip to the north-west at an angle of about 45°.

B. To the south of the kenyte a very coarse agglomerate sets in. The boulders comprising this agglomerate, many of them 18 inches or 2 feet in diameter, are usually spherical in shape, with a concentric orientation of the felspars, and this appearance was much accentuated in those blocks which had been exposed to sub-aerial denudation for a considerable time by a concentric type of weathering. This resulted in a series of different rings, varying from brown on the outside, where the iron salt had been converted into limonite, through red to the natural black of the rock. The blocks examined seemed to be of a fairly even texture throughout, but, despite this absence of the vesicular bomb-structure, the fragments must have been ejected from the crater in a semi-molten state, for a high degree of plasticity would be necessary to account for the very perfect orientation of the phenocrysts. If this is the method of formation of these blocks, this particular portion of the lava must have been remarkably free from occluded water.

The ground mass consists of an aggregate of fragments of volcanic glass, small fragments of the local kenyte with platy felspars, fragments of felspars, and of fine-grained brown cement.

C. This bomb agglomerate is succeeded by a flow of kenyte of the same type as the last about 20 feet thick, and this again is succeeded by,

D. Bed after bed of tuffs, some of fine material, showing bedding planes, and others of coarse boulders, with less of fine cement, appearing quite massive, and with no visible evidence of stratification.

Material of every size is present in this series of beds, from the massive boulder to the finest dust, and the alternation of these types has given rise at the southern end of the exposure to a splendid series of crags and pinnacles exactly like the spires of a cathedral, and the picturesque effect is much heightened by the way the weathered fragments stand out like great bosses from the tuff-like cement.

Fig. 1. INACCESSIBLE ISLAND, SHOWING ITS GLACIATED SUMMIT, LOOKING TOWARDS THE E.S.E. HEIGHT ABOUT 450 FEET

Fig. 2. N.E. END OF INACCESSIBLE ISLAND, SHOWING FROST-SPLINTERED CLIFF OF BASIC LAVA

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All the boulders observed in the agglomerates were of the same type as the kenyte of the flow, and no erratics were seen, because the cliffs are covered with an ice-cap almost to their edge.

A very noticeable point about the kenyte exposures was that along every line of weakness, as, for instance, at a junction between rocks of a different hardness, wind and water together had worked and hollowed out gullies of considerable size, at the foot of which the weathered material was piled up in fan-shaped screes.

*The Skuary.** The Skuary is an area of bare land abutting on the southern border of the Cape Barne Glacier, and some 6 or 7 miles south of winter quarters. On November 18th a trip was made with the motor to the Turk's Head, and the Skuary was visited *en route.* The exposed land is about 2½ square miles in extent, and, except for the cliff-faces along the shore, and some of the more important and steeper of the hills and ridges, it is covered with a thick mantle of morainic material, which seems to be, however, as far as could be judged in such a cursory visit, mainly of local extraction.

Some small fragments of tuff of a variety which is *in situ* at the Turk's Head were noticed, but there seems to be a total absence of the plutonic, hypabyssal, and sedimentary erratics of continental type with which Cape Royds is strewed. The evidence points to recent glaciation by a local Erebus glacier, since the maximum extension of the continental ice-sheet and, indeed, the Skuary is still bounded on the side adjacent to the mountain by what is probably the shrunken remnant of this same glacier.

The moraines consist almost entirely of very similar rock to the country rock, a compact brownish kenyte somewhat lighter coloured than those met with at Cape Royds, and with rather clearer and lighter coloured porphyritic felspars. This kenyte, being in an exposed position, is most beautifully weathered, and the gravels which cover the depressions, and the bed of the various little rills that drain the place, are full of felspars, mostly occurring as cleavage masses, though some of them, to our surprise, were whole felspars, with their edges distinctly rounded off as if by the action of running water. A curious fact was that all these felspars were so unaltered, chemically, that they were almost transparent and a very light yellowish colour.

The cliffs in places are from 80 to 100 feet in height, and seem to consist of lava-flows one above the other, and with scarcely any dip.

Examined under the microscope, one of the specimens secured showed large phenocrysts of anorthoclase and a few porphyritic crystals of olivine, embedded in a holocrystalline ground mass of interlacing felspar-laths with small grains of leucite and some magnetite, and it thus appears to be of the same type as a specimen collected by Ferrar in 1903 from the same locality, and described by Prior in the *Discovery* Expedition Geological Memoir.

* Since re-named Cape Evans by Captain Scott (1910).

Scattered about the Skuary are a number of small cones, consisting mainly of angular fragments of a brownish kenyte, with here and there a fragment of a fairly fine-grained tuff. Along the margin of the glacier which borders the rock there is arranged in a fairly regular row a few paces apart a large number, ten or twenty, of similar cones. There was very little time to examine them, as it was necessary to meet the motor at Inaccessible Island. I am inclined, however, to think that most of these cones are eskers left bare by the retreat of the glacier, though the presence of one cone which seemed to be of massive kenyte makes one somewhat doubtful of the origin of those which have not yet been examined.

At the time when this visit to the Skuary took place the thaw had just set in in earnest. This particular day was cloudy, and the streams of thaw-water had been frozen, but the ridged appearance of the snow-drifts and the ice in the stream-channels all spoke powerfully of the sun's influence exerted during the past one or two days. On November 18th there was still a quantity of snow left, but the Western Party, when passing this spot a few days later in the beginning of December, remarked the fact that scarcely any snow remained in spite of a drift-laden wind which had blown for three or four days at the end of November.

BEAUFORT ISLAND

This high conical volcanic island lies about 13 miles N.N.E. from Cape Bird. As it lay right in the path of the former Ross Barrier during maximum glaciation, it would be a matter of great interest to determine up to what level the ice-sheet formerly ascended its flanks.

Fig. 1. TENT ISLAND, SHOWING COARSE VOLCANIC AGGLOMERATE
The low white wall in the foreground is edge of the ice-foot. The men are standing on sea ice

Fig. 2. BEAUFORT ISLAND, A VOLCANIC ISLAND 13 MILES NORTH OF CAPE BIRD

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CHAPTER XII

ORGANIC LIFE

LICHENS

Several varieties of lichen were found coating lumps of kenyte at Cape Royds, and were observed extending over a height of at least 1000 feet above sea-level up the flanks of Mount Erebus.

This plant on the whole appears to have a conserving influence on the rocks which it incrusts, but the branching lichen, resembling *Usnea*, commonly called by members of the expedition the forest lichen, because of its relatively large size and branching habit, tends to break up the blocks of kenyte on which it grows, and does this in a very efficient manner.

Mosses were represented by four species belonging to three genera, viz. *Dicranella Hookeri*, *Sarconeurum Glaciale*, *Bryum Argenteum*, and *Bryum Antarcticum*.*

These mosses were found growing in crevasses amongst the kenyte or granite rocks, or forming tiny tufts in sheltered spots where there was a little sand moistened by thaw-water. These were too insignificant to play any rôle of importance, as far as we were able to observe, in either conserving or destroying rocks, or contributing to form organic deposits. A short preliminary description of these lichens and mosses is given by our colleague, Murray (*op. cit.*, Part I., pp. 4–5). He also describes in the same work (pages 5 to 6) what was, from the geological point of view, by far the most important plant at present flourishing in the Antarctic. It is a fresh-water weed, probably an alga. This was of a pink to brown colour, from warm sepia-brown to nearly vermilion,† and presented a most remarkable appearance. It flourished in enormous quantities in the lakes of Cape Royds and Cape Barne. One of the smaller lakes at the latter locality, between Deep Lake and Terrace Lake, looked like a miniature Red Sea, so thickly were its frozen waters interspersed with large specimens of this red plant. As described in the section relating to peat, these organisms on dying contribute a considerable

* British Antarctic Expedition, 1907–9. Report on the Scientific Investigations, vol. i., Biology, part 4. Musci by Jules Cardot, pp. 77–79.

† This red colour may have been due to the enormous numbers of red-coloured rotifers adhering to the plant.

amount of organic material to the bottoms of the lakes, which gradually passes into a type of peat. The individual plant organisms were often of a large size, at least 2 to 3 feet in diameter, with a depth of approximately equal amount.

Diatoms abounded in all the lakes in the neighbourhood of Cape Royds, and contributed largely to form muds on the lake bottoms. A large triangular diatom, apparently allied to *Triceratium*, was specially abundant in the muds of Clear Lake. In the neighbourhood of the Ross Barrier ice-cliff the waters of Ross Sea for a considerable distance to the north of the ice-cliff were observed by us to be olive-green from the abundance of diatoms. R. N. Rudmose Brown states that Dr. W. S. Bruce has observed the same thing in the sea water off Louis Philippe Land.*

ANIMALS

Foraminifera. Foraminifera evidently abound in Antarctic seas. A later chapter of this Report by Mr. F. Chapman describes the varieties met with in the raised marine deposits of Ross Island and of South Victoria Land. In the case of the raised marine deposit near Mount Larsen, the well-known genus *Biloculina* was so abundant as almost to constitute *Biloculina* clays, like those so well known in the neighbourhood of the Arctic Circle.

Sponges. Sponges were wonderfully abundant, so much so as to be quite important contributors to the muds and oozes forming at present at the bottom of McMurdo Sound and Ross Sea. Certainly a considerable portion of the floor of McMurdo Sound must be almost as white as snow, owing to the presence of a continuous deposit of siliceous sponge spicules, derived from the breaking up of sponge stocks. Such spicules must be intermixed with boulders, rock dust, and fragments of angular felspar, dumped by floating ice floes or by ice bergs. These siliceous sponges frequently attain a very large size, of from a foot to 1½ feet in diameter.

Corals. Only one variety of coral was observed by us, the specimen discovered by Mackay in the upthrust marine muds near the foot of Backstairs Passage, in the Drygalski region. This is a solitary type of coral, and has already been figured in "The Heart of the Antarctic," vol. ii., Plate facing p. 320. No living specimens of coral were obtained by means of dredging. The specimen just referred to was found in the upthrust muds which there overlie some very old glacier ice.

Echinoderms. Echinoderms were extraordinarily abundant. On looking through the clear ice one could see that the sea bottom was almost completely covered in places with echini. They, too, must form no unimportant contribution to the marine deposits now forming in McMurdo Sound. These seas also abound

* Scientific Results of the Scottish National Antarctic Expedition, vol. iii. p. 13. The Problems of Antarctic Plant Life. By R. N. Rudmose Brown, D.Sc. The Scottish Oceanographical Laboratory, Edinburgh, 1912.

in Polyzoa. In the upthrust muds of Backstairs Passage we observed an abundance of Polyzoa, the commonest of which Mr. E. F. Hallman considers to be a *Lepralia*.

Ostracods. Ostracods are also abundant in the raised marine muds, both at Ross Island and South Victoria Land. These are described later in this Memoir by Mr. F. Chapman.

Amongst the Brachiopods, *Lyothyrina* was found in the raised muds of Backstairs Passage, associated there with remains of Dentalium and Chiton, in what may be termed the *Biloculina* Clay.

Mollusca are well represented by several forms, of which the more important were an *Anatina* and *Pecten Colbecki*. The large gastropod *Neobuccinum* must occur in great numbers on the sea bottom near Cape Royds, as we almost invariably found that several specimens of it found their way into our fish trap, attracted by the seal meat which we used as bait for the fish. Judging by the large numbers met with in the stomachs of the seals, the Antarctic seas must teem with fish, but we did not happen upon any fish remains in the raised beaches or upthrust marine muds.

Remains of Penguins and Seals no doubt sparingly contribute to the organic deposits now forming on the floor of Ross Sea. Amongst organisms of less importance may be mentioned Star Fish, Brittle Stars, and Holothurians. The remains of these would no doubt contribute, though to a very limited extent, to the material of the Antarctic marine muds. An extremely important constituent of all these muds are of course the diatoms. In fact, of all the organisms which have been mentioned, it appears to us at present that probably the most important contributors to the organic deposits on the floors of these seas are the diatoms, the siliceous sponges, and the foraminifera. Remains of rotifers are also extremely abundant, but these are mostly of a perishable nature.

Serpulæ. Serpulæ were found by us in some quantity in the raised marine deposits of Ross Island and of Backstairs Passage. At the latter locality a very abundant form was that shaped like a drain-pipe, and figured in "The Heart of the Antarctic," vol. ii., Plate facing p. 320, also on Plate LXXXVIII. Fig. 3 in this work. We found that there was a considerable deposit of serpulæ intermixed with sponge spicules alongside of Glacier Tongue at a depth of 157 fathoms.

CHAPTER XIII

STRATIGRAPHICAL GEOLOGY

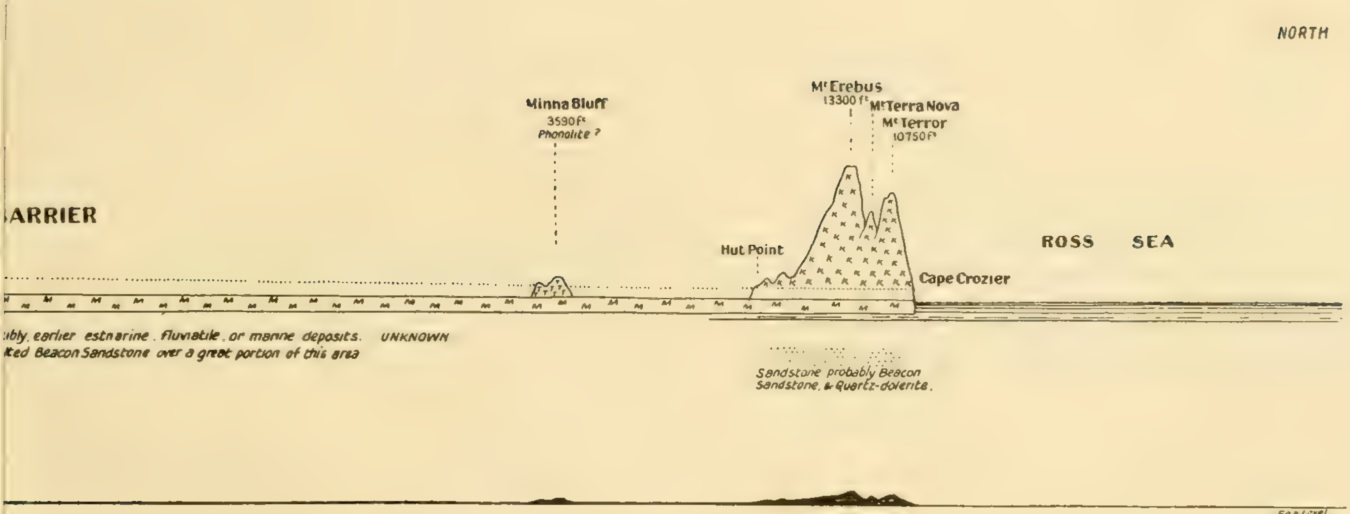
Our ideas as to the general sequence of geological formations in the Ross region are illustrated in Figs. 1, 2, and 3 of Plate LXXV. All three sections commence on the inland ice, cross the great Antarctic Horst, and terminate in Ross Sea. As these sections explain themselves, we may now pass on to consider in detail the different formations represented.

PRE-CAMBRIAN

Rocks of the Pre-Cambrian age were traced at intervals by various members of our expedition from Cape Roberts near Granite Harbour, on the north, to possibly the Beardmore Glacier, on the south. We say, "possibly," because some of the granites of the Beardmore Glacier, though gneissic, may not necessarily be of Pre-Cambrian age. The most typical exposure of what appeared to us to be Pre-Cambrian gneiss *in situ* was that visited by the Northern Party at Cape Roberts, a few miles south of the southern headland of Granite Harbour. In his notes on the Petrology of South Victorian Land, at the end of this volume, Mawson states that he considers that the gneiss of Cape Roberts closely resembles that of the South Neptune Islands in South Australia. He states that this Antarctic gneiss contains frequent basic schliers. These granite gneisses at Cape Roberts are traversed by dykes consisting of coarse pegmatite at their margins, with fine aplite at the centre. The folia of gneiss strike about N. 25° W., and dip about W. 25° S. at about 60°. On the mainland, opposite Dunlop Island, at 17 miles south-west from Cape Roberts, there is an outcrop of gneissic granite, the folia of which dip about north-west at approximately 30°. It is doubtful whether the whole of this rock can be considered true gneiss. It has rather the appearance of belts of puckered gneiss caught up in a grey gneissic granite. Amongst the erratics of Cape Royds were several of very coarse gneiss and augen-gneiss rich in black mica. We did not discover this rock *in situ*. Prior * describes a gneiss, closely allied to that of the rocks met with at Cape Royds, as occurring *in situ* at the point marked D4 on Ferrar's geological map in the Kukri Hills of the Ferrar Glacier Valley. He also describes the red augen-gneiss from the Cathedral Rocks, and from the same locality a hornblende diorite. He adds that hornblende schists are associated with these gneisses.

* National Antarctic Expedition, vol. i., Geology, p. 125.

PLATE LXXV



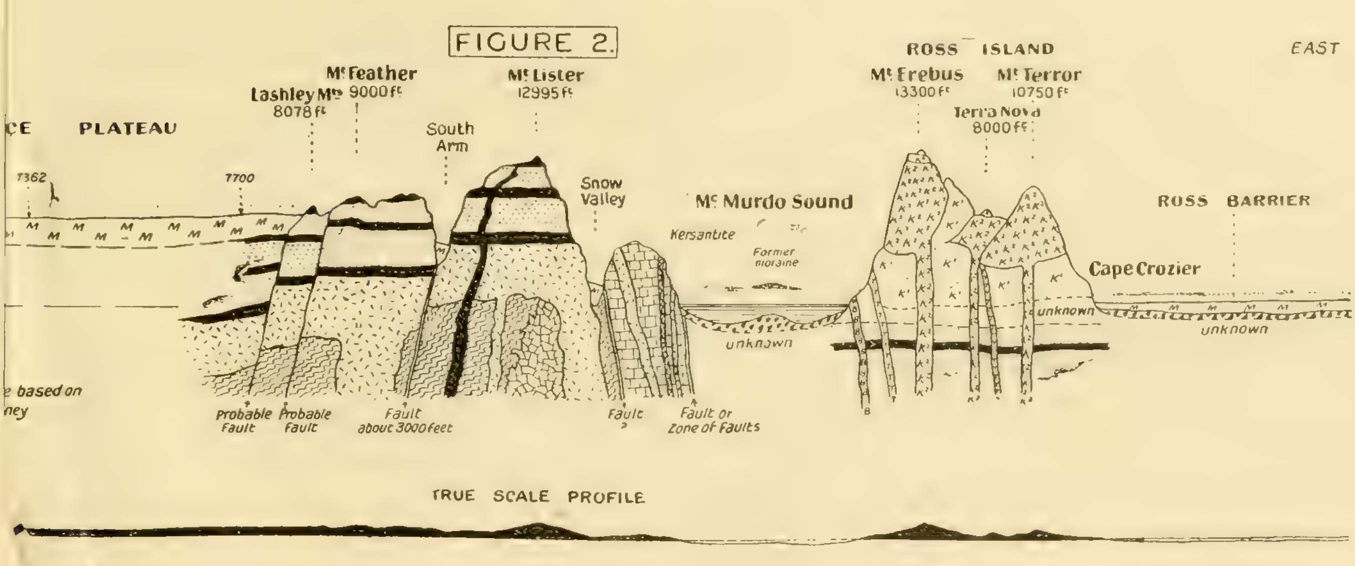


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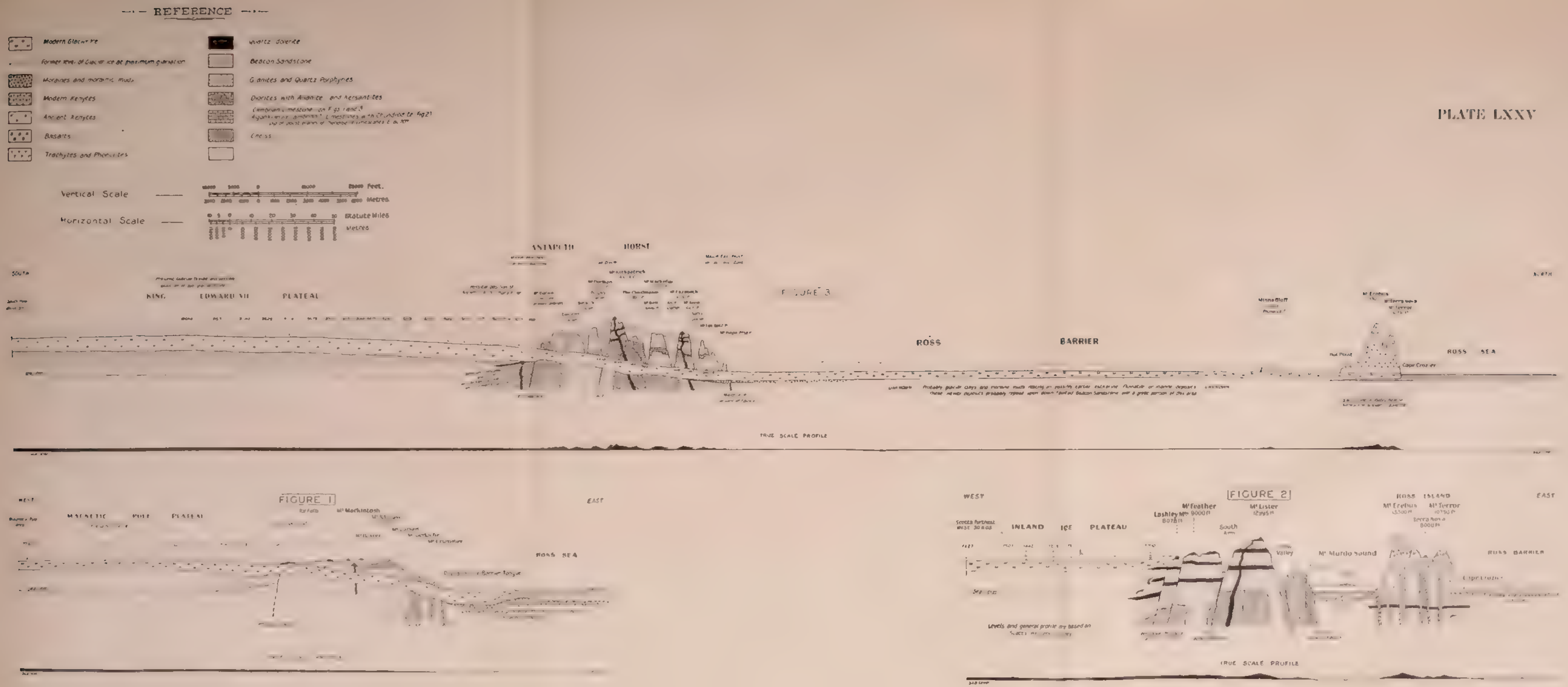
PLATE LXXV



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Mawson records the occurrence of an erratic block of granite at Cape Irizar weighing several tons. This shows well the early stages of gneissification. He says, "The felspars usually show crush only round the edges. It contains, besides the usual constituents, a little grey sphene, pleochroic yellow-brown allanite, and small apatite prisms." He also notes that a gneissic granite occurs *in situ* at a rocky point about 8 miles south of Cape Irizar. Amongst the accessory minerals he notes several grains of faintly coloured fluorspar. It seems doubtful to us whether either of these two specimens belong to Pre-Cambrian time, though it is possible that they may do so. On the other hand, there can be little doubt that the erratics collected by one of us (Priestley) at Dry Valley, and described by Mawson respectively as banded gneiss and mica schist with large poikiloblastic felspars from Dry Valley, and a sphene-bearing actinolite-gneiss from the upper glacial moraine of the Ferrar Glacier, are really of Pre-Cambrian age.

It is clear from these observations, combined with those of our party at Cape Roberts, that there is a great development of gneissic rocks, apparently Archæan, extending at any rate from the Ferrar Glacier Valley to Granite Harbour, a distance of over 50 miles. At Marble Point, about 16 miles south of Dunlop Island, there is a fine outcrop, on the coast, of very ancient metamorphic rocks, and these consist of amphibolite rock with large hornblendes up to as much as 3 inches in length, the general grain size being about half an inch. Calc schists and much contorted mica schist are associated together with granite and aplite. We saw no evidence of any massively intrusive granite there. The trend of the chief lines of folding in this metamorphic series was about N.N.W.

At Cape Bernacchi, about 5 miles south of Marble Point, there is a fine outcrop of what appear to be Pre-Cambrian crystalline rocks. The most conspicuous member of this group is coarse-grained saccharoidal marble containing flakes of graphite. It contains also iron pyrites, copper pyrites, reddish biotite, garnet and epidote. It is associated with tourmaline schists, and much epidote also occurs in bands as well as a mica granulite, pyrite- and epidote-bearing quartz veins, and irregular patches, a few feet in diameter, of coarse biotite-bronzite rock. The reddish-brown biotite of the Marble Point series was found by Mawson to contain a notable percentage of manganese. This belt, extending from Cape Bernacchi to Marble Point, is most promising for the occurrence of economic minerals. The following sketch illustrates the mode of occurrence of this series at Cape Bernacchi.

The folia at Cape Bernacchi are much contorted; at the extreme point it was observed that they dip north at about 15 degrees. Several fragments of similar marble were collected at the Stranded Moraines. These also are graphitic, and contain small quantities of quartz, apatite, iron pyrites, and copper pyrites. In the moraines of Dry Valley several fragments of schist and gneiss were collected. In Mawson's opinion, they seem to have originated from the alteration of calcareous slates and sandstones. The erratics of scapolite-bearing granulite, described at the end of this volume by A. B. Walkom, possibly should be referred to this Pre-Cambrian crystalline series. Professor Woolnough has also described several varieties of Pre-Cambrian rocks amongst the erratics of Cape Royds. These he characterises as actinolite-gneiss, actinolite-schist, tremolite-schist, and quartz-schist ; the last mentioned may not be as old as Pre-Cambrian, but may possibly be referred to one of the Cambrian limestones replaced by silica. In his description of some of the rocks brought back by the Southern Party from the neighbourhood of the Beardmore Glacier Valley Mawson includes several gneissic specimens (either meta-granites or meta-arkoses of the composition of granite).

As described by Ferrar and Prior, the crystalline limestones, which seem to constitute the prevailing rock of the northern and southern foothills, occupy a belt along the coastal platform and foothills to the east of the Royal Society Range for a distance of about 40 miles south of New Harbour. Amongst these Prior records

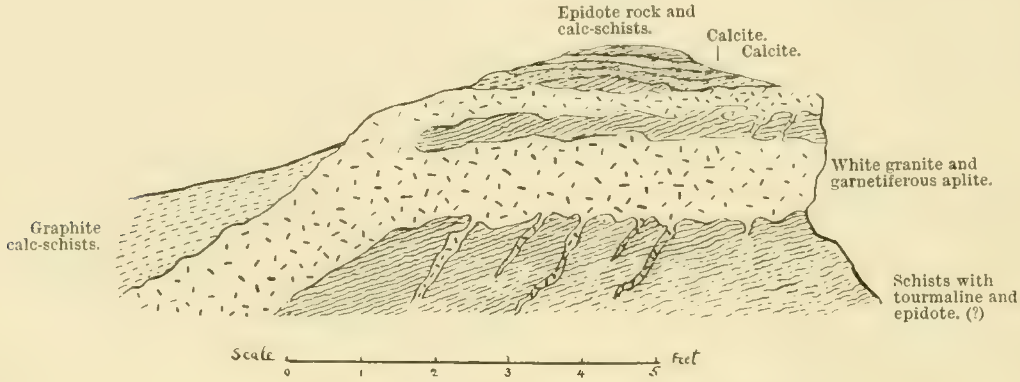

FIG. 61. Section of Pre-Cambrian (?) rocks at Cape Bernacchi

the occurrence of a crystalline limestone with chondrodite. The specimen occurred as a fragment found by Dr. Wilson along Discovery Gulf near the mouth of the Koettlitz Glacier. There is therefore every probability that a foundation complex of Pre-Cambrian rock extends from at least as far north as Granite Harbour to at least as far south as the Koettlitz Glacier, a total distance of over 90 miles from north to south ; the width of the belt is probably not less than 50 miles.

The reason why we assume provisionally the age of these rocks to be Pre-Cambrian is that, as will presently be shown, limestone breccias were found at the Beardmore Glacier containing fragments of fossiliferous Cambrian limestone, and these pieces of limestone show very little sign of serious alteration. It is therefore assumed that the graphitic saccharoidal marbles, with their associated schists, gneisses, pegmatites, and aplites, are perhaps much older. The limestone fragments above referred to contain well-preserved embryonic forms, referred by Mr. T. Griffith Taylor to the *Archæocyathinæ*, and also dendroid organisms which Mr. F. Chapman considers to be allied to *Solenopera*. This entire series may therefore be considered Cambrian. In this case it is not unreasonable to class the older series as Pre-Cambrian.

CAMBRIAN

Rocks provisionally referred by us to this horizon are represented in the form of a limestone breccia at the foot of the great granite cliffs at Lower Glacier Depot on the north-west side of the entrance to the Beardmore Glacier, about 8 miles southerly from Mount Hope. The specimen of this breccia, in which what we considered to be Cambrian fossils were obtained, was collected by Wild of the Southern Party of the Shackleton Expedition. This rock has been described in detail by Professor E. W. Skeats, D.Sc., in Part II. of this work. Professor Skeats states that about forty sections and eight hand-specimens of limestone were submitted to him for description, possibly all of Cambrian age. The rock referred to from Lower Glacier Depot is described as strictly a dolomitic breccia; the breccia is dark grey in colour, the fragments contained in it being darker than the cementing material, which is calcareous. Professor Skeats considers that the rock was completely dolomitised before it was broken up. He mentions that intermixed with the dominant dolomite are occasional small fragments of calcareous and micaceous sandstone, chert, dark cherty shale or silicified oolitic limestone. Angular fragments of quartz are sometimes abundant. The breccia occurred in very large blocks, and form apparently part of the left lateral moraine of the Beardmore Glacier. The great interest which attaches to this breccia is that it contains two dominant types of fossils, of which one has been determined by Mr. T. Griffith Taylor as being referable to the *Archæocyathinæ*. Remains of the sponge spicules, and what appeared to be fragments of crusts of trilobites, may also be recognised. Mr. Taylor confidently asserts that the bulk of the calcareous organisms are fragments of the *Archæocyathinæ*. As the individual fragments in the breccia are small, as a rule not exceeding one-third of an inch in diameter, it is only the embryonic forms of the *Archæocyathinæ* that are at all complete. Mr. Taylor believes that he can identify the following:—

Archæocyathus akin to *A. profundus*.

A hand specimen of *Protopharetra*, akin to *P. radiata* (Bornemann), *P. rete* (Taylor), *P. dubiosa*.

The following is Mr. Taylor's detailed description, with figures:—

*Introduction.** Amongst the specimens collected on the Beardmore Glacier by Sir Ernest Shackleton's Expedition was a piece of yellowish limestone breccia. This was cut into sections at the University of Sydney, and was found to contain numerous microscopic fossils, which it was suspected were allied to the *Archæocyathinæ*.

I was able to confirm this, and the sections, numbering about twenty, were

* By Griffith Taylor, B.Sc., B.E., B.A., F.G.S., Senior Geologist, Brit. Ant. Exped., 1910–1913.

handed over to me for examination. Unfortunately the sections were not cut in series, for it was not at first supposed that they were of such great palæontological interest. Since the specimens are very fragmentary, I have felt it advisable to describe them first of all seriatim with reference to the photographs. In this description I have given numerous references to the Memoir * on the *Archæocyathinæ*, published by the Royal Society of South Australia, completed earlier in 1910.

The bearing of this discovery on the climate of the Cambrian Age is, I understand, being investigated by Professor David; but I cannot refrain from drawing attention to the geographical position of this *Archæocyathinæ* horizon. In the Memoir (p. 69) I give a diagram (Fig. 3) illustrating the extra-tropical character of the localities. Hitherto, although none have been discovered in lower latitudes than 30°, the occurrence nearest the Poles had been that of Waigatch Isle to the north of Russia (lat. 70° N.). The present specimens come from much higher latitudes, probably from 85° S.—for the actual specimen was not found *in situ*, but among moraine material near the Cloudmaker.

One may hazard the speculation that in the Cambrian, the period of luxuriant life at the Poles was correlated with conditions of great heat at the Equator (far in excess of those obtaining at present), which may be shown by desert sandstones such as are so characteristic of the Triassic. It will be most interesting in this connection if a Triassic fauna and flora is found to be developed in Antarctica.

DETAILED DESCRIPTION OF SPECIMENS IN MICROSCOPIC SECTIONS

Plate LXXVI. Fig. 1. A cross-section of a small regular *Archæocyathus* only one-third of a millimetre in diameter. It is of interest as being one of the smallest specimens described, but yet shows every characteristic of the mature *Archæocyathus*, such as the rather dense outer wall and the highly perforate inner wall and septa.

Here the data seem to show that in these organisms there is no simple calcareous beaker-form (without septa), but that the youngest skeleton has a number of regular septa.

As in the South Australian specimen the primitive number of septa seems to be six, so far as we can reconstruct the cup shown in the figure.

Plate LXXVI. Fig. 2. This is an oblique sagittal section of a very young cup. It is extremely interesting; perhaps one of the best sections so far noted at this stage. The section shows the outer wall, several septa, and the large pores of the inner wall, for in the upper portion the section is practically parallel to the inner wall.

In photo 46, Plate VIII. of my Memoir (on the left towards the top), is a cup

* Griffith Taylor: Mem. R. Soc., South Australia, 1910, ii. part 2.

cut in much the same direction. It is much older, however, for in the Antarctic specimen the pores of the inner wall are nearly as large as the loculi (between the septa). This illustrates a feature of the *Archæocyathinæ*—the constancy in the size of the mural pores. Of the latter there are nine to the millimetre, which is a usual number.

Another interesting feature is that the walls here are waved, as if the structure arose through the adding of one rounded cell at the side of another. This is lost in almost all mature forms (except perhaps *A. wirrialpensis, vide* photo 44), and perhaps indicates the origin of the *Archæocyathus* in a foraminiferal-like organism of the Textularian type. This minute specimen bears out my statement that the inner wall and septa are present in the earliest stages, which do not consist of simple stalked beakers, as was suggested by Von Toll. (*Vide* pp. 167–8 Memoir.)

Plate LXXVII. Fig. 1. This is a vertical section through a small cup of a much more irregular nature than that represented in Slide (2) 68, photo 1. The thickened basal portion and thicker outer wall are quite usual, and have been noticed in many young forms. The inner wall and septa are not clearly differentiated. Probably it is a *young Protopharetra* in which the intervallum is occupied by irregular meshwork. If so, it is of interest as tending to confute Bornemann's argument that the *Protopharetræ* are merely vegetative or rooting stages of the more regular forms. (*See* p. 113 Memoir.)

Plate LXXVII. Fig. 2. A fragment of a *regular Archæocyathus* showing three septa cut transversely. (*See* also Slide 118, photo 34 (12) next following.)

Plate LXXVII. Fig. 3. Fragment of three parallel septa are here preserved. They show that regular *Archæocyathinæ* were present. They recall the close-set regular septa of certain of the Siberian species, such as *A. ijizkii* of Von Toll. (*See* Fig. 26, No. 3 in Memoir.)

Plate LXXVII. Fig. 4. Five septa of an anastomosing species like *A. profundus.* Notice the solid dark core and irregular powdery zones in the outer portion of the septa.

The septa are somewhat less than a millimetre apart. There is some appearance of an outer wall on the right. This photo should be compared with that given in the Memoir, Plate IX., photo 53, of an allied species, *A. dissepimentalis.*

Plate LXXVII. Fig. 5. A fragment of an irregular *Archæocyathus*, possibly akin to *A. profundus*, showing anastomosing septa.

The differentiation of the septal laminæ into light and dark zones is remarkable, for here the inner band is the lighter and the outer more dense, whereas the opposite is the usual appearance. It is possible that the feature (in both cases) is purely secondary.

Slide 110 shows a similar fragment. Three septa and a dissepiment of the same form as in the photo above, but the *central* laminæ are the denser here.

Plate LXXVII. Fig. 6. Three septa of a regular *Archæocyathus* with dissepiments. These are much slighter structures than usual, and belong to a different species from those shown in Slides 70, 121, &c. The specimen is too fragmentary for identification. It may perhaps be allied to *A. dissepimentalis.* (Taylor, *op. cit.*, Plate IX., photo 53.)

Plate LXXVIII. Fig. 1. Portion of outer wall cut somewhat obliquely and showing one septum. The thick wall and pores are characteristic. Plate XV. (Bornemann) shows * a similar feature in *A. spatiosus* (Plate LXXVI. Fig. 4 sketched herewith), and this may tentatively be allied therewith. .

Plate LXXVIII. Fig. 2. Portion of the inner wall of a regular *Archæocyathus.* It is cut transversely, and shows large mural pores and fragments of septa. The fragments remind one of the section of *A. ajax* shown in photo 18 on Plate IV. of my Memoir, but it is obviously impossible to draw any conclusions as to species.

Plate LXXVIII. Fig. 3. The figure shows a vertical section through one-half of an *Archæocyathinæ* cup. It belongs to the *Protopharetra* division of the class, for the intervallum is crossed by an irregular meshwork and not by regular septa. On the left is the outer wall, which is evidently rugged and denticulate. The septal network connects the outer wall to the inner wall. A portion of the latter (at the top on the right) appears to be cut parallel to its surface. This wall is here seen to be perforated by rows of small pores—about four to a millimetre, a very common distribution. It is perhaps akin to *P. radiata* (Bornemann); for the intervallum seems too narrow for *P. rete* (Taylor), and the meshwork is rather more regular. It is, of course, impossible to identify it without a cross-section, which might ally it with *Dictyocyathus.*

In Plate LXXVI. Fig. 5 is reproduced a figure of Bornemann's (*op. cit.*, Plate XIX. Fig. 7), which shows how the organism would appear if it were complete. In the Antarctic specimen only the left half of the section is present.

Plate LXXVIII. Fig. 4. This appears to be a section of one-half of a cup, which differs considerably from any so far recorded. The structure on the right, appearing as a dark, dense, irregular zone, is most probably a section of the outer wall. Then occurs a zone of irregular reticulate material, which occupies, I believe, the intervallum; and on the left is a row of large, regular meshes, which represents the inner wall.

This conjectured explanation will be seen to have points of resemblance to several *Archæocyathinæ*, notably *A. retezona* ((Taylor, *op. cit.*, p. 121) and *Ethmophyllum dentatum* (Taylor, *op. cit.*, p. 130). But the latter have very regular septa, which are certainly not present in this specimen. In its septation it agrees with *Protopharetra*, but none of the latter have the regular meshed structure shown on the left of the photo.

It may be provisionally termed *Protopharetra retezona*, but further material is required for a complete description.

Description of Species. General form unknown; probably cylindrical, like most *Protopharetræ.* Outer wall dense and irregular. Septa represented by an irregular

* Verstein. Cambrischen Schichtensyst. Sardinien, 1866, t. 15, f. 2.

meshwork as in other *Protopharetræ*. Inner wall unusual, and formed of a *coarse regular mesh* with large oval openings. Possibly 6 millimetres in diameter when complete.

Probably fragment of a *Protopharetra* like *P. rete* (Taylor). The structure shown reminds one of the septa in Photo 73, Plate XIII. The differentiation into two zones, an outer paler portion and denser median portion, has been noticed in several *Protopharetræ* and allied forms—especially in the "pillars" of *P. dubiosa* (*op. cit.*, p. 150 Memoir), though it is more regular than the latter species.

Plate LXXVIII. Fig. 6. This body, though undoubtedly organic, is very indefinite in structure. It resembles *P. dubiosa*—in itself a doubtful species—more than any other of the *Archæocyathinæ*. It seems to consist of irregular enveloping laminæ from which structures of a lobe-like nature originate. Some appearance of parallel rods also recalls the "pillars" of *P. dubiosa* (*op. cit.*, p. 150), with which it may be provisionally allied. At the same time its irregularity is so pronounced that it is not impossible that it is merely a form of rooting attachment.

Plate LXXIX. Fig. 1. This organic material is too indefinite for identification. It may be portion of a rooting structure, and the same remarks apply to this section as to Slide 118.

Plate LXXIX. Fig. 2. In this slide a very curious organism is shown in cross-section. The appearance is that of an annulus of about 2 millimetres diameter, built up of contiguous oval cells, some fifty or sixty completing the circle. A fragment of this annulus reminds one of a cross-section of *Halysites*, but the resemblance is merely accidental. Within this outer circle are indications of inner circles of a delicate nature, and there is some appearance of rays or spines connecting the circle.

No sign of this extraordinary organism appeared in other slices, so that it is impossible to say if this circular section indicates a sphere, cylinder, or cone. It cannot, I think, be classed with the *Archæocyathinæ;* though *Rhabdocyathus*, a most aberrant ally (*op. cit.*, p. 169) of the class, might conceivably give a cross-section like this.

Plate LXXIX. Fig. 3. Several organic fragments appear in this slide. The photo figures some of them, notably one which resembles a cross-section of a trilobite, but the material is too much altered for identification.

There is also a minute hour-glass-shaped body of unknown affinities, certainly unrelated to the *Archæocyathinæ*.

Plate LXXIX. Fig. 4. An indeterminate fragment.

*Tuning-fork Spicule of Lelapia.**

Plate LXXIX. Fig. 5. The occurrence of this very interesting spicule deserves to be recorded, though there is little probability that it is derived from the *Archæocyathinæ*. In the South Australian specimens numerous isolated spicules were detected, and some are figured in my Memoir (Plate VI., photo 35). The shape of

* Treatise on Zoology, part 2, 1900, p. 102, fig. 72*o*.

the Antarctic spicule recalls those characteristic of *Lelapia*, which are figured by Minchin.

Plate LXXIX. Fig. 6. This spicule may be derived from a Lyssacine Hexactinellid, and is of the same nature as those discussed briefly on p. 163 of the Memoir. It is, I imagine, quite unconnected with the *Archæocyathinæ* present.

SUMMARY

Of the five families of the *Archæocyathinæ* alliance (Taylor, *op. cit.*, p. 105), two are certainly represented—the *Archæocyathidæ* and the *Spirocyathidæ*. The specimens are, in general, too fragmentary for one to detect the presence of tabulæ, so that none can be referred to the *Coscinocyathidæ*.

The aberrant form, figured on Plate LXXIX. Fig. 2, may possibly be allied to the *Syringocnemidæ* (by way of *Rhabdocyathus*), but it is doubtful.

Of special interest are the three young stages, which I think tend to refute the statement that the immature forms take the form of "Calcareous Gastrulæ," as Von Toll supposes. On the other hand, they closely resemble the youthful stages described from South Australia. Two specimens are probably *regular* species of *Archæocyathus;* the third young stage is to be referred to the *Protopharetræ*, on the evidence of the irregular nature of the intervallum.

The specimens of regular *Archæocyathus* species are of two classes, with straight regular septa, which may be allied provisionally with group IV. (including *A. ijizkii*, *A. Proskurjakowi*, and *A. wirrialpensis*) on the chart in the Memoir.

The majority of the regular specimens, however, belong to group V., with somewhat irregular septa and a few dissepiments. They are very probably akin to *A. dissepimentalis* and the original type, *A. profundus*.

The most interesting of the larger species occur in Slides 123 and 112 of two forms which are certainly *Protopharetræ*, the former being akin to *P. radiata*, while the latter is a new species with a peculiar netted inner wall, like that characteristic of *A. retezona*, which is a species of another genus. I have given this the provisional title of *P. retezona*.

Two highly irregular specimens may belong to the doubtful species *P. dubiosa*. They are irregular masses of calcareous laminæ, and not improbably are merely rooting attachments.

A very curious organism, showing only in one section as an annulus formed of a single row of oval cells, with indefinite rays and concentric walls within, is described briefly, but no attempt is made to name it. It is very doubtful if it belongs to the *Archæocyathinæ*.

As in the South Australian specimens, large isolated spicules—not derived from the *Archæocyathinæ*—occur. One perfect "tuning-fork" is preserved, and has been photographed.

PLATE LXXVI

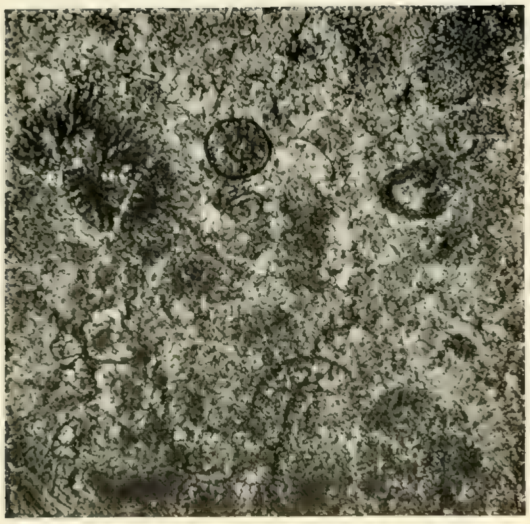

Fig. 1

Fig. 2

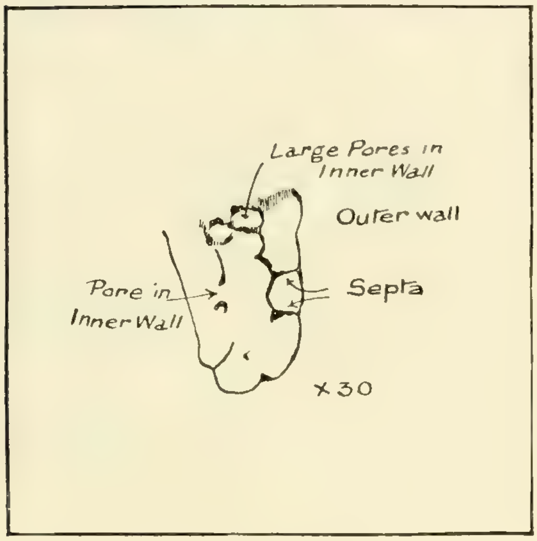

Fig. 3

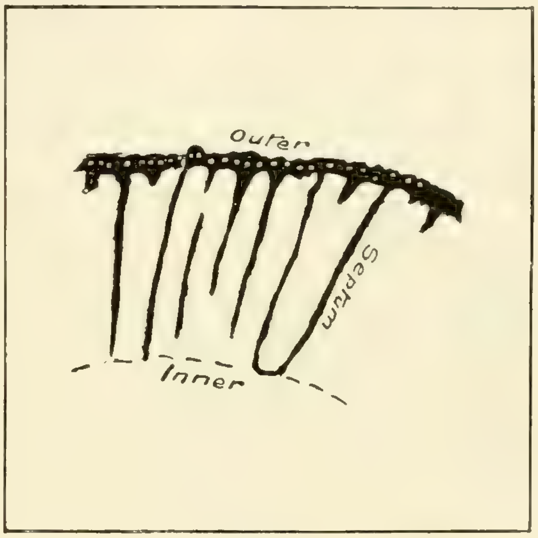

Fig. 4

Fig. 5

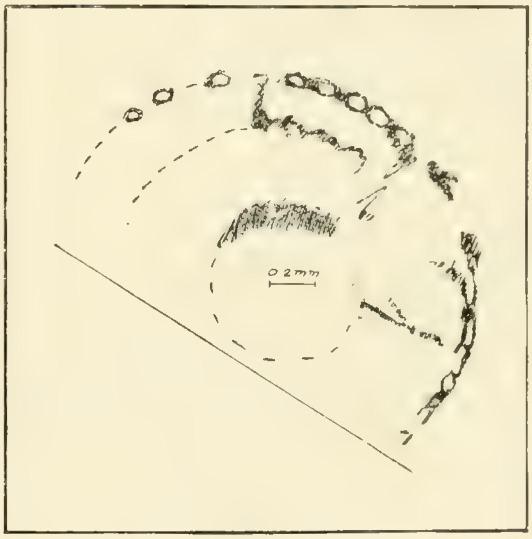

Fig. 6

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PLATE LXXVII

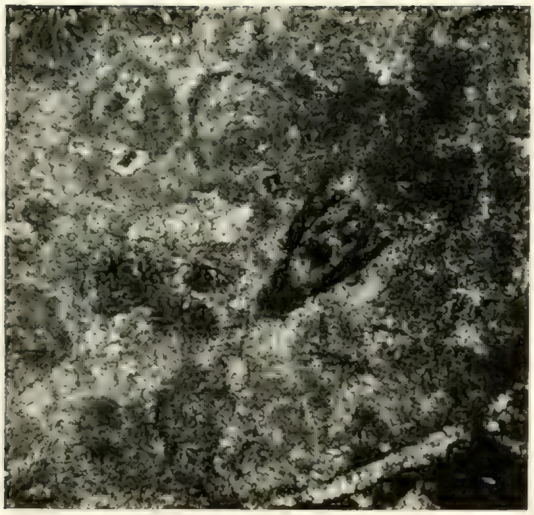

FIG. 1

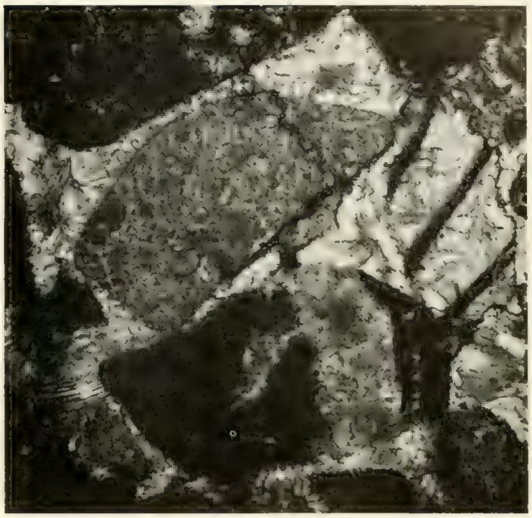

FIG. 2

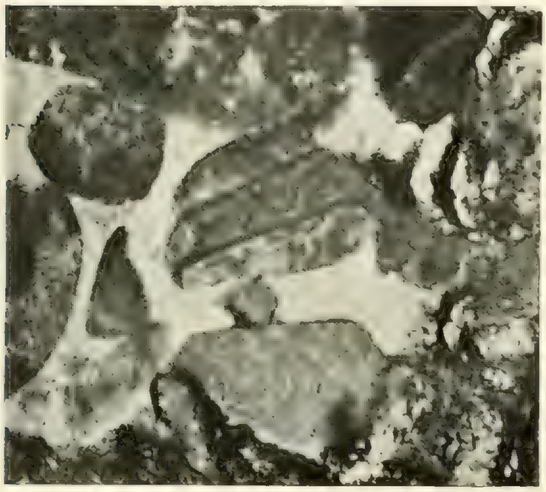

FIG. 3

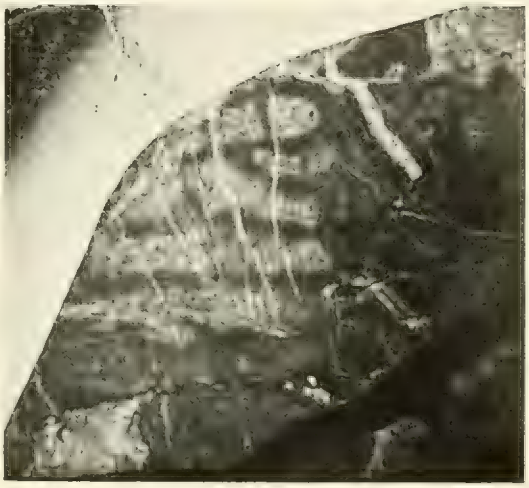

FIG. 4

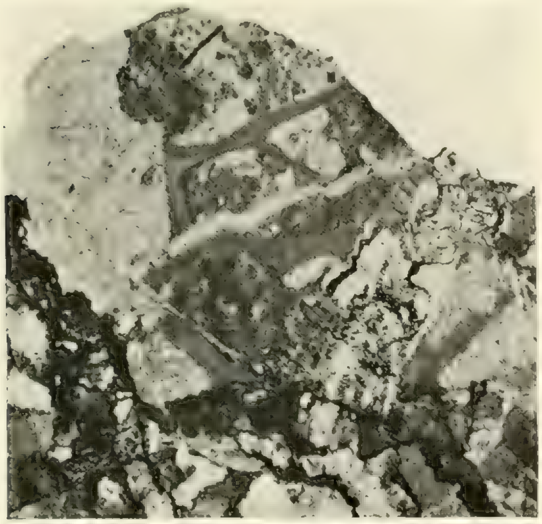

FIG. 5

FIG. 6

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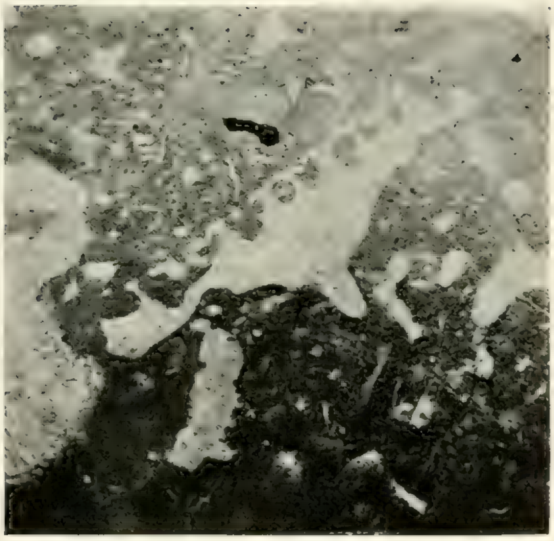

FIG. 1

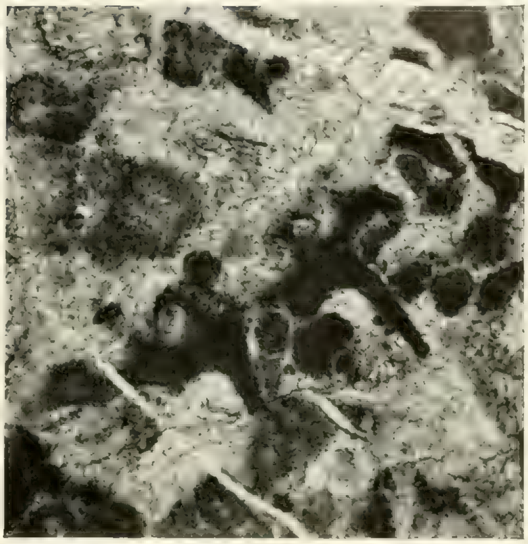

FIG. 2

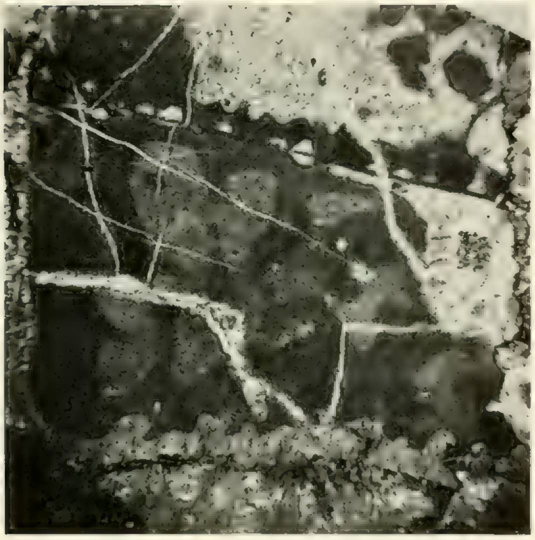

FIG. 3

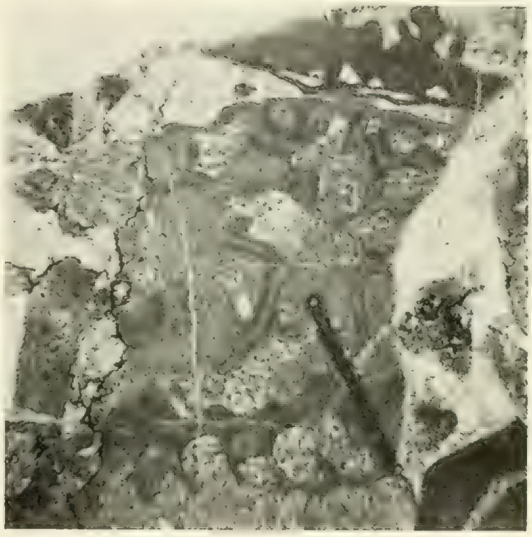

FIG. 4

FIG. 5

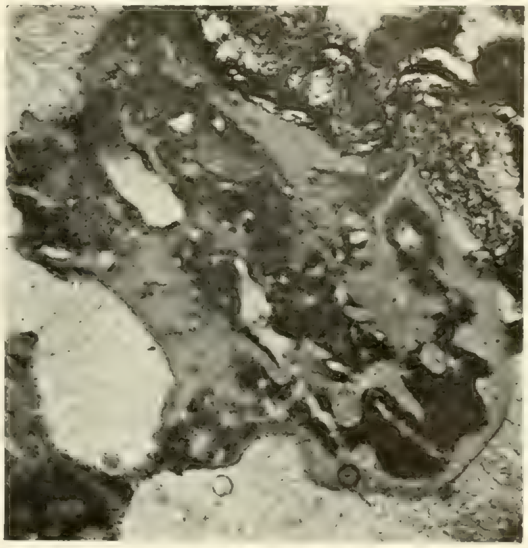

FIG. 6

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PLATE LXXIX

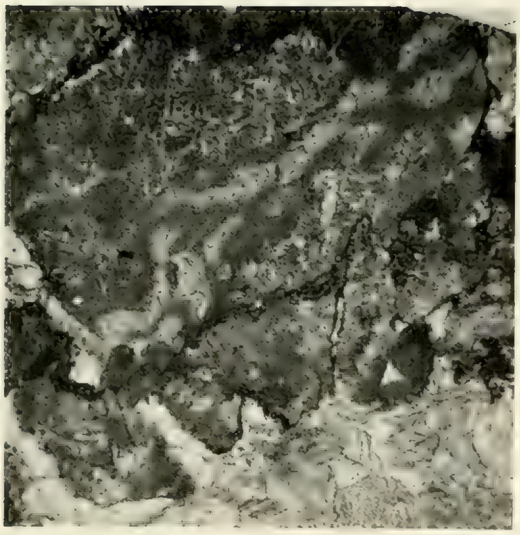

Fig. 1

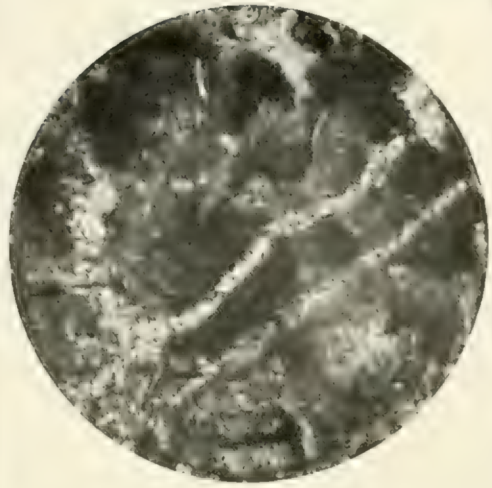

Fig. 2

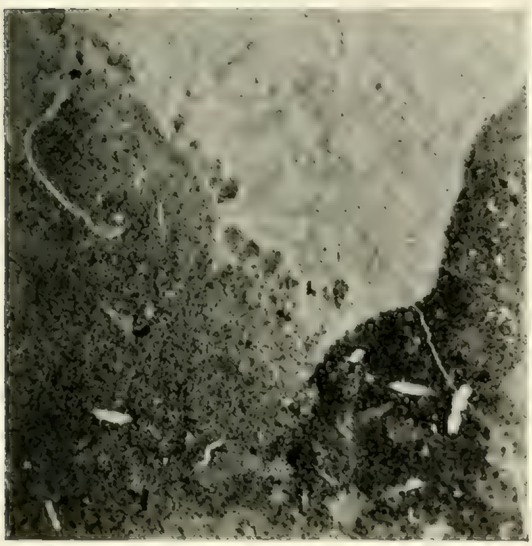

Fig. 3

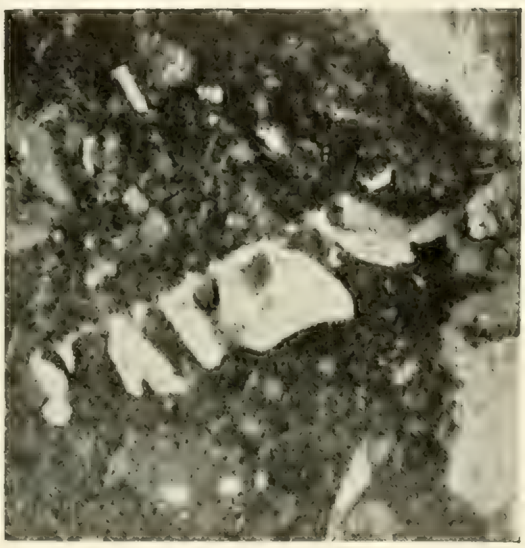

Fig. 4

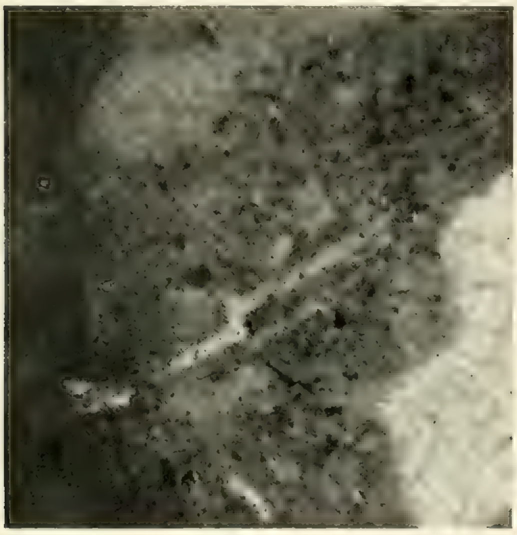

Fig. 5

Fig. 6

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Associated with these remains of the *Archæocyathinæ* is a very abundant dendroid organism, which shows in dark arborescent radiating forms in the lighter matrix of the limestone. Mr. R. Etheridge of the Australian Museum, Sydney, W. S. Dun, Palæontologist to the Geological Survey, Sydney, and Mr. Frederick Chapman, Palæontologist to the National Museum, Melbourne, all agree in referring this organism to some kind of calcareous plant, such as *Solenopora*.

Mr. Chapman concludes that this plant may be compared with *Confervites primordialis* of Bornemann, from Sardinia, also recorded by Von Toll from Siberia; *Epiphyton flabellatum* (Bornemann), from Sardinia; and *Siphonema* (= *Girvanella*) *incrustans* and *S. areaceum* (Bornemann), from Sardinia. Mr. Chapman considers it most nearly allied to the *Epiphyton*, though he also admits that it has affinities with *Solenopora*.*

On the assumption that the fragments of limestone with the breccia are of Cambrian age, the question suggests itself, what is the age of the breccia as a whole? Obviously it must be Post-Cambrian. The breccia, as far as we are aware, has not yet been discovered *in situ*, but as this discovery is to be made the special quest of the British Antarctic Expedition of 1910–12, it is highly probable that the breccia will now have been located *in situ*. It is possible that it is a basal breccia at the base of the Beacon Sandstone formation. On the other hand, Sir Ernest Shackleton was of opinion that the massive limestone *in situ* at Buckley Island, at the head of the Beardmore Glacier, was actually interstratified in the Beacon Sandstone formation. Mr. F. Wild was of the contrary opinion, and considered that the limestone, though in altitude a little higher probably than the Beacon Sandstone, was in reality dipping underneath it. The photograph of Buckley Island shows a slight dip of the Beacon Sandstone formation down the Beardmore Glacier Valley, but the angle of this is low, and it is doubtful whether, without the intervention of a fault, the Beacon Sandstone can be considered to be stratigraphically above the limestone. This is a question which no doubt has been definitely settled by the scientific members of the British Antarctic Expedition of 1910–13 under Captain Scott. In the section (Plate I. Fig. 3, accompanying this Report) from the inland ice across the great horst and the ice barrier to Mount Erebus, we have adopted the view that the limestone of Buckley Island is identical with that which has supplied the fragments to the limestone breccia, that Mount Darwin is therefore Cambrian, and that the breccia has been derived from the waste of this limestone, and forms a basal bed under the Beacon Sandstone. It may be noted that Ferrar describes (*op. cit.*, p. 41) the occurrence of thin limestones interstratified in the Beacon Sandstone, and a fragment of fine-grained argillaceous limestone discovered by us at Dunlop Island is also probably derived from this horizon. The latter showed traces of organisms resembling some

* Professor Garwood has recently described *Solenopora*-like organisms from the Carboniferous rocks of Great Britain.

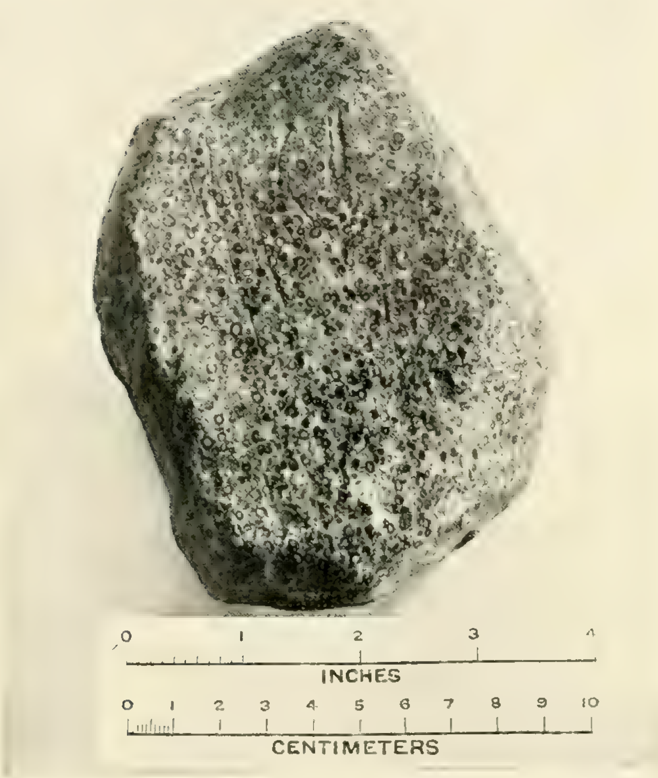
kind of fossil seed, like *Carpolithes*, but the specimen was imperfectly preserved. These limestones interstratified in the Beacon Sandstone appear to be distinct from the dolomitic limestone of Buckley Island.

It will have been noted already that limestone occurs on a grand scale in the so-called Algonkian rocks, between Cape Bernacchi and the Koettlitz Glacier. It is still possible that these massive graphitic saccharoidal marbles may not be Algonkian, but may represent locally metamorphosed limestones belonging to the Cambrian. The limestone *in situ* at Buckley Island is described by Professor Skeats as in part being distinctly dolomitic, the other is not dolomitic. Professor Skeats states that "obscure traces of fossils, including *Archæocyathinæ*, can be seen." If this determination by Professor Skeats is quite unquestionable, it will at once settle the problem as to the age of the Buckley Island limestone, for the limestone there is actually *in situ*, in masses many hundreds of feet in thickness, and on this determination it is obviously of Cambrian age.

The Buckley Island limestone is traversed by curious dark greenish streaky material. Professor Skeats considers that these probably represent a finely-divided tuff "from a rather alkaline intermediate rock, such as a porphyrite or somewhat basic trachyte on the one hand, and fine-grained micaceous detrital material on the other."

Amongst the erratics at Cape Royds some specimens were obtained of a well-marked silicified oolite. This very closely resembles some of the silicified oolites in the Lower Cambrian rocks of South Australia, as near Hallett's Cove on St. Vincent's Gulf and near Crystalbrook north of the head of Spencer's Gulf. Dr. G. J. Hinde, F.R.S., compares these Antarctic silicified oolites with the Durness limestone of Scotland. Under the microscope the grains show much radiating black carbonaceous material, which in places appears to have an obscure netted structure, hence it was thought by one of the authors (T. W. E. D.) that it might represent an older radiolarian rock. It is, however, very unusual for radiolarian shells to be preserved in a rock that was originally a limestone. It is probable that as the Beardmore Glacier Cambrian (?) limestones show a tendency to oolitic structure that these silicified oolites are also derived from the same formation.

Small erratics of limestone were found on the summit of Mount Hope at 2700 feet above sea-level, also pieces of a red limestone were obtained from the marginal moraines on the western side of the Beardmore Glacier. It appeared to the members of the Northern Party that there was limestone underlying the sandstones which form a flat-topped capping to Mount Nansen. Small pieces of limestone were obtained by that party from the old moraines to the south-east of Backdoor Passage, southerly from Mount Larsen. It was not possible to determine whether these limestones were below the Beacon Sandstone or interstratified with it. As far as could be observed by inspection with a good field-glass the limestones were below the sandstone. In this case they too may be of Cambrian age. Professor Skeats



GLACIATED BOULDER OF CAMBRIAN (?) OOLITIC LIMESTONE, FROM BEARDMORE GLACIER

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has discovered sponge spicules in an ancient dense limestone, intermixed with submarine tuff from the Stranded Moraine in the east fork of the Ferrar Glacier. The fossils noticed are several broken pieces of sponge spicules; the fragments are each in length about two or three times the diameter of the spicule. In each case the central canal is clearly preserved, and the silica remains in its original colloidal form. Professor Skeats compares them with sponge spicules which he has found in cherty rocks of the Heathcoatian series in Victoria, which is believed to be either Lower Ordovician or Upper Cambrian. Dr. Hinde agrees with Professor Skeats in referring these organisms to sponge spicules.

In addition to limestones of Cambrian age there are certain rocks, termed by Mawson arkose-greywacke, which may perhaps also be Cambrian, though it is possible that they are of Beacon Sandstone age. Mawson states "by a study of the marine derived specimens it is not possible to say how far the quartzites represent the Beacon Sandstone, or to what extent they proceed from older formations." Mawson suggests that the red colour of some of the limestone fragments, as well as of the arkose, suggests that they may have been deposited under semi-arid, possibly semi-glacial, conditions. Only one other formation is known to us in South Victoria Land which may be considered to belong to the Cambrian formation. This is a greenish-grey slate, numerous fragments of which were found lying upon the surface of the Beardmore Glacier in the neighbourhood of the Cloudmaker. They had obviously been blown on to the ice from slate rocks *in situ* from the hills farther south. The slates are probably at least older Palæozoic in age.

DEVONIAN

BEACON SANDSTONE (IN PART)

The announcement was made by Mr. Griffith Taylor to the Royal Geographical Society that the fossil fish plates discovered by F. Debenham and himself at Granite Harbour are considered by Dr. A. S. Woodward to be undoubtedly of Devonian Age, obviously an extremely important discovery.*

* Hence the lower part of the Beacon Sandstone will hereafter probably have to be classed as Devonian.

CHAPTER XIV

ERUPTIVE ROCKS, PROBABLY POST-CAMBRIAN AND PRE-GONDWANA

As already stated, there is a considerable development of folded granitic rocks in the Pre-Cambrian group, and it is very difficult to differentiate between the true Pre-Cambrian gneisses and the gneissic granite or sub-gneissic granite of localities such as Depot Island, Mount Crummer, &c. For example, at Depot Island there are large included masses of quartzite caught up in the sub-gneissic granite, together with very numerous inclusions of a basic type of sphene-bearing diorite. It is possible that these masses of quartzite have been torn out of the basal portion of the Beacon Sandstone. If so, this sub-gneissic granite would be Post-Gondwana instead of Pre-Gondwana. For the present we are considering such granites as Pre-Gondwana, looking upon the quartzites as something older than the Beacon Sandstone formation.

These eruptive rocks, following Dr. Mawson's and Professor Woolnough's classifications, we may group as follows:—

I. Granites and associated dyke rocks.
  1. Granites.
  2. Dyke rocks.
    (i) The porphyries.
      Granite porphyry, granophyric granite porphyry, orthoclase porphyry, quartz porphyry, halleflinta-like porphyries, aplitic granite porphyries.
    (ii) The aplites.
    (iii) The pegmatites.
    (iv) The granophyres.
    (v) The porphyrites.
    (vi) The lamprophyres, minettes, kersantites, &c.

II. Syenites, including sodalite-syenite with wohlerite.

III. The diorites.
  Quartz diorites and basic diorites rich in sphene, the latter occurring in places as inclusions in granite.

IV. The gabbros.

I. GRANITE AND ASSOCIATED DYKE-ROCKS

1. *The Granites.* These comprise grey granites containing little or no hornblende, with biotite, zircon, and allanite. The granite of Cape Irizar and Mount Larsen may be taken as typical of this variety. This granite is distinctly alkaline. The fact that pink felspar is absent from the arkoses of the Beardmore Glacier leads Mawson to the conclusion that these grey granites, which are represented in the arkose, are older than the pink granites.

In the neighbourhood of the Beardmore Glacier is a coarsely crystalline porphyritic grey granite apparently allied to the Cape Irizar and Mount Larsen types.

Quite distinct from the grey granites, and obviously newer, are the pink granites. Ferrar considered that these pink granites intrude the dolerite sills which have burst their way through the Beacon Sandstone. If this view is correct the dolerite is Post-Gondwana, and the pink granite still later in geological age. We were unable to see the spot where Ferrar believed that there was evidence of the intrusion of the pink granite into the dolerite. So far as our observations extended, it seemed to us that the pink granite was on the whole older than the dolerite, and we propose provisionally to class it as such, without of course intending to exclude the possibility that there may be a later local development of pink granite which may intrude the dolerite. For the petrological details of these rocks readers are referred to the chapters by Dr. Mawson and Professor Woolnough at the end of this work. We are specially concerned with their field relations.

In the lower diagram of Plate XCII., Chapter XX., an attempt has been made to show the relations of these rocks to one another in chronological order.

The order seems to be as follows :—

1*a*. *Diorites.* At the southern slope of Mount Crummer fine examples were observed of a greyish granite intruding masses of dark dioritic rock.

It was very obvious that the granite rock was the newer. There is, therefore, clear evidence here of a sequence from older basic rocks into newer acid types. It is not possible to separate these in geological time from the diorites. The locality where the junction was sketched is Camp Lake, at the foot of Mount Crummer. Mawson suggests that the characteristics of the diorite rocks are not typical of normal diorites, but are suggestive of lamprophyric separations. In his comparative analysis he places side by side the diorite from Camp Lake, that from the Moraine about 20 miles south-east of Mount Larsen, and that from Cathedral Rocks, Ferrar Glacier, together with a kersantite intersecting the pink granite at Cape Irizar. Obviously in geological time the last-mentioned rock is much newer than the diorites of Camp Lake.

1*b*. *Gabbros.* These were not met with *in situ*, but being often sphene-bearing, appear to be closely related to the sphene-diorites included in the sub-gneissic granite of Depot Island. They comprise typical gabbros with sphene, sphene-bearing amphibolite, hypersthene gabbros, bronzite gabbros, and uralite porphyry. The following photograph shows the relation of the inclusions of basic sphene-bearing diorites at Depot Island :—

2*a*. *Grey granites with their granophyres, granite porphyries, quartz porphyries, aplitic granite porphyries, pegmatites and aplites.* The quartz and felspar porphyries, aplites, and pegmatites, are obviously a little newer than the granites. (See Fig. 37.)

2*b*. *Pink Granites.* No actual junction was seen by us between the pink granite and the grey granites, but nevertheless, for reasons already given, we agree with Ferrar in considering the pink granite to be newer than the grey.

3. *Dyke rocks of basic type, such as lamprophyres, minette, kersantite, &c.* These basic dykes appear to belong to a newer cycle altogether than that which has produced the older diorites, gabbros, and grey and pink granites. The well-marked quartz and felspar porphyry dyke at Backstair Passage, near Mount Larsen, may perhaps be a complementary dyke rock in the kersantite group. A feature of special interest in the diorite and gabbro group is the abundance of sphene.

The analysis shows that TiO_2 is present to the amount of 2·34 per cent. Rolled crystals of titaniferous iron were observed by us in erratics of quartzite at Cape Royds. These evidently were derived from some old rocks rich in titanium, possibly the diorites or gabbros already mentioned.

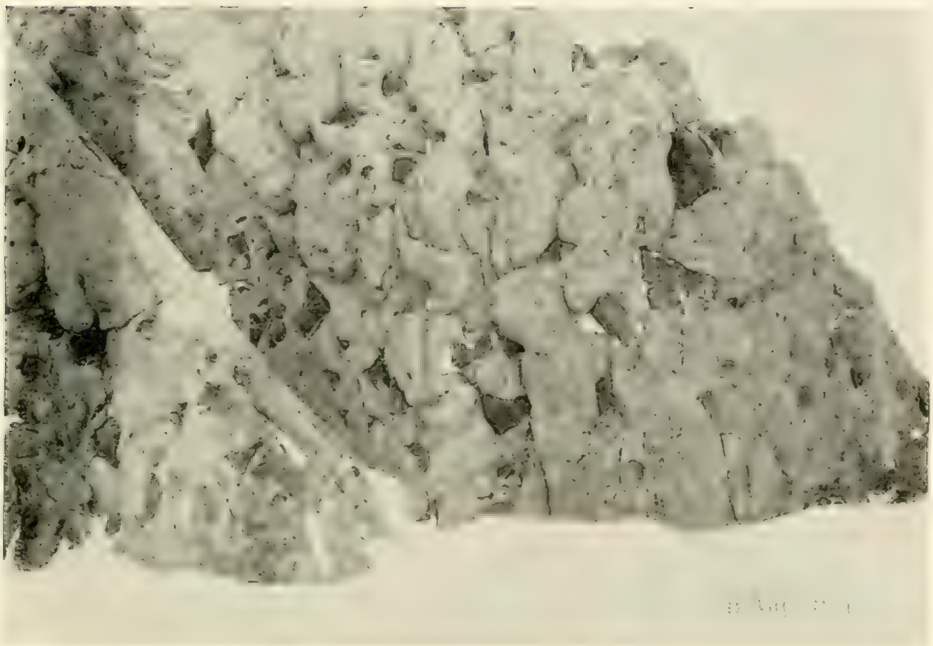
It is also interesting to note that even at this early epoch the plutonic rocks show a tendency to being alkaline. The grey granite, for example, of Mount Larsen contains Na_2O 3·13 per cent., K_2O 2·87 per cent., while the pink granite of Cape Irizar contains Na_2O 3·88 per cent., K_2O 4·72 per cent.

There is thus a tendency for the newer granite to be somewhat more alkaline than the older. This region was thus early marked out as a province for the alkaline rocks.

The interesting question now suggests itself, do these plutonic and hypabyssal rocks show any distinct affinities with the rocks of the South American Andes? In his account of the petrology of the specimens collected by Dr. Charcot's Expedition, M. Gourdon emphasizes the fact, to which Dr. Otto Nordenskjöld has already called special attention, that on the American side of the Antarctic the petrological characteristics of the Andean chain of South America are distinctly repeated. The rocks from that locality show predominance of lime with a little soda, so that the felspars are essentially lime-soda felspars rather than soda-potash. The felspars also exhibit very well the zoning which is so characteristic of Andean rocks. Gourdon records the occurrence of one rock only—an erratic of micro-granite with soda pyroxene and soda hornblende—which is alkaline in character. In regard to this he makes the following statement :—

"Ne serait-elle pas l'indice de l'existence plus au sud d'une province pétrographique

PLATE LXXXI



INCLUSIONS OF SPHENE-DIORITE IN FOLIATED GRANITE. DEPOT ISLAND

[Photo by D. Mawson

[*To face p.* 246

nouvelle et, dans le cas où elle serait indigène, ne constitue-t-elle qu'une exception dont il serait en tous cas intéressant, au point de vue théorique, de préciser la portée ?"

The question as to the general relation of the eruptive rocks of the great horst to those of the South American and Antarctic Andean rocks will be further discussed in the summary at the end of this work.

III. METAMORPHIC ROCKS

It has already been stated that these rocks in part are probably of Pre-Cambrian age. There can be little doubt that in part they represent sedimentary rocks, possibly of Cambrian or Ordovician age, which have been metamorphosed through the intrusion of large masses of granite. Mawson describes an erratic specimen from Marble Point, 5 miles north of Cape Bernacchi. This rock he terms epidotised granite. As regards sediments of metamorphic origin which may belong to the period of time intermediate between Pre-Cambrian and Gondwana, it is possible that the saccharoidal marbles and tourmaline schists between Cape Bernacchi and Marble Point represent Cambrian limestones locally metamorphosed by granitic intrusions. At the same time there is equal likelihood of their representing Pre-Cambrian limestone beds. On the whole we are disposed to provisionally group these metamorphic saccharoidal marbles and their associated schists as Pre-Cambrian.

GONDWANA

BEACON SANDSTONE FORMATION (IN PART)

The Beacon Sandstone formation in the type area of the Ferrar Valley, where it was first described by H. T. Ferrar, is shown to have a thickness of at least 1500 feet, and consists mostly of sandstone regularly, and almost horizontally, bedded, varying from fine to coarse occasional bands of conglomerate, with a few strata of clay shales and argillaceous limestone. Through the courtesy of Dr. J. T. Prior, one of us (T. W. E. D.) was able to examine under the microscope slices of this limestone. Its original structure had suffered much from recrystallisation, and no trace whatever could be seen in it of any organisms. The following is an ascending section as given by Ferrar :—

100 feet dolerite which caps the sandstones.
200 ,, yellow sandstones.
100 ,, sandstones with occasional yellow bands.
100 ,, sandstones with ferruginous concretions.
200 ,, yellow sandstones.
100 ,, sandstones with cylindrical casts.
200 ,, yellow sandstones with ferruginous concretions.

50 feet white sandstones.
200 ,, yellowish sandstones.
100 ,, marble-like sandstones.
50 ,, nearly white sandstones.
10 ,, stalagmitic sandstones.
60 ,, almost white sandstones.
30 ,, variegated brown and yellow sandstones. Chard. 2 feet ferruginous concretions, sandstones altered.

Side by side for comparison is a section obtained by Frank Wild on the Shackleton Expedition. The latter shows in descending order

500 feet . Sandstone.
about 300 feet . Coal-measures, containing seven seams of coal from 1 foot up to 7 feet in thickness.

This is succeeded by 700 feet at least of sandstone.

The general appearance of these coal-measures is shown on Plate XXXII. of Chapter V. of this Memoir.

Near the base of the formation water-worn quartz pebbles were observed in the sandstone. These pebbles are about a couple of inches in diameter. Ferrar, at the Ferrar Glacier Valley, collected quartz pebbles up to about 4 inches in diameter, and one of these is now in the British Museum. They are obviously well water-worn.

As seen at Buckley Island, the dark grey Cambrian (?) limestone was wedging out southwards, and widening towards the north, and it underlies the Beacon Sandstone. The argillaceous limestone of the Ferrar Glacier Valley is probably not on the same geological horizon as this very massive and pure limestone. In addition to actual seams of coal vast numbers of blocks of greyish-brown sandstone and laminated black carbonaceous sandstone were seen in the great median moraine below the Buckley Nunatak, following the course of the valley for fully 50 miles. Fragments of clay shale were observed in places in this moraine, and they exhibited traces of fossil rootlets.* The most interesting fossil so far discovered in this Beacon Sandstone area is a fragment of fossil wood imbedded in a loose piece of the sandstone collected from this median moraine derived from Mount Buckley. This has been carefully examined by Professor Goddard of Victoria College, Stellenbosch, South Africa, who has furnished the following description:—

"Specimens from *Medial moraine*, December 11, 1908.

"Longitudinal sections of the included dark masses give a homogeneous banded appearance of a distinctly organic nature. The banded appearance is due to the

* Obviously this is a fact of great importance, as showing that the vegetation of the coal-measures grew where the seams now occur. At present this area is in darkness for five months in the year, and yet abundant vegetation, with trees, flourished there once.

vascular nature of the organic elements composing the mass. The whole structure recalls to one's mind the appearance given by longitudinal sections of the xylem portion of the vascular area of a gymnosperm, such as *Pinus*. Only the xylem area is represented in the specimen, no traces of medullary, cortical, or phloem tissue being visible. Medullary rays are present, as shown in the microphotograph.

"The xylem itself is composed of a homogeneous mass of vessels, tracheidal in nature, no differentiation as regards the vascular elements being present. In places one may readily make out in longitudinal sections dark opaque bands of much greater size individually than the tracheides. These in all probability represent resin passages belonging to the xylem. It would seem, further, that these masses might be considered as being nothing more than an aggregation of material similar in nature to that of the walls, and due to changes under the process of petrifaction. This, however, is opposed by the fact that they occur even in these small sections fairly commonly, and at the same time are all of exactly the same size as regards width. At all events they represent some definite structure, and in all probability resin passages.

"The walls of the tracheids themselves seen under the high power of the microscope appear to be pitted, but the preservation is by no means good enough to warrant any remarks on this except that, in the common wall of adjacent tracheides, clear spaces occur of the same relative importance as the bordered pits of such a gymnosperm as *Pinus*. These clear spaces occur regularly along the length of the tracheides, and stand out strongly against the dark colour of the walls in their preserved condition.

"The nature of the xylem itself leads to the conclusion that it is a portion of a gymnospermous plant, resembling strongly in nature the same portion of a coniferous plant."

Since the time that Professor Goddard's description was published in "The Heart of the Antarctic," vol. ii. p. 300, slides of the wood have been prepared by Dr. Newell Arber, and in his opinion one would not be justified in stating anything further about this fossil organism beyond the fact that it is definite wood. Still later, in March 1912, further sections have been prepared at the University of Sydney which show traces of occasional coarse cellular patches amongst the finer tubes. These were not observed in any previous sections.

The evidence of this wood is of importance chiefly as bearing on the downward limit of age of the Beacon Sandstone formation. The lower limit of the age of the Beacon Sandstone cannot well be carried below Lower Carboniferous or Upper Devonian. The wood is of course of no value for determining the upward limit in geological time of the Beacon Sandstone.

The chemical composition of the coal obtained by F. Wild from one of the seams *in situ* is also of interest. The following is the analysis of this coal from latitude

85° S. by Mr. J. C. H. Mingaye, F.C.S., Government Analyst and Assayer to the Department of Mines, New South Wales :—

Hygroscopic moisture . . .	3·16 per cent.
Volatile hydrocarbons . . .	14·5 ,,
Fixed carbon	68·84 ,,
Ash	13·43 ,,
Total . .	99·93 per cent.

No true coke formed.
Sulphur in coal 0·274.

The fact that the coal is slightly hydrous is suggestive of its being not older than Newer Palæozoic. In Australia it is exceptional to find coal seams as old as the Permo-Carboniferous period containing more than about 1 per cent. of hygroscopic moisture. The chemical composition of the coal therefore suggests an age not older than Late Palæozoic. On the other hand, the degree of induration of this unfaulted plateau sandstone suggests a fairly high geological antiquity. H. T. Ferrar has shown on one of his sections that Beacon Sandstones are intruded by the pink granites, a statement which we had not an opportunity of confirming. In this case the induration may be explained as simply the result of contact metamorphism. There can be no doubt whatever that it has been very strongly and extensively intruded by vast sills of quartz-dolerite. This of course will have produced a great deal of quartzite as the result of contact metamorphism. Similar contact metamorphism has been recorded in the case of the Permo-Carboniferous and Trias-Jura rocks of Tasmania, where they too have been invaded by immense sills of quartz-dolerite. Indeed so like is the general appearance of much of the south-east coast of Tasmania to that of the plateau sandstone regions of Ross Sea, than an observer familiar with Tasmanian geology would at once be inclined to correlate the Beacon Sandstone formation with the Trias-Jura of Tasmania, and in the light of the most recent evidence such a correlation would not appear unreasonable. We think, therefore, that our original suggestion that the Beacon Sandstone formation may be of Gondwana Age may be provisionally accepted. Certainly a considerable induration of the rocks, in view of their comparatively undisturbed state, suggests an age for them wholly ante-dating the Tertiary and probably ante-dating the Cretaceous as well. It is of course possible that the actual coal-bearing formation which lies near the top of the Beacon Sandstone may be of distinctly newer age than the Beacon Sandstone proper underlying it, but as far as we were able to observe the whole series is perfectly conformable, and therefore to be referred probably to one and the same system.*

* It has been proved recently by Taylor and Debenham's discoveries on the last Scott Expedition that at Granite Harbour, at all events, the lower part of the great sandstone formation is of Devonian Age, as argued by Dr. A. S. Woodward on the evidence of fossil fish plates collected by the above geologists.

As regards the petrological character of the Beacon Sandstone, Mawson explains that its constitution varies through wide limits "from a nearly pure quartzose sandstone to a highly felspathic arkose, and felspathic garnet and rutile are frequently present as accessory minerals. The cement while usually siliceous is frequently calcareous." Mawson makes the significant remark that "quite fresh felspar grains are not uncommon. These grains are usually much rounded, but a considerable portion are merely sub-angular." Mawson concludes from the fresh state of the fragmental felspars that the Beacon Sandstone was probably laid down under severe climate conditions, that is, the dry conditions which would result through the interception of snow near the Antarctic Circle during a glacial epoch. Under these conditions, far south there might be a considerable absence of thaw. Such undecayed felspars are very characteristic of the Permo-Carboniferous glacial beds of Australia, India, South Africa, and South America. As a result of the rare distribution of the calcareous cement of the Beacon Sandstone calcareous concretions are formed in the rock in some places.

The concretions often contain within themselves much clay as well as calcareous material. The central portions are but loosely cemented, so that when the outer shell of the concretion is fractured as the result of weathering this soft central portion is rapidly removed by erosion, so that the concretions become hollowed out into cups. Mawson determined that the calcareous cement in the centre of the concretions for a width of 4·6 centimetres was in optical continuity.

In some of the Beacon Sandstone, as in the case of the arkose from the Upper Glacier Depot of the Beardmore Glacier, small garnets are seen to be present in the sandstone. The particles of garnet are about 0·12 millimetre in diameter; rutile needles are abundant. The felspars are chiefly orthoclase, microcline, and anorthoclase. Both muscovite and biotite mica are present sparingly in small particles. "These are usually partly converted into chlorite, and are often much bent. Rutile is present as microscopic hair-like inclusions in the quartz or occurs as isolated grains."

The analysis of the Beacon Sandstone by Messrs. A. B. Walkom, B.Sc., and G. J. Burrows, B.Sc., quoted at the end of this work, show the Beacon Sandstone to be fairly high in alkalies, the percentage of Na_2O being 3·33 and that of K_2O 2·63.

As regards colour, the Beacon Sandstone is either whitish to buff or light greyish-brown, but occasionally develops a greenish tint; this latter is due to the presence of chlorite. Mawson records the fact that "carbonaceous material appears along the bedding planes of some of the specimens from the Beardmore Glacier, just as is the case with some from the Ferrar Glacier."

As regards the details of the coal seams contained in the middle 300 feet of sandstone with bands of clay shale no detailed section was measured, but

F. Wild suggests the following, reading from above downwards, as an approximation to the section :—

1 foot to $1\frac{1}{2}$ feet, coal seam.
Strata.
7 feet, coal seam with bands of grey shale.
Strata.
5 feet, coal seam, apparently formed of clean coal.
Strata.
3 feet (about), coal seam.
Strata.
3 feet (about), coal seam.
Strata.
3 feet (about), coal seam.
Strata.
3 feet (about), coal seam.

As regards its horizontal extent, the Beacon Sandstone has now been traced from 85° S. lat. up to Mount Nansen in 74° 35′ S. lat., a distance of 625 geographical miles, or over 700 statute miles. While it has this extent from north to south, the Beacon Sandstone formation extends certainly for a distance of over 50 geographical miles from east to west, and to judge from the inclosures of sandstone in the material of the parasitic cones of Mount Erebus, it probably continues for a farther distance of about 30 miles east, that is, a total proved east and west extent of about 80 geographical miles, or 93 statute miles.

It is premature to estimate the gross quantity of coal within this area even approximately. All that can be said in this relation is that the superficial area of the Beacon Sandstone formation has already been proved to be originally in round numbers over 60,000 square miles; but from this has to be deducted a strip of variable width on the upthrow side of the great horst, from which the Beacon Sandstone has been denuded away. This strip may have an average width of about 20 miles, which would give an area of 14,000 square miles to be deducted from the original 60,000; this leaves 46,000 square miles. From this again further deductions must be made to allow for the Beacon Sandstone having been completely denuded off the highest parts of the horst in places, as at Mount Larsen, Mount Gerlache, Mount Bellinghausen, Mount Neumeyer, &c. This would still further reduce the area by probably at least 6000 square miles, thus leaving 40,000 square miles of this area. About 28,000 square miles would lie on the downthrow side of the great fault between the west coast of McMurdo Sound and Erebus, and would be considerably below sea-level. This would leave only about 12,000 square miles of Beacon Sandstone actually now exposed above sea-level in the plateau of the great horst, which would represent the whole amount available for coal-mining at present if the coal-measures were developed over the whole of this area. It is improbable that such is the case. For example, the Ferrar Glacier Valley was carefully explored by Armitage, by Ferrar, and other members of the *Discovery* Expedition under Captain Scott, and yet, with the exception of some carbonaceous laminæ in places in the sandstone, no seams of coal were met with either *in situ* or in the morainic material. As a matter of fact, the only portion of this 12,000 square miles of the Beacon Sandstone formation which has as yet proved to be actually coal-bearing is the Buckley-Bartlett Nunatak at the head of the Beardmore Glacier, the total area of which is about 100 square miles. There can, therefore, be no reasonable doubt that the exposed portions of the Beacon Sandstone with the occasional coal seams form but an insignificant selvage to a vast coalfield thrown down to the west of the great horst, and now buried to a depth of probably from 1000 to 2000 feet under ice. In order to reach the coal in this vast field it would at present be necessary to sink shafts through the ice for the full amount of the thickness of the ice, say about 1500 feet, then if the overlying cover of 500 feet of sandstone were present the shaft would have to be continued a farther depth equal to that amount, that is, a total depth of at least 2000 feet, at which depth the first seam of coal might perhaps be reached. If the thickness of the productive coal-measures as observed at the Buckley-Bartlett Nunatak is maintained under the down-faulted plateau west of the great horst, in a farther depth of 300 feet, that is, a total depth of 2300 feet below the surface, the whole of the productive coal-measures might be penetrated. The great difficulty of keeping open a workable shaft in slowly-moving glacier ice would be of course at present prohibitive, if attempts were made to reach this vast coalfield under this ice carapace. If metallic minerals of economic value are discovered in the rocks of the great horst in the near future, as is nearly certain, and attempts are made to convert the region into a second Alaska, probably a sufficiency of coal will be found in the rocks of the horst to last for all the needs of the region for a long time to come.

Such coal-measures could be worked by means of adits, the coal being allowed to descend by gravitation. It is of course premature, until good average samples are obtained from the whole thickness of these coal seams, to say whether any of them are really workable. Traced from Brazil through the Rio Grande Do Sul and the Serra Geral towards the Argentine in the neighbourhood of Sierra de Cordoba the Gondwana coal-measures yield only thin seams having a high percentage of ash. The appended section taken from the report by Dr. White is inserted for comparison.

Thicknesses of the various seams in descending order at one part of the Santa Catarina basin are as follows :—

0·60 metre
1·60 ,,
0·60 ,,
0·15 ,,
0·80 ,,
0·30 ,,

4·05 metres = about 13 feet.

The following is a descending section of the coal seams in order in another part of the basin :—

0·20 metre
4·00 ,,
0·26 ,,
0·20 ,,
0·20 ,,
0·10 ,,
0·20 ,,
0·15 ,,
0·20 ,,
0·05 ,,
0·12 ,,
0·15 ,,
0·08 ,,
0·05 ,,
0·15 ,,
6·11 metres = about 20 feet.

As regards information then, up to the present the total thickness of coal in the Santa Catarina system of South America varies from about 13 feet to 20 feet, while that of the coal at the great nunatak at the head of the Beardmore Glacier, inclusive of some clay bands, is about 25 feet. There can be no question, in our opinion, that there is a very large coalfield on the downthrow side of the great horst westwards. This coalfield has to be estimated by such amounts as 100,000, possibly several hundred of thousands, of square miles. For example, if it were 700 miles in length and 143 miles in width from east to west, it would have an area in round numbers of 100,000 square miles. At the most conservative estimate of only 100,000 square miles, and if only a thickness of 12 feet of the coal be workable, about one billion and a quarter, say approximately one billion tons, of coal would be available, that is, about ten times as much as is roughly estimated to be available for output at present in the unworked coalfields of the whole of New South Wales.

It is possible, therefore, that in the far future, if deglaciation makes this coalfield accessible to man, it will prove an important factor in the world's supply of fuel when existing coalfields have been largely exhausted.*

If the Beacon Sandstone formation is considered the equivalent of the Permo-Carboniferous coal-measures of Australia, it seems strange that no trace has been observed of any glacial beds associated with it. Mawson has already suggested that the abundance of undecomposed felspar in the sandstone implies a dry climate, perhaps like that of a tundra. It is of course conceivable that tundra conditions might prevail at a pole when intense glaciation was being experienced in comparatively low latitudes, as unless the polar regions could be fed under those circumstances

* Some deduction should be made from the quantity of exploitable coal on account of the damage caused to the coal by the intrusive sills of dolerite.

FIG. 1. THE WESTERN PARTY CAMPED ON THE FERRAR GLACIER ON DECEMBER 18. HANGING GLACIERS ON THE HILLS

FIG. 2. SILL OF QUARTZ-DOLERITE WITH GRANITE ABOVE IT, AND HEAVY SCREES RESULTING FROM FROST-WEATHERING AT ITS BASE
[Photo by Sir Philip Brocklehurst

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by snow by high-level air currents they would be starved of snow supplies. It is probable, for reasons already stated, that even when the belt of glaciation had spread equatorwards to about the parallel of 40° S., as was probably the case in Permo-Carboniferous time, there might still then, as now, be supplies of snow carried by high-level cyclonic circulation to the South Pole. Tundra conditions would be most unfavourable to the development of coal, and one must assume that at the time the coalfields of the Beardmore Glacier were being deposited the climate, though possibly cold, was humid. Rain of course now never falls within this region. There must necessarily have been a rainfall, and therefore a more genial climate than at present, in order to support the growth of coal-forming vegetation, including perhaps coniferous trees, the existence of which the fossils from the Beardmore Glacier may suggest. If, then, the Beacon Sandstone and its coal-measures are to be classed provisionally as Gondwana, they probably belong either to the top of the Permo-Carboniferous formation, such as the Newcastle Coal-measures, or to the coal-measures of the Trias-Jura system.

QUARTZ DOLERITE

The quartz dolerites which form such conspicuous members of the cliff sections of the great horst have been described in detail with analyses at the end of this Memoir by Mr. W. N. Benson, B.Sc. They occur in the form of huge sills, like that of Finger Mountain in the Ferrar Glacier Valley, cutting obliquely across the planes of bedding of the Beacon Sandstone.

The quartz dolerite is characterised by interstitial patches of granophyre; in places it contains rhombic pyroxene, and in its amount of potash closely approaches to essexite. The predominant pyroxene in some varieties is hypersthene, other types pass over into olivine and norites. In the typical quartz dolerites both rhombic and monoclimic pyroxenes are present, the rhombic forms being represented by bronzite or enstatite. From the presence of micropegmatite and nearly uniaxial enstatite augites these rocks show great resemblance to the Konga type of diabase so well known in Sweden. The presence of micropegmatite has already been recorded by G. T. Prior.* Mr. Benson speculates as to whether the granophyric inter-growths are derived from intrusions of granophyre into normal gabbros or dolerite, or are formed by magmatic mixing, or again are due to the intrusion of the acid residuum from the crystallising basis rock. Mr. Benson inclines to the third view. He discusses the parallel distribution of quartz dolerite in Tasmania, South Africa, and parts of South America. He concludes that "the similarity between the occurrence of dolerite in Tasmania and South Victoria Land is so striking as to strongly support the view that the two areas form part of a geological unit."

Dr. G. T. Prior and Professor W. G. Woolnough have already pointed out the

* Geological Memoir of the National Antarctic Expedition, 1901–4, p. 136.

close microscopic similarity between quartz dolerites of the Antarctic and those of Tasmania. As regards geological age the Tasmanian dolerite sills have strongly intruded the Trias-Jura rocks, and are themselves intruded by the Tertiary basalts. Moreover, in the neighbourhood of Launceston their surface has been eroded to considerable depths and then covered by the rocks of the Windmill series, which are probably of Eocene or at all events Early Tertiary age. Thus the Tasmanian diabase intrusion takes place somewhere between early Tertiary and late Jurassic time. Its date of intrusion is therefore possibly Cretaceous. In South Africa similar dolerite sills were intruded into the rocks of the Karoo series either in late Jurassic, or possibly in lower Cretaceous time. In British Guiana the quartz dolerites, occurring there as dykes and sills, are considered to be intruded in Mesozoic time.

Mr. Benson compares also with the Antarctic dolerites the quartz dolerites near New York forming the famous palisades on the Hudson. These intrude the Newark system, perhaps of Trias-Jura age.

Dr. G. T. Prior has shown in his account of the quartz dolerites of Natal and Zululand that they are strikingly similar to those of the palisades and of the Antarctic.

There is here a strong probability of the Antarctic quartz dolerites and those of Tasmania forming part of one great tectonic hinge. If, as seems probable, the Tasmanian dolerites were intruded in Cretaceous time, the age of the Antarctic dolerites would be also Cretaceous. They serve, therefore, to fix the upward limit for the date of the Beacon Sandstone. Thus the coniferous wood practically limits it downwards to Carboniferous, while the quartz dolerite places its upward limit below the Cretaceous.

PLATE LXXXIII

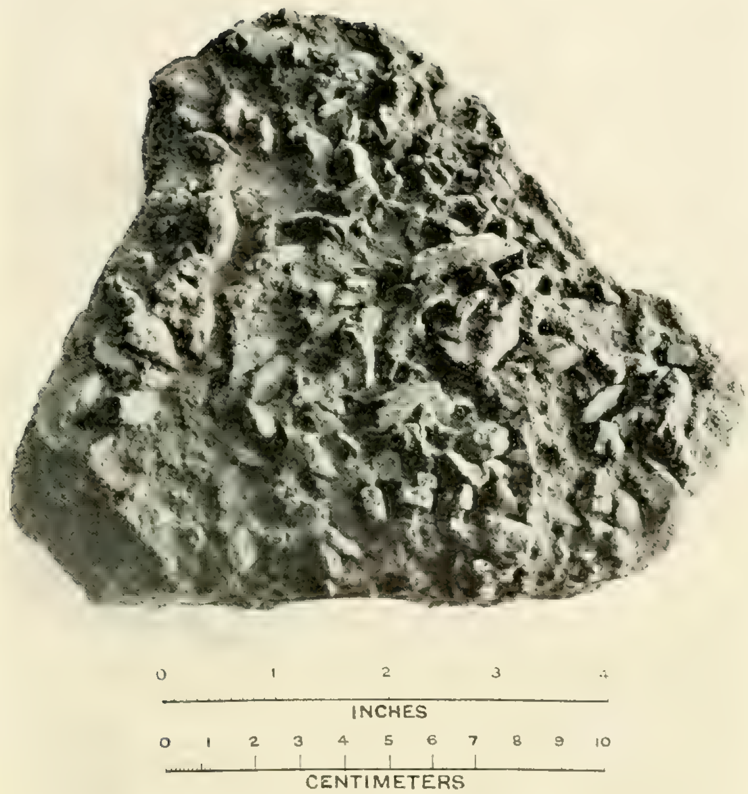

FIG. 1. TYPICAL WEATHERED SURFACE OF KENYTE LAVA SHOWING ANORTHOCLASE CRYSTALS IN RELIEF

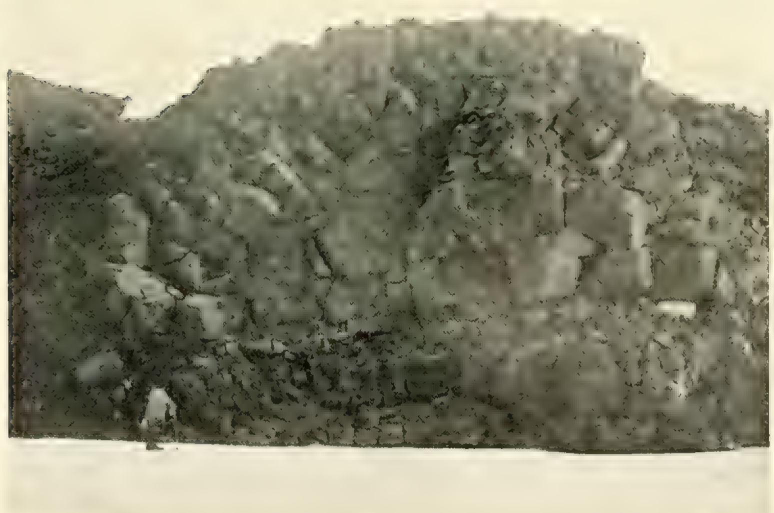

FIG. 2. VIEW SHOWING JOINTING IN KENYTE LAVA NEAR SUNK LAKE, CAPE BARNE

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CHAPTER XV

CAINOZOIC

LAVA AND TUFFS OF EREBUS

These are described in detail by Dr. H. I. Jensen in Part II. of this Memoir. He classes these as follows :—

1. Trachyte.
2. Acid kenyte.
3. Intermediate to basic kenytes.
4. Trachydolerites (porphyritic basalts with alkaline phonolites).
5. Leucitophyres, tephrites, and basanites.
6. Basalts without olivine.
7. Olivine basalts.
8. Limburgites, magnesian basalts.
9. Magnetic basalts.

The trachytes are most typically represented by the phonolitic trachytes of Mount Cis. These contain included fragments of orthophyre and sanidinite, as well as pyroxene granulites, diabase, and fragments of metamorphosed sandstone. The last mentioned is, in our opinion, probably derived from underlying masses of Beacon Sandstone. The felspars are mostly anorthoclase and soda-sanidine. Leucite, sodalite, interstitial nepheline (?), and analcite are also present. Ferro-magnesian minerals are represented by aegirine-augite with some cossyrite-like hornblende and a little riebeckite.

From a parasite cone he describes fragments of oligoclase trachyte included in kenyte breccia. This is formed essentially of anorthoclase, augite, and nepheline.

He describes the rocks of Observation Hill near Hut Point as kaersuetite (?), aegirine-augite-trachyte. He refers to a phonolitic trachyte from Inaccessible Island composed of anorthoclase, albite, pyroxene, analcite, or nosean, and much dark glass. Most of these trachytes contain a little olivine.

For the trachydolerite and kenyte group he proposes three divisions, viz. (1) acid kenytes, basic kenytes, and trachydolerites. It is this group, characterised by rhomb-shaped or almond-shaped large phenocrysts, mostly of anorthoclase in a dark ground mass, which gives its distinctive character to the volcanic system of Mount Erebus. Certainly the surface rocks of Ross Island are dominantly formed of this trachydolerite or kenyte group, the trachytes, basalts, and limburgites being quite subordinate in volume.

As seen in the field, the rocks of the kenyte group occur in dome-shaped elevations or rounded ridges; both are jointed, and, where they have for some time been exposed to weathering, very much frost splintered, so much so that the traveller has to beware of trusting to any support from what appear to be solid masses of lava. When a slight weight or pull was put upon the mass we frequently found that it crumbled to fragments immediately. This of course was the result of frost weathering. The large phenocrysts of anorthoclase usually resist weathering better than the ground mass, and so come to stand out in relief, giving the rock a rough bristling appearance. In the most recently erupted kenyte, as already described under the head of Vulcanism, we found that the anorthoclase crystals had been dropped clean out of the glassy matrix, and had fallen in showers at some distance from the central active crater, and they have accumulated in such numbers to the north-west of crater No. 2 that they have contributed in no uncommon measure towards filling that crater. In places the ground mass of the lavas of the kenyte group becomes pitchy and glassy. This is notably the case with the recently erupted kenyte bombs of Mount Erebus.

Apart from the section afforded by the precipitous inward slope of the active crater of Mount Erebus, as well as by the great inner wall of the second crater, it is difficult to make out any traces of stratification in the lavas and tuffs of Mount Erebus; in fact it is often difficult to decide whether the rock material belongs to a massive lava flow or to a tuff bed, inasmuch as frost weathering for the most part covers the rock surfaces with a mantle of fine rubbly and earthy material in which fragments of fresh felspar are very conspicuous. At first sight we took these zones of finely-comminuted material produced by weathering for tuff beds, but subsequent examination showed that they were merely the weathered residues of what were probably superimposed lava sheets, the junction line between which was hidden by the debris. Flagstaff Point was an exception to the above rule, in that there the lava showed distinct evidence of bedding, having beneath it a somewhat glassy pumiceous layer.

A description has already been given under the heading of Vulcanism of the various parasitic cones in the neighbourhood of the Skuary * and Cape Barne. At the Skuary there is also a trace of stratification. The cliffs there are from 80 to 100 feet in height, and seemed to consist of lava flows one above the other, with scarcely any dip. Examined under the microscope, one of the specimens secured showed large phenocrysts of anorthoclase and a few porphyritic crystals of olivine embedded in a hollow crystalline ground-mass of interlacing felspar laths, with small grains of augite and some magnetite.

Of the numerous small cones in the neighbourhood of the Skuary at least one was undoubtedly, in the opinion of one of us (R. E. Priestley), the plug of an eroded

* Cape Evans.

parasitic cone. Dr. Jensen describes the kenyte of the Skuary as being characterised by a low content of TiO_2, with much orthoclase and pure alkali-pyroxene, a little olivine and magnetite, and a ground-mass as in trachytes.

One of the most interesting spots for studying the relations of the lavas and tuffs of Mount Erebus is Cape Barne. At Cape Barne basic kenytes, like those also represented at Turk's Head, are well developed. These are characterised by a high content of TiO_2, with acid plagioclase felspar, titaniferous alkali pyroxene, much olivine and magnetite, and a tephritic ground mass.

Sections have already been given showing the nature of the junction line between the basic kenytes of Cape Barne and the magnetite basalts of the same locality. These sections show that the magnetite basalts are strongly intrusive into this type of kenyte.

A remarkably interesting tuff cone and the parasitic cone known as Mount Cis have already been described in the chapter on Vulcanism. The rock of the tuff cone is basic and obviously tufaceous, consisting only of fragments of blackish-grey to light grey porphyritic lavas. The fragments are mostly from 5 to 15 millimetres in diameter. In addition there are a few fragments of micro-crystalline basic rocks, much decomposed and reddened by hæmatite, about 10 to 15 millimetres in diameter. There are occasional angular fragments of a yellowish-brown friable rock resembling palagonite tuff, also sprinkled by angular fragments of felspar. Dark included fragments are rendered porphyritic by plagioclase felspar, probably mostly anorthoclase with numerous glassy inclusions. These are set in a micro-crystalline base of titaniferous augite, plagioclase, and magnetite. In some of the fragments the base is glassy. The large 80 millimetre inclusion is a type of kenyte more acid than that found at Cape Royds, and nearer to the type met with at the Skuary.

The basalts of Cape Barne are described by Dr. Jensen as being either of the variety poor in olivine, limburgite, in places basanitic, or magnetite basalts.

The magnetite basalts of Cape Barne are somewhat remarkable rocks; they are also represented at Tent Island. Dr. Jensen considers them to be the most differentiated portions of the parent kenyte magna. They are formed chiefly of basic labradorite accompanied by small rods of augite with corroded olivines, the base being made up mainly of magnetite and dark isotropic glass. Dr. Jensen considers that the magnetite has been one of the last minerals to form.

Near Hut Point interesting representatives of the tephrite family are met with, together with enstatite olivine basalt or basanite and limburgite. Limburgite and limburgitic basalt are represented at Hut Point and at the adjacent Observation Hill, while leucite tephrite occurs *in situ* at the top of Crater Hill. "This is a reddish porous rock," says Dr. Jensen, "the vesicles of which are arranged in planes or bands. The core of the specimen is dark, looking rather like a basalt, and has small leucite and nosean phenocrysts of minophyric size studded through the aphanitic base. The leucites are, under the microscope, seen to be altered to a mosaic of orthoclase and nepheline (pseudo-leucite), and vary in size from just megascopic to microscopic (minophyric to miniphyric)." Dr. Jensen concludes that "one of the most striking points about the Antarctic lavas examined is the highly differentiated nature of the effusive products. The abundance of limburgites, magnetite basalts, olivine nodules, sanidinite inclusions, and the occurrence of basalts without olivine, felspar basalts, and olivine basalts, in different interbedded flows, show that differentiation was very complete, and that the eruption tapped now one and now another portion of the magma." He points out that "the same highly differentiated nature of Antarctic eruptive rocks is evidenced by the alkaline, sub-alkaline, and basic lavas obtained by Borchgrevink at Cape Adare," and that "there seems to be little difference, if any, between the alkaline volcanic rocks of Ross Island and those of the mainland. He adds that "the sequence of these lavas appears to have been the same as that which is so characteristic of the Australian alkaline province, that is, from acid to basic."

The rocks collected at Cape Bird by Dr. Mawson were not obtained *in situ*, but had evidently not travelled far from that locality. They are described by Dr. Jensen as strongly alkaline trachytes, generally containing pseudomorphs after basaltic hornblende, kulaites or trachydolerite rocks with the opaque pseudomorphs after basaltic hornblende which characterise kulaites, sub-alkaline basalts and dolerites, some enstatite-bearing, some olivine-bearing.

Dr. Jensen suggests that the rocks of Cape Bird, on further examination, will probably reveal "a much more complete series of acid alkaline eruptives than has been poured from the Erebus vents." The important collection of erratics described by Dr. Woolnough shows that alkaline granitic rocks are represented on the mainland of South Victoria Land. As these granites are mostly, if not wholly, older than the Beacon Sandstone, the age of which latter is provisionally considered to be Pre-Gondwana, the region of South Victoria Land and Ross Island must have been marked out early in geological time as an important province for alkaline rocks.

We would invite special attention to Dr. Jensen's conclusions as to the sequence of effusive products in Ross Island at different levels. He emphasizes the important part played by specific gravity, "the molten magma has differentiated in the magma reservoir, and probably tongues of differentiated rocks have been thrust into surrounding formations. Fissures may tap one or all of the differentiation products, but the more elevated vents situated over the centre of the magma chamber will tap the lavas in the order of their specific gravity, and will continue to pour out each type of lava much longer than the subsidiary vents and fissures. Thus, if Cape Barne represents lavas poured from the fissure, which has tapped sill-like offshoots of the main reservoir, the whole sequence might be completed in this locality while the summit of Erebus is still in the kenyte phase of eruption and the summit may become extinct before emerging from this stage, the forces being insufficient in the final stages of eruption to raise the subjacent basic lavas to the summit, so that these may never reach the surface except by side fissures. Yet the order of eruption would be from acid to basic wherever the several lavas have flowed through the same vent, and where flows from different vents have not intermingled or overlapped."

It is of course necessary to read carefully the whole of Dr. Jensen's valuable report in order to appreciate the arguments which have led him to the above important conclusion. This is published in Vol. II. of this Memoir.

CHAPTER XVI

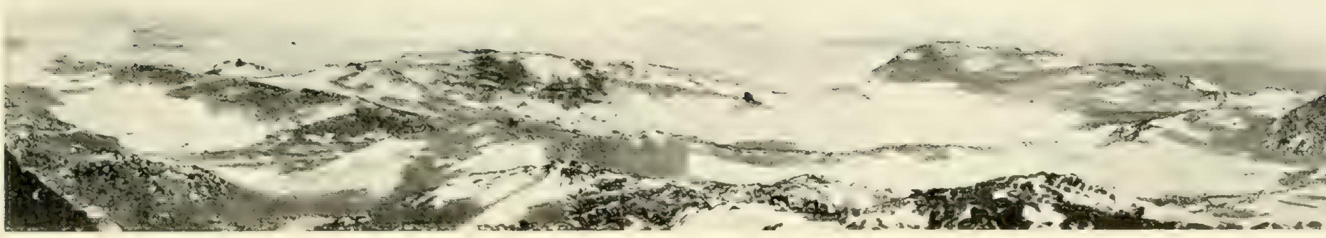
OLDER MORAINES AND ERRATICS

DESCRIPTIONS have already been given (Chapter V., pp. 94–98) of the old moraines of the East Fork of the Ferrar Glacier, of Dry Valley, and of the Stranded Moraines, while in the same chapter (pp. 110–113) descriptions are given of the principal moraines on Ross Island.

Perhaps the most interesting of these old moraines are those of Ross Island, chiefly relics of the moraines formed by the Ross Barrier at a time when, at its maximum, it completely enveloped Ross Island, converting it into a gigantic nunatak. The barrier ice rose to a height of at least 1000 feet above sea-level on the flanks of Erebus, and to about 800 feet above sea-level on the eastern slopes of Mount Terror. A general view of these moraines is shown in the view of Erebus forming the Frontispiece to this Memoir. It will be seen from this photograph that the moraines have the appearance of a huge hummocky terrace, rising to a height of a little over 1000 feet (305 metres) above sea-level. Between the hummocks are numerous desiccated tarn or lake basins containing thin deposits of algal peat with dried lake muds enclosing diatomaceous remains. These moraines are of two kinds: (1) Moraines left by the old Ice Barrier. These are characterised near Cape Royds by the presence of numerous erratics of granite, quartzite, &c., wholly foreign to Ross Island. (2) Ancient moraines of the glaciers of Mount Erebus, and composed of fragments of the local lavas and tuffs of Ross Island intermixed with a little redistributed moraine of type 1. What are probably upthrust portions of the marine sediments of McMurdo Sound were discovered by us at about 160 feet (49 metres) above sea-level above Backdoor Bay, near the extreme left of the Frontispiece, and also near Cape Barne, towards the right of the picture. These are described in detail in Chapter XVII.

The general appearance of the glaciated area in the vicinity of Cape Royds is shown on Plate LXXXIV. The bulk of the morainic material is in the form of a firmly compacted rubble and gravel. The fragments, mostly of Ross Island lavas, are from 1 to 2 inches in diameter, with a good deal of finer material between, chiefly powdered or splintered felspars.

These rubbly rock fragments are mostly angular and sub-angular, and while they show evidence of having been bruised a good deal, seldom exhibit striæ. The general appearance of the moraine rubble left by the old Ross Barrier when it filled McMurdo Sound is shown on Plate LXXXV. Fig. 2.



GENERAL VIEW LOOKING SOUTHERLY FROM CAPE ROYDS TO CAPE BARNE

Showing the heavily glaciated surface of kenyte lava and moraines near Cape Royds. The dark lump in the middle distance is an erratic about fifty tons in weight. Pony Lake, to the right, is a shallow, glacier-scooped rock basin. During the epoch of maximum glaciation, the whole of this area was buried under an ice sheet to a depth of from 800 to 1000 feet (244–305 m.)

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Fig. 1. MORAINE MOUNDS, POSSIBLY ESKERS, BLUE LAKE, CAPE ROYDS

Fig. 2. MORAINES LEFT BY THE OLD ROSS BARRIER

Above Backdoor Bay, Cape Royds, and 500 feet above sea-level. Traces are shown of the "white paths," perhaps contraction cracks, which develop with change of season, or cracks connected with settlement of the moraines resulting from the melting of old glacier ice, or the creep of glacier ice beneath them

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PLATE LXXXVI

Fig. 1. TYPICAL STRIATED BOULDER OF FINE-GRAINED QUARTZITE

From the old moraines left by the ancient Ross Barrier on the slopes of Mount Erebus, near Cape Royds

Fig. 2a

Fig. 2c

Fig. 2b

SMALL STRIATED BOULDERS FROM OLD GLACIAL MORAINES OF ROSS REGION OF ANTARCTICA

Figs. 2a and 2b. From summit of Cape Irizar

Fig. 2c. Limestone breccia, with fragments of Cambrian limestone, from Shackleton's Lower Glacier Depot, to south of Mount Hope, at lower end of Beardmore Glacier Valley. These fragments contain Archæocyathinæ and *Solenopora*-like organisms

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On the other hand, the erratics, foreign to Ross Island, of granite, gneiss, mica schist, quartzite, quartz- and felspar-porphyry, are mostly in the form of small round pebbles, just like water-worn pebbles, from an inch up to about 6 inches in diameter. Occasionally one meets with larger blocks, chiefly of granite, up to from 3 to 5 tons in weight. These are usually intensely smoothed, and in some cases exhibit grooving on their under surfaces.

This was noticeably the case just north of Backdoor Bay, Cape Royds. Granite erratics could be seen there, close to Flagstaff Point, at depths of 10 to 20 feet below sea-level; the intense rounding which the granite blocks at these lower levels had undergone suggests that they had been pushed along for a considerable distance under the old ice-sheet.

Frost-weathering is so potent at Cape Royds that one never sees striæ on the upper surfaces of any of the boulders, as the original glaciated surface has been completely splintered off. Nevertheless if the boulders be turned over and their under surfaces examined, in many cases they exhibit well-marked striæ, as shown on Plate LXXXVI.

We observed that at about 1350 feet (412 metres) above sea-level, about 2 miles east of Cape Royds, the surface of the kenyte of Mount Erebus appeared to be grooved by glacier ice which had moved from about E.S.E. to W.N.W., evidently an ancient local glacier descending from Mount Erebus.

It is probable that much of this hummocky moraine stranded along the western slopes of Erebus rests in places upon an ice foundation. One of us (R. E. Priestley) found that the upthrust marine muds near Cape Barne rested on an old foundation of glacier ice, evidently an actual relic of the ice of the former Ross Barrier. Ferrar has commented on the fact that during the summer thaw so much thaw-water flows from under these moraines, that it can only be accounted for on the supposition that glacier ice underlies the moraines in places.

We also observed another phenomenon, possibly due to collapsing of the moraine, and consequent cracking as the result of the removal by thawing of the underlying ice. This phenomenon is what we called the "white paths," and is illustrated in Fig. 2 of Plate LXXXV. At first we supposed that these paths, which evidently represented depressions in the surface of the moraine, were formed by seals crawling inland, but they were too closely set and widely distributed to be explained in such a way. Possibly these "white paths" are contraction cracks, resulting from alternate expansion and contraction of the moraines with change of season, or they may be due to the creep of glacier ice beneath them. Neither of these suggested explanations seems wholly satisfactory.

In the direction of Cape Barne it was noticed that foreign erratics were mostly wanting. This is no doubt due to the fact that, as the last ice age reached its climax and began to wane, the Cape Barne Glacier, then far larger than now, was able to assert itself and overpowered the shrinking Ross Barrier, pushing it and its lateral moraines eastwards, and eventually sweeping nearly all this moraine with foreign erratics into the sea.

A curious feature in the moraines of Cape Royds are the curious conical mounds on or in the ice of Blue Lake. These have already been referred to in Chapter V. Their general appearance is shown on Fig. 1 of Plate LXXXV.

They occur at a short distance from the eastern shore of Blue Lake. We were not able to ascertain whether their foundation was lake ice or rock. An interesting feature was observed in the distribution of erratics near the top of Crater Hill, near Hut Point.

Crater Hill rises about 1000 feet above sea-level, and its crater is about 200 feet deep (Ferrar, *op. cit.*, p. 12). Small erratics were discovered by us within this crater.

The occurrence of these small erratics at the top of Crater Hill makes it very surprising that the hill should have retained such a perfect form, for its rim is knife-edged. We were for a long time inclined to think that Crater Hill was post-glacial on account of this sharpness of its rim, but in the light of the evidence at present available this seems impossible, and we can only surmise that the glaciation to which it was subjected was very slight.

It is curious that all the erratics met with at Hut Point were uniformly small. No single specimen contained more than three-quarters of a cubic inch of rock. This is remarkable when these are compared with those comprising the moraines at Cape Royds, where blocks of every size, from half a cubic inch to many cubic feet in mass, are to be seen. It seems also that off Cape Armytage the ship traversed a moraine just deep enough to allow of her passage and some hundreds of yards broad, and composed of material more comparable with that comprising the moraines at Cape Royds than those at Hut Point. Possibly the erratics at Cape Royds may have been transported thither by some glacier from the Western Mountains like the Koettlitz Glacier, or some glacier farther south, whose moraine missed Hut Point, but reached Cape Royds.

Amongst the specimens picked up were several of quartzite, and a sandstone not unlike the Beacon Sandstone of the west, whilst many kinds of felspar-porphyry and granite were common, while other specimens, more indeterminate in hand specimens, were probably diorite and dolerite.

Beyond these small fragments of foreign rocks the moraines generally consisted of large and small, often sub-angular, fragments of basalt, the olivine basalt with included nodules being quite common, and also both black and red non-porphyritic basalt, and a red glassy scoriaceous basalt containing numerous small phenocrysts of augite. It was curious that trachyte fragments were not very common away from the neighbourhood of Observation Hill, in which that rock occurs *in situ*.

Reference has already been made (Chapter V.) to the occurrence of great moraines on the western side of the Beardmore Glacier, together with the immense median moraine of the Buckley Nunatak. But in addition to these recent moraines older moraines extend to at least 200 feet above the glacier in many places, and in the case of Mount Hope, at the junction of the Beardmore Glacier with the Ross Barrier, the erratics and the moraine are actually found capping the granite top of the mountain at a level of no less than 2000 feet above that of the adjacent glacier ice. Mention was made in Chapter IV. of moraine occurring on top of Cape Irizar at the north end of Lamplugh Island, at about 500 feet above the level of the adjacent Clarke Glacier.

Three small striated boulders are shown on Plate LXXXVI. Fig. 2, two from the ancient moraines of Cape Irizar, and one from an old moraine near the west side of the Beardmore Glacier, just south of its junction with the Ross Barrier.

The general absence of true till, in the sense of a tenacious boulder clay, seemed to us remarkable. Its absence may be due to the fact that deglaciation has not yet progressed sufficiently far to reveal "till" under the piedmont or glacier ice, or perhaps the sandy nature of the Beacon Sandstone—that most ubiquitous of the Ross area formations—and the friable character of the kenytes may be inimical to the formation of a true boulder clay or till.

Certainly near Cape Royds, in this intensely glaciated region once 800 to 1000 feet under ice, the moraine which there may be termed bottom or ground moraine (*moraine profonde*) seldom exceeded a thickness of more than a few feet. The bedrock was everywhere close beneath it.

CHAPTER XVII

UPTHRUST MARINE MUDS AND RAISED BEACHES

As pointed out by Mr. C. Hedley, the expression "raised beach" is somewhat of a misnomer as applied to the geologically recent uplifted parts of the ocean floor of Antarctica. Mr. James Murray, the biologist of our expedition, has explained that shell beaches, like those developed in temperate and tropical latitudes, cannot form in the Antarctic on account of the grinding action of ice-floes and the grating of small bergs over the bottom of the sea. The deposits about to be described are considered by Messrs. Chapman and Hedley to have been upheaved from depths of as much as 100 fathoms. They may be described therefore rather as raised marine muds than as raised beaches.

Raised marine muds were observed at three distinct localities on the western and south-western slopes of Ross Island, also at Dry Valley near New Harbour, just north of the mouth of the Ferrar Glacier, also near the foot of Backstairs Passage near the Drygalski Piedmont, between Mount Crummer and Mount Gerlache. The position of the two chief deposits on the west slopes of Ross Island are shown on the detailed geological map of the Cape Royds area.

1. *Upthrust Marine Mud or Raised Beach near Backstairs Passage, south-east of Mount Larsen.* This deposit is formed of a bluish-grey calcareous clay or ooze, in which large foraminifera and echinoid spines are conspicuous. It also contains numerous worm-tubes of serpulid origin, polyzoa represented by *Lepralia cheilodon* (McGillivray), a well-preserved brachiopod, *Liothyrina antarctica* (Blockmann), numerous sponge spicules, valves of a chiton, species undetermined, as well as the following, determined by Mr. C. Hedley: *Pecten Colbecki* (Smith), *Thracia meridionalis* (Smith), *Valvatella crebrilirulata* (Smith), *Lovenella antarctica* (Smith), *Lepeta antarctica* (Smith). Mr. Chapman, who has described the ostracods and foraminifera, concludes that the deposit may have been formed at a depth certainly of about 100 fathoms, if not greater. He records twenty-four species of foraminifera, twelve of which have already been noted from the sub-antarctic islands of New Zealand. A solitary coral and a large compound siliceous sponge were also obtained from this deposit; the latter is of special interest in reference to its mode of occurrence.

As regards the general appearance of this raised deposit, it is of the nature of a

Fig. 1. MORAINE CONE WITH RAISED BEACH MATERIAL
Mount Larsen on the right. "Backstairs Passage" is behind the cone

Fig. 2. UPTHRUST SERPULÆ DEPOSITS
About 160 feet (49 m.) above sea-level, near Backdoor Bay, Cape Royds. The figures show the position of the deposit of serpulæ. Cape Royds, bounding Backdoor Bay on the west, is in the middle distance; beyond is McMurdo Sound and the Royal Society Range

[*To face p.* 266

low elongated mound with occasional conical projections. One of these is shown in Plate LXXXVII. The raised beach proper is capped by angular blocks of moraine material, chiefly formed of quartz and felspar porphyry, with thin greenish crusts of epidote. Associated with these blocks were fragments of apatite-allanite-granite, these fragments being mostly smaller than those of the quartz- and felspar-porphyries. Some of these pieces were striated, others showed evidence of having been crushed, apparently by ice pressure. Occasional blocks were observed of a very curious porphyritic granite with singly twinned orthoclase crystals up to 4 inches in length. Fig. 62 illustrates the mode of occurrence of this raised beach, or more probably upthrust marine mud.

From this it will be seen that the top of the cone is formed of breccia, composed of blocks of granite, quartz-porphyry, &c. This rests on the french-grey marine muds, and these in turn repose on a conical mass of ice. The base of the cone is surrounded, as shown in the sketch, by the larger blocks of the moraine. It was a great surprise to us to find a foundation of ice underneath the raised beach. We tested this ice and found it was slightly saline superficially, but not as salt as typical sea ice. We observed that some of the serpulæ tubes were attached to the blocks of quartz- and felspar-porphyry as well as to the granite. It may be argued that such tubes probably became attached to these blocks below present sea-level, and that the blocks had subsequently been pushed up by ice pressure up to their present elevation of about 20 feet above sea-level. This explanation is slightly more difficult of application to the large delicate siliceous sponge attached to the granite block, and shown in the sketch. (B enlarged, Fig. 62.)

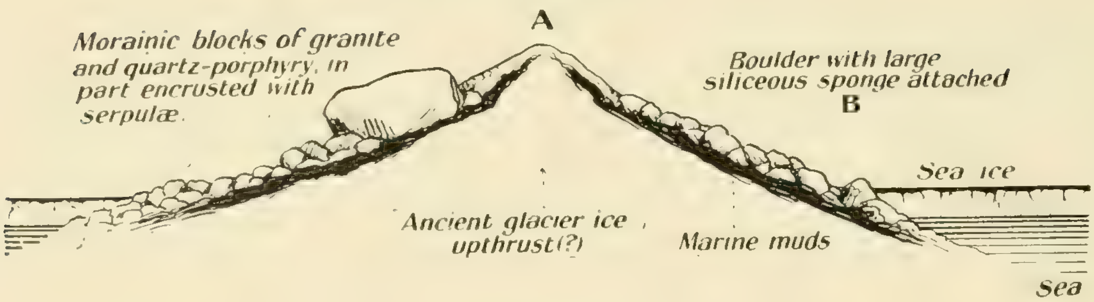
This sponge was about 2 feet long and 1 foot wide, built up of delicate siliceous fibres woven into at least sixteen distinct sacks, as shown in the sketch. The whole structure was delicate and fragile, and yet perfectly preserved. It was obvious to us that this sponge was in position of growth, and that the block to which it was attached must have been under the sea at the time. This block was only a few feet above sea-level, but was evidently part of the raised marine muds, which, as already stated, ascend to a little over 20 feet above sea-level. There is here a somewhat difficult problem. How are we to account for the existence of a raised marine deposit over a surface of ice? The ice on the whole appears to be land ice, with its surface rendered saline by submergence in sea water. How can ice, which is so much lighter than water, be held under the water so as to admit of marine deposits being formed on top of it? Much light has recently been thrown on the subject of so-called Raised Beaches in Arctic areas by an important paper by G. W. Lamplugh, F.R.S.,* as well as by Professor A. G. Nathorst.†

Professor De Geer has also given a very interesting account of the glacial

* "On the Shelly Moraine of the Sefström Glacier and other Spitzbergen Phenomena illustrative of British Glacial Conditions." Proc. Yorkshire Geol. Soc., vol. xvii., part 3, 1911.

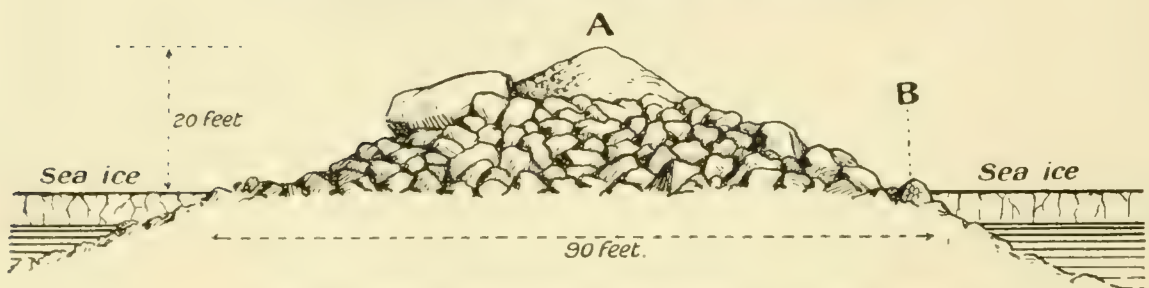
† Bull. Geol. Instit. of Upsala, 1910, vol. ix. pp. 261–415.

Section through cone "A"



Cracked bulge in sea ice about 1 foot high, possibly due to settlement of sea ice on to a concealed boulder.

Section across cone of ancient glacier ice, coated by marine sediments, in turn covered by large angula[r] blocks of morainic quartz-porphyry and granite.



Near the foot of Backstairs Passage to S.E. of Mt Larsen.

"B" enlarged.

Block of granite with large compound siliceous sponge attached to it about 2 feet long by 1 ft wide.

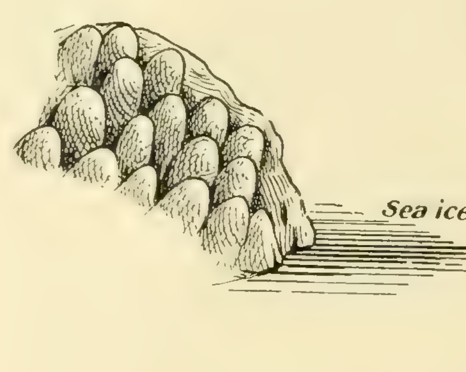


Fig. 62

phenomena of this region. In Spitzbergen it is generally admitted now that there are elevated marine deposits of two distinct modes of origin: (1) True raised beaches, due to a negative movement of the ocean's surface or a positive movement of the land, or to both. Raised beaches of this kind are found in Spitzbergen up to about 430 feet (130 metres) above sea-level. (2) There is a type of elevated moraine material consisting partly of shelly muds, partly of moraine, which may be described as upthrust moraine and morainic deposits. Those in the neighbourhood of the seaward front of the Sefström Glacier reach a height above sea-level of from 70 to 80 feet. The material, partly morainic, partly morainic shelly mud, rests, as does that of Backdoor Bay in Antarctica, on a foundation of glacier ice.

The origin of these Spitzbergen upthrust and push moraines is very clearly explained in Lamplugh's paper. Some of the Spitzbergen glaciers, like that of Sefström, are subject to rapid spasmodic advances succeeded by an epoch of retreat. In 1882 the Sefström Glacier, with its front $4\frac{1}{2}$ miles in width, pressed rapidly forwards over the sea floor of Ekman Bay, ploughing out the material accumulated on the sea floor and partly pushing it in front of it, and partly driving it up along a series of overthrust planes. After considerable retreat the glacier again advanced in 1896 as far across Ekman Bay as Cora Island, and once more the process was repeated. Subsequently the glacier once more retreated, leaving between its terminal front and Cora Island a deep canal of sea water separating it from the fractured extremity of the glacier with all its overthrust faults and upthrust moraines and marine muds stranded on Cora Island. The marine muds intermixed with moraine at Backstairs Passage near Mount Larsen may very likely have had a similar mode of origin. It has already been shown in this Memoir that in the neighbourhood of the Drygalski-Larsen-Reeves Piedmont there has been considerable bending and fracturing of the ice with an upthrust of diatomaceous material and foraminiferal mud. It is now suggested that the whole of the elongated domes of marine muds, capped by angular moraine and underlaid by glacier ice, have been pushed up from some depth from the adjacent sea bottom by the thrusting force exerted by the Larsen Glacier, aided by that of the Drygalski Ice Barrier Tongue. This explanation would satisfactorily account for the remarkable fact, emphasized by Mr. F. Chapman, that the foraminifera and ostracods found in this deposit belong normally to a depth of about 100 fathoms. As has been stated, the height above present sea-level of the deposit falls immensely short of 100 fathoms, as it only slightly exceeds 3 fathoms. Mr. C. Hedley has pointed out the same anomaly in the case of the important elevated marine deposits discovered by one of us (R. E. Priestley) between Cape Barne and Backdoor Bay near Cape Royds. Mr. Hedley and Mr. Chapman agree in expressing a similar opinion in regard to this so-called raised beach, viz. they think that whereas it is now only about 160 feet above sea-level, it was formed in the first case at a depth of about 100 fathoms. This beach too, like that of Backstairs Passage, is, partly at any rate, underlaid by glacier ice. There can be no doubt that the ice underlying the Cape Barne raised beach is a relic of the Great Ice Barrier.

Fig. 63 below shows the theoretical structure of the Drygalski-Larsen-Reeves Piedmont ice, the section being taken from south-east to north-west, nearly at right angles to the "rib" of the Larsen Glacier. The thrust has come chiefly from the direction of the great Drygalski Glacier "rib," which has transmitted its thrust, not of course through the two "open channels" to its left (these are shear planes), but through areas nearer the shore-line, where the shear plane walls are firmly in contact with one another.

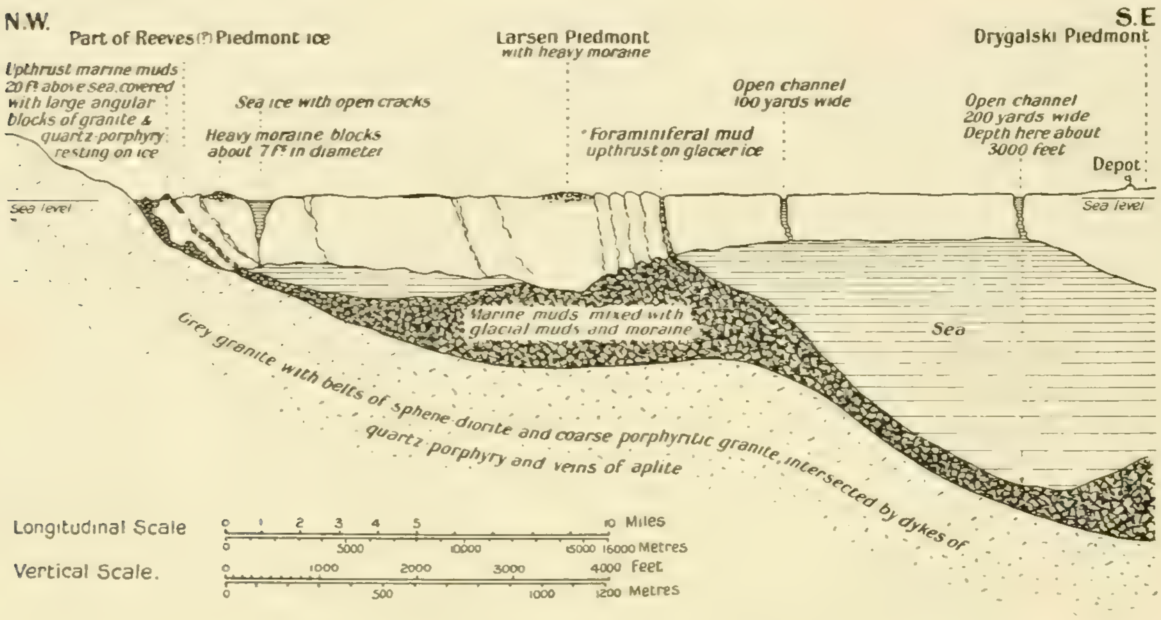


Fig. 63. Upthrust Marine Muds and Raised Beaches

The following alternative explanation to the upthrust hypothesis may be suggested :—

The region near Backstairs Passage is one where there is a large amount of moraine material either upon the ice or embedded in it. As already explained, absorption of the sun's heat by blocks of rock leads to their being so warmed up that they rapidly melt their way into the ice beneath and become englacial. Thus the glacier ice in the neighbourhood of moraines becomes heavily loaded with blocks of rock, and so its mean density may be so much increased that it exceeds that of sea water and becomes what may be termed rock-loaded, or rock-logged. A submergence of the land taking place later sea-level relatively rose, and the glacier ice, weighted down by its rocks, was not able to float up to the surface, consequently for a time it formed the actual sea floor. Marine muds with the numerous organisms described were then deposited, various types like the *serpulæ* and the incrusting sponges spreading over the blocks of rock belonging to the old moraines. Later there has ensued an elevation of certainly at least 20 feet, and, according to Mr. F. Chapman's opinion, of perhaps as much as 600 feet. If the original submergence and subsequent elevation has been as extensive as Mr. Chapman thinks is suggested by the nature of the marine organisms, traces of this submergence should surely have left their mark on the coast-line in the form of rock terracing. There certainly is some appearance of this kind on the western slopes of Mount Crummer, but the evidence is not conclusive.

The levels of these terraces as given in the sketch are only roughly approximate, and, as stated, probably do not exceed about 600 feet. In regard to the question as to whether, if this second alternative explanation is adopted, this retreat of the ocean and complementary elevation of the land is still in progress or not, it may be mentioned that we observed in places that the level surface of the ice, apparently old sea ice in this case, was broken by small domes of ice projecting a foot or so above the general level and traversed by radiating cracks. (See second diagram of Fig. 62.) These had all the appearance of being due to the settlement of ice around some large boulder, which by its resistance caused the ice to be bulged up and split open. Ferrar * records a similar phenomenon. His description reads as follows:—

"Near the isolated moraines in the bay between White Island and Black Island, on floating glacier ice, there are five or six mounds 2 feet high, and up to 5 feet across of the same white salt.† The mounds are entirely composed of the salt, which is in well-formed crystals, though the outer ones have effloresced to some small extent. The moraines near these mounds contain *Balanus* shells, together with ice-scratched granite and other boulders."

It is singular that near White Island such mounds, formed by hydrous sodium sulphate (mirabilite or Glauber's salt), are associated with raised marine shells like those of *Balanus*. Unfortunately we did not specially test the ice in the fractured domes at the Backstairs Passage raised beach. There was nothing in their general appearance to suggest that they were other than ordinary ice, but as mirabilite is of course clear and translucent, it might easily escape detection when embedded in ice. Ferrar does not suggest an explanation of how the White Island domes came to be formed and fractured. His description is somewhat suggestive of an actual expanding or swelling action of the mirabilite. This can hardly be due to weathering, as mirabilite of course when exposed to the weather undergoes a process of exanthalosis, whereby it parts with its water, instead of taking up more water and deliquescing. The tendency, therefore, in the case of mirabilite would be for the mineral mass to decrease in size with weathering, and this dwindling would be much accelerated by the extreme dryness of the Antarctic air in those latitudes.

* National Antarctic Expedition. Natural History, vol. i., Geology, p. 91, Fig. 55.

† Mirabilite (T. W. E. D.).

It is doubtful, therefore, whether the cracking open of the domes near White Island can be due to the presence of mirabilite. That phenomenon at present is unsolved. Provisionally the explanation above suggested of settlement of old sea ice around large boulders may perhaps account for the curious cracked domes of ice at Backstairs Passage. It may be suggested as a possible explanation that mirabilite may have been distributed in a small proportion throughout a large mass of old sea ice, or possibly old lake ice, and subsequently, acting under the law of affinity of like for like, in the case where one mineral is present in smaller proportion in another mineral, have gradually withdrawn itself from the other mineral (in this case ice), and concentrated itself upon certain centres where con-

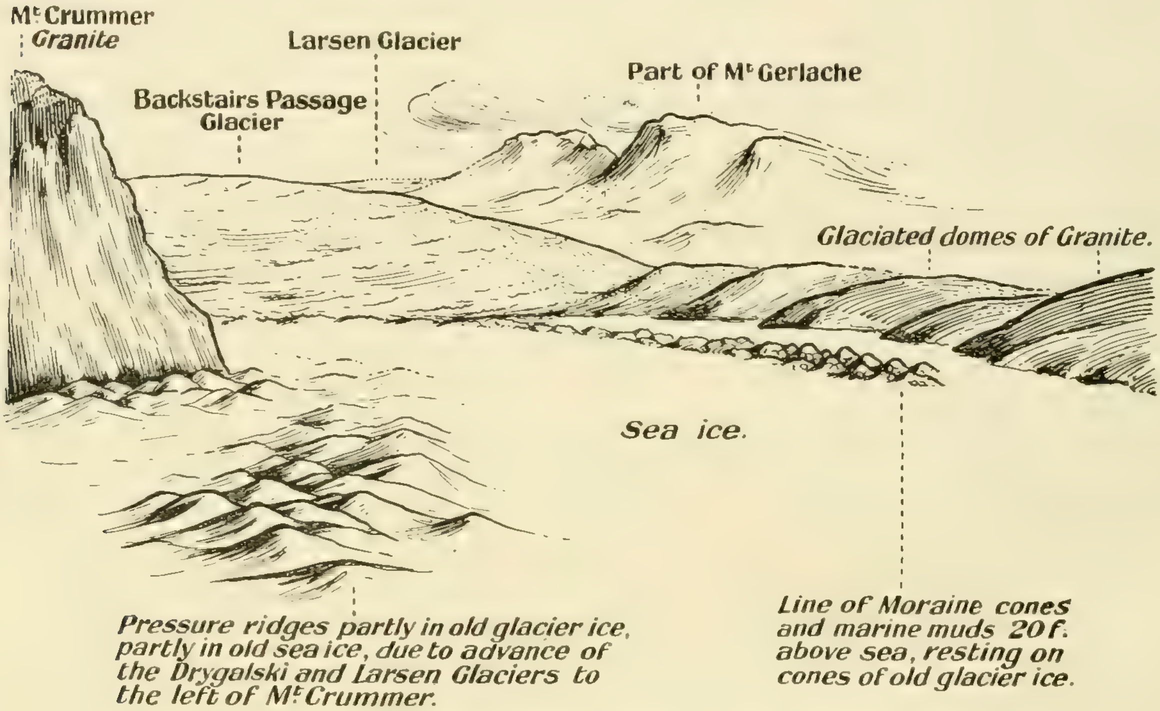


Fig. 64. Rough Sketch of Upthrust Marine Moraine Cones, Backstairs Passage Bay

cretionary groups of mirabilite crystals may have formed, subsequently added to by accretion, and thus these masses may have exerted an expansive force upon the ice around them.

From what has been said, it will appear that this locality presents many fascinating problems which yet await solution. One conclusion which possibly may be deduced at present is that in recent time the ocean has here undergone a negative movement of at least 20 feet, possibly as much as 600 feet. The evidence of the ostracoda, according to Mr. Chapman, agrees with that of the foraminifera, "for they seem to indicate deposits formed at a far greater depth." Descriptions of the organisms by Mr. F. Chapman, Mr. C. Hedley, and Mr. E. F. Hallman are given in the second volume of this Memoir.

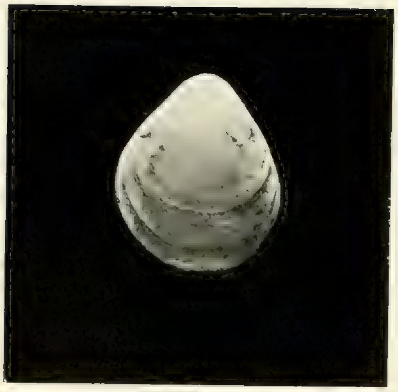


Fig. 1. LIOTHYRINA ANTARCTICA (BLOCKMANN)

Fig. 2. SILICEOUS SPONGE SPICULES

From raised marine muds, Ross Island

Fig. 3. TUBES OF SERPULÆ, POLYZOARY OF LEPRALIA, AND VALVE OF CHITON

From upthrust marine muds near Backstairs Passage, Mount Larsen

Figs. 4 and 5

UNDESCRIBED SIMPLE CORAL

From the marine muds, Backstairs Passage, Mount Larsen

[To face p. 272

Fig. 1. PECTEN COLBECKI, SEALS' TEETH, APPENDAGE OF CRUSTACEAN, AND RAISED DEPOSITS FROM DRY VALLEY

Fig. 2. A TANGLED MASS OF SPONGE SPICULES FROM RAISED DEPOSITS FROM HUT POINT, ROSS ISLAND

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As regards the geological age of the raised marine muds, it may be added that a considerable amount of fragments of *algæ* were distributed throughout the deposit, and these show little signs of decomposition or alteration. Mr. Hallman comments on the fact that "at one point there are remains of a small chitinous avicularium, attached to one of the specimens of *Lepralia.*" The fact, therefore, that the animal matter has not yet been lost is proof of the comparatively recent age of this deposit.

These observations clearly point to the elevated muds belonging to very recent geological time, and if the ice domes in the neighbouring areas are due to settlement, consequent on withdrawal of the ocean, the movement is actually still in progress. On the whole, we strongly favour the view that the marine muds near Backstairs Passage owe their elevation to upthrust by glacial action. A few of the larger marine organisms of this deposit are shown here on Plate LXXXVIII.

2. *Dry Valley.* About 148 miles southerly from the "raised muds" just described, one of us (R. E. Priestley), in company with Bertram Armytage, discovered a raised beach at Dry Valley near New Harbour. This beach consisted of dark gritty sand containing numerous entire valves of *Pecten Colbecki*, up to elevations of about 50 feet above sea-level, and at a distance of several hundreds of yards inland from the present shore. Associated in abundance with these pectens was an *Anatina;* two double-valved shells of another species of bivalve (*Lima*) were obtained by digging several inches below the surface of this sand. Both the pecten and *Anatina* have extremely fragile shells, yet hundreds of valves, of the pecten especially, were practically intact, ears and all being perfectly preserved. They have a very recent aspect. The only reasonable explanation of the occurrence of such vast numbers of delicate and well-preserved shells in this deposit is that it is a genuine raised beach. It is obvious that in this case also, as at Mount Larsen, an elevation of more than 50 feet is implied. Such deposits of pecten and *Anatina* shells might have formed at depths like those in Backdoor Bay near our winter quarters at Cape Royds, where we used to dredge up such shells from depths of 10 fathoms. Perhaps, therefore, these shells indicate a recent elevation of this part of the coast of possibly as much as 100 feet. Some of the marine organisms from these deposits are figured on Plate LXXXIX.

3. *Backdoor Bay.* The first spot discovered by Bertram Armytage on the eastern shores of Backdoor Bay, 60 chains east by north from the winter quarters at Cape Royds. (See lower fig. of Plate LXXXVII. p. 266.) It consists of fine gravel and earthy material resulting from the decomposition of kenyte. Intermixed with these are numerous remains of serpulæ, with a few foraminifera and echinoid spines. Serpulæ were found to be very abundant in the armings of the lead used for sounding at Glacier Tongue in about 157 fathoms.

The serpulæ remains in this patch of raised marine mud were much comminuted, which suggests that the deposit is almost certainly of an upthrust portion of the sea floor. Adjacent to this deposit are some shallow, dried-up tarns containing abundance of diatoms and lacustrine algæ.

4. *Cape Barne.* The fourth raised marine mud deposit is about half-way between Cape Royds and Cape Barne, distant about 15 chains from the small bay near where the position of the green and blue flags are shown on the geological map. This deposit was discovered by one of us (R. E. P.), and has proved specially rich in remains of ostracods and foraminifera, as well as in several types of mollusca. The ostracods and foraminifera are described in detail by Mr. Frederick Chapman, and the molluscan remains by Mr. C. Hedley, in Vol. II. of this Memoir.

Mr. Chapman remarks that, in addition to the forms mentioned, Polyzoa (*Callaria*) and other genera, some echinoid test fragments and spines, and numerous siliceous sponge spicules (*Tetractinellia*) are present. He states that the valves of the ostracods were exceptionally well preserved, and must have been floated together and gathered up by very gentle sedimentation. He makes the following remark, specially important from the raised beach standpoint: "Judging from the general foraminiferal fauna of the Mount Erebus raised beach deposit they were formed in moderately deep water like the preceding series from south-east of Mount Larsen, viz. at or near 100 fathoms. The presence of many delicate-shelled ostracoda in the material from locality two indicates to my mind a decided clarity of conditions, as distinguished from the more salty or terrigenous deposit of the sample from the south-east of Mount Larsen."

If the view of Mr. Chapman be adopted, this raised beach of Cape Barne indicates an elevation of considerably more than that represented by that of the altitude at which they occur at present above sea-level. In fact they may indicate an elevation of as much as 760 feet.*

5. *Possible Raised Beaches near Hut Point.* As already stated, Ferrar has recorded the occurrence of *Balanus* shells attached to ice-scratched stones of moraine cones between White Island and Black Island. These moraines are also probably to be looked upon as of glacial upthrust origin. Like the raised beaches of Backstairs Passage, they appear to rest on a foundation of ice. This is described by Ferrar as floating ice, and it may be so; but if floating, it is hard to understand how the sea could have extended over the top of it so as to account for the present position of the *Balanus* shells, unless the latter are of the nature of push moraine upthrust from some depth. The level of the raised beach between White and Black Island is not given by Ferrar, but, judging from the height of the Barrier cliffs when broken away to the farthest point south in the direction of White and Black Island, it cannot be less than 50 feet. At Hut Point the discovery was made of several balls of white, finely-felted material, which proved to be entirely built up of delicate spicules of siliceous sponges. These were discovered by one of us (R. E. P.) on a

* This is of course on the assumption that the Cape Barne deposit is a genuine raised beach rather than an upthrust part of the adjacent floor of McMurdo Sound.

visit to Hut Point in November 1908. These balls were about half an inch in diameter, and for some time were supposed to be derived in the same way as the feathery balls which occurred as the excreta of Skua Gulls that had been feeding on penguins. The discovery of the sponge spicule raised beach deposit near Cape Barne, however, led to a closer examination of these balls being made, when they were found to consist of the spicules of siliceous sponges. There is no north wind blowing in this district with sufficient strength to convey these sponge spicules to Hut Point. It seems probable, therefore, that there is a deposit here of sponge spicules analogous to that of Cape Barne. This, too, is perhaps upthrust moraine.

SUMMARY

In regard to the question as to whether there are true raised beaches indicating negative movement of the ocean, or positive movement of the land to the vertical extent of their present elevation above sea-level, or whether they are upthrust moraines analogous to those of Spitzbergen, has not yet been indisputably settled. At the same time the preponderance of evidence appears to be greatly in favour, in the case of most of them at all events, of their being of the nature of upthrust moraines. In our paper to the International Geological Congress in Stockholm in 1910 we inclined to the opinion that these deposits were genuine "raised beaches," chiefly for the following reasons:—

1. At Cape Barne there was no evidence of comminution of the shells or striation, the valves being mostly double and hinged together. The same feature was noticed at the Dry Valley deposits, where the shells were almost exclusively composed of the very fragile variety *Pecten Colbecki*. It was also observed that at the Backstairs Passage deposit near Mount Larsen a large boulder of granite was encrusted with a huge and very fragile siliceous sponge, obviously in position of growth.

2. In the case of two of the deposits, viz. that of Cape Barne and that at Backdoor Bay, they are both at almost exactly the same elevation, viz. about 160 feet above the sea. This is of course suggestive of a continuous water-level at that horizon.

3. There is evidence near Cape Bird, at Backdoor Bay, and on the seaward face of Mount Crummer, of marked terracing. The terrace at Backdoor Bay was, however, quite devoid of any trace of marine organisms as far as we were able to ascertain. We had no opportunity for searching the terraces at Cape Bird or at Mount Crummer. It is possible that there these terraces are rather of the nature of parallel roads, and may have been formed by wave action in supra-glacial lakes on the surface of the former tongue of the Great Ice Barrier when it filled McMurdo Sound. Such an opinion will hardly apply to the Mount Crummer phenomena; but these are much less clearly marked than are the terraces of Cape Bird and Backdoor Bay.

Evidence for the true "raised beach" character of the deposits, when critically reviewed in the light of modern discoveries at Spitzbergen, does not seem strong.

The following features may be emphasized in favour of the theory that the deposits result from glacial upthrust:—

(*a*) At least three of the five deposits between Mount Larsen and Hut Point rest on a foundation of glacier ice, just as do the push moraines of Cora Island in advance of the Sefström Glacier.

(*b*) In at least one of these deposits, that of Backdoor Bay, the marine organisms have obviously been much comminuted and fractured, and the deposit is extremely peaty. The same remark applies, though in a less degree, to the deposit at Backstairs Passage near Mount Larsen.

(*c*) The latitude above sea-level of each of the deposits is variable, ranging from 20 feet in the case of the Backstairs Passage deposit, to 160 feet in the case of the Cape Barne and Backdoor Bay deposits, the last two being the only two which show any agreement in level.

(*d*) The following appears one of the strongest arguments: the bathymetric aspect of the organic remains in the Cape Barne deposit, as well as in the Backstairs Passage deposit, proves that these organisms lived originally at a far greater depth (some 600 to 760 feet below sea-level) than is suggested by their present height above the sea. If, as Messrs. Chapman and Hedley hold, the Cape Barne and Backstairs Passage deposits were formed at from 600 to 760 feet below sea-level, it is obvious that an elevation of land or general depression of sea-level by an amount of from 20 up to 160 feet would be quite incompetent to raise such deposits above sea-level. It seems then that the only agent which may reasonably be assumed to be capable of explaining such a work is glacier ice.

(*e*) There is conclusive evidence to show that in quite recent geological time the whole of McMurdo Sound has actually been occupied by a thick tongue of the former Ross Barrier when at its maximum extension. It can be proved from the height to which this tongue once rose (moraines around the foothills of Mount Erebus ascend to fully 1000 feet above the present sea-level) that it must have pressed hard even on the deepest portions of the floor of McMurdo Sound. Such masses of glacier ice, moving thus with great force and weight over the sea floor, must surely have produced large upthrusting of the displaced marine sediments in the Antarctic, just as has been proved to be the case in the Arctic.

We, therefore, wish now to withdraw our previous views as expressed in the paper read before the International Geological Congress at Stockholm in 1910 as to the true "raised beach" character of the above deposits in favour of the view that they are of the nature of upthrust moraine, except probably in the case of the Dry Valley deposit of *Pecten Colbecki.*

CHAPTER XVIII

RECENT DEPOSITS

MIRABILITE

A DEPOSIT of this mineral was discovered by one of us (R. E. Priestley) near Cape Barne, at the spot marked on the geological map. After the summer thaw had been in progress for some time, many ridges in sheltered positions, which had remained snow covered during the winter, were exposed to view through the snow being dismantled by the heat of the sun. It was on one of these ridges, at the north end of Deep Lake, near Cape Barne, that a deposit of white salt was found in February 1909. The deposit was lenticular in shape, a few yards in extent, and had a maximum thickness of a little over 2 feet. It occurred in rough irregular masses, the largest of which were several pounds in weight, and was encrusted by a white powder evidently formed from the dehydration of the salt. These blocks on freshly fractured surfaces showed a perfect cleavage and a vitreous lustre, cleavage flakes, even when several inches in thickness, being quite transparent. The salt was determined by Dr. Mawson to be mirabilite ($Na_2SO_4 + 10H_2O$), and the efflorescent powder was identified by him as exanthalose ($Na_2SO_4H_2O$).

The mirabilite at Deep Lake is evidently the result of a process of concentration of the waters of an ancient saline lake. Possibly, during the recent elevation of the land, small ocean basins have been isolated, the salts in the sea water then underwent concentration by evaporation, the sodium salts being further added to by material leached out of the volcanic rocks of Erebus, which are themselves rich in soda. That such leaching process is in progress was proved by the very alkaline character of the waters of the lakes in Dry Valley. The following is an analysis by Mr. J. C. H. Mingaye, F.C.S., &c., Analyst and Assayer to the Geological Survey, Department of Mines, New South Wales, respectively of the mirabilite and of the exanthalose :—

Mirabilite. Clear mineral of glassy translucency from Deep Lake near Cape Barne, Ross Island, Antarctica.

Water	55·420 per cent.
Soda	19·478 ,,
Sulphur trioxide	25·160 ,,
Chlorine	minute traces.
Insoluble matter	0·006 per cent.
	100·064 per cent.

2 N

The mineral has a feebly saline bitter taste.
Heated in the closed tube it gives off water in abundance.
Gave an intense yellow colour to the flame.
Readily soluble in water.
A very pure sample of mirabilite ($Na_2SO_410H_2O$).

Material from Atmospheric Weathering of Mirabilite-Exanthalose (?).

Chemical composition—

Water	0·45 per cent.
Soda	42·62 ,,
Sulphur trioxide	54·99 ,,
Chlorine	trace.
Insoluble matter	1·93 per cent.
Organic matter	trace.
	99·99 per cent.

Practically a dehydrated sodium sulphate.

The general appearance of the mirabilite deposit and of the mirabilite crystals is shown on Plate XC.

PEAT DEPOSITS

Deposits of a remarkable type of alga were observed by us in nearly all the lakes of Ross Island, on the floors of dried-up lakes in the same area, as well as in the neighbourhood of Dry Valley on the coast of South Victoria Land. The alga grows to a considerable size, individual specimens being fully 2 to 3 feet in diameter. They are of a brown to red colour, almost vermilion in places.* There can only be a few weeks available for the growth of this organism during the year, that is, the period of time when the ice has thawed in the lakes. This extends from about the middle of December to late in January. The exact period of thaw depends largely on the nature of the rock forming the sides of the lake. Where the rock consists of black lava, the lakes begin to thaw early where the ice is in contact with such black rocks, and thus the algæ are set free to grow. Small deposits of this alga are found chiefly on the leeward side of the lakes. The deposits are formed by the wind, which causes rapid ablation of the ice surface, removing by abrasion with snow crystals the tips of the algæ as they come to project with the progressive ablation from the surface of the lake ice. Thus a quantity of small fragments of the algæ form an algous drift of insignificant proportions, as is the case near Green Lake at Cape Royds. During the period of thaw a kind of algous slush is produced by the action of the blizzard winds on the surface waters of lakes, such as Green Lake. At Green Lake, for example, it was observed that during a heavy drift-laden gale coming from the south, in February 1909,

* The red colour may have been due to the red rotifers feeding upon the algæ in vast numbers.

PLATE XC

FIG. 1. CRYSTALS OF MIRABILITE
From recent deposit on col at north end of Sunk Lake, near Cape Barne

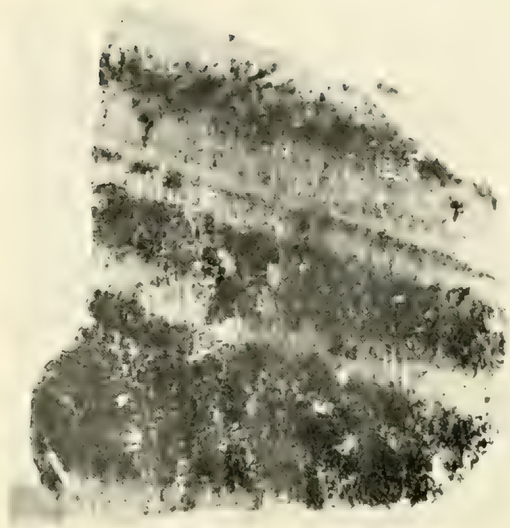


FIG. 3. ALGAL PEAT EMBEDDED IN LAKE ICE, COAST LAKE, NEAR CAPE ROYDS
[Photo by D. Mawson

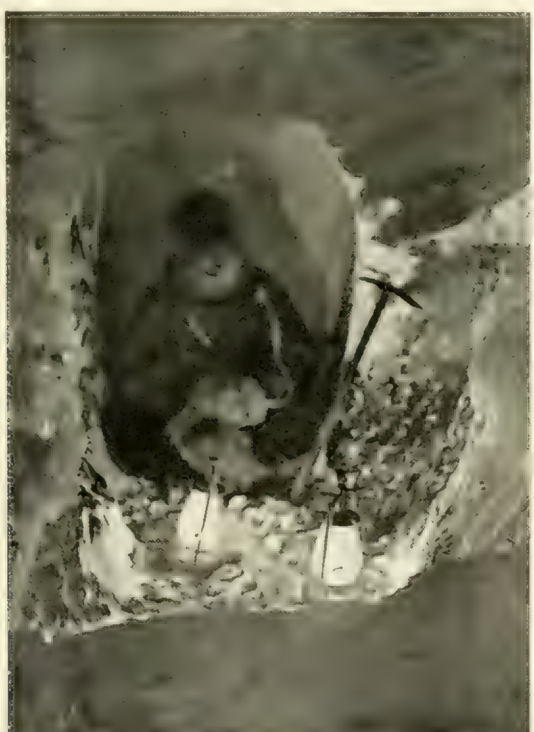


FIG. 2. SHAFT SUNK IN ICE OF COAST LAKE, NEAR CAPE ROYDS
Showing bed of algal peat. The peat commences about one-third of the way

[To face p. 278

BLOCKS OF ICE HUNG IN THE WIND AT THE WINTER QUARTERS IN ORDER TO ASCERTAIN THE RATE OF EVAPORATION

[*To face p.* 278

the slush in the lake water was piled up on the leeward side of the lake in small ridges.

At the north end of this lake the algous deposit is very sparse except for short distances, within 2 feet, of the ice margins, where in places it is fairly common. The maximum width of the algous belt is at the north-east corner of the lake, where it is about 12 paces wide; this decreases to 6 paces in width at the north-west corner, where three distinct ridges are to be detected raised sharply 1, 2, or 3 inches high respectively at 3, 4, and 5½ paces outwards from the lake margin. These small

Ft.	In.	
0	1	Layers of ice separated from one another by layers of bubbles.
0	$0\frac{1}{12}$	
0	$1\frac{1}{2}$	
0	10	Ice divided into eleven laminæ by sheets of bubbles.
0	10	Ice strongly fibrous and prismatic, with numerous vertical bubble holes. The bottom ice for 6 inches in depth is yellow.
0	9	Peaty fungus and ice mixed.
1	4	Alternating laminæ of fungus-peat and ice passing downwards into 4 inches of gritty peat.
0	3	Pebbles of kenyte lava with algæ, cemented by ice.

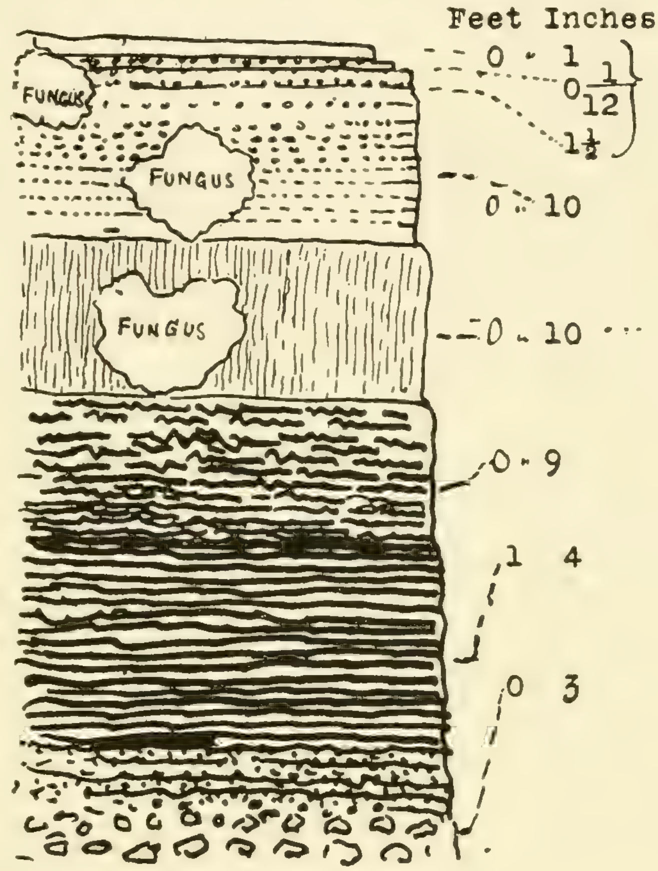


Fig. 65. Section through deposit of Algous Peat, Coast Lake, Cape Royds

ridges perhaps represent the level of the surface of the lake at different periods. At the same time they are in part due to the piling up action of the small waves of the lake during blizzards. In places the algæ are sufficiently abundant to form a species of algous peat. The only lake where this was observed to be the case was Coast Lake. The general character of this and the layers of ice with which it is associated is shown on the accompanying section.

Another section was compiled from the evidence obtained by three trenches and two bores in Coast Lake. These have shown the presence of a stratified organic deposit, ranging in thickness from 2 feet (60 centimetres) in the centre of the lake to a few inches near the margin. A descending section of the peat deposit where thickest was as follows :—

(*a*) 18 inches (45 centimetres), cloudy ice with regular layers of bubbles at intervals varying from $1\frac{1}{2}$ inches to $\frac{1}{2}$ inch in thickness. In most of the lower layers the bubbles tended to become drawn out and to be thermometer-shaped, a tendency that increased with the depth. The layers were less well defined and more numerous in the lower few inches.

(*b*) From 18 inches to 24 inches (45 to 60 centimetres), ice of similar type, but yellow, and malodorous owing to gases produced by partial decomposition of the plant tissues.

(*c*) A layer 9 inches (22·5 centimetres) thick of the algous peat, which proved on melting to be composed of small flakes of the algæ.

(*d*) A thin layer of ice fairly free from algæ and containing a series of small snow tabloids and partially filled gas bubbles.

(*e*) A thickness of 1 foot 3 inches (37·5 centimetres) of regularly stratified layers of peat separated by very thin seams of fairly clean ice, and ending in a layer 4 inches (10 centimetres) thick of dense peat containing rather more gritty rock particles than the upper layers.

It will be seen that the whole thickness of this deposit, including a good deal of interlaminated ice, is about 4 feet. It will be noticed that immediately above the top of the peat bed the ice is rendered conspicuously fibrous owing to very numerous vertical bubble holes like the capillary tubes of thermometers. These seem to have been formed by bubbles of escaping gas.

One of the most curious facts about the occurrence of this peat is its regularly stratified appearance, rendered most conspicuous by the laminæ of almost pure ice which support the beds. The reason for the intercalation of these ice laminæ is hard to ascertain, for we have every reason to believe that the ice at Coast Lake was thawed right to the bottom during both of the summers which we spent at Cape Royds.

The following is an analysis of the peat by Mr. F. B. Guthrie, F.C.S., Analyst to the Department of Agriculture, New South Wales :—

Sample of Algal Peat, Coast Lake, Cape Royds.

	Per Cent.
Moisture	12·05
*Volatile matter	55·59
Ash	32·36
	100

* Containing nitrogen, 0·39.

The ash is red in colour, and contains a considerable proportion of ferric oxide.

Analysis of Ash of Algal Peat.

(Made by Mr. T. O. Heinrich.)

	Per Cent.
Insoluble	67·92
Soluble silica	11·86
Fe_2O_3 and Al_2O_3	12·16
Phosphoric acid (P_2O_5)	2·64
Lime (CaO)	2·13
Magnesia (MgO)	1·00
Potash (K_2O)	1·59
	99·30

Behaviour of Algal Peat on Subjecting to Destructive Distillation.

	Per Cent.
Aqueous distillate (crude pyroligneous acid)	10·01
Charcoal	60·20
Tar	19·15
Uncondensed gases, &c.	10·64
	100

The proportion of charcoal and of tar are very high. Groves and Thorp, "Chemical Technology," vol. i. p. 206, give as an average of a number of samples of Irish peat made by Kane and Sullivan the following figures:—

	Per Cent.
Water	31·4
Tar	2·8
Charcoal	29·2
Gas	36·6
	100

Some results of the dry distillation of a few of our local hardwoods may be of interest for purposes of comparison. Here again the proportions of charcoal and of tar obtained from the algal peat is comparatively very high.

Products of the Dry Distillation of some New South Wales Timbers.

The accompanying table gives the results obtained by subjecting some specimens of New South Wales timbers to destructive distillation in such a way as to convert them into charcoal.

The wood was cut into small pieces, and introduced into a retort, a low heat being applied at first. The temperature was gradually increased to a bright red-heat. The retorts used were filled with the wood, so as to conduct the operation in the presence of as little air as possible. The samples were not thoroughly seasoned, and contained about 20 per cent. water.

The charcoal was, in nearly all cases, of good and even appearance, though no special test was made as to its quality.

Products of Dry Distillation of some New South Wales Timbers.

	Charcoal.	Crude Pyroligneous Acid.	Pure Acetic Acid.	Tar.	Uncondensed Gases.
Stringy-bark	28·00	46·90	3·15	9·42	15·68
Stringy-bark	28·10	47·76	2·64	8·62	15·52
Yellow-box	26·00	47·72	3·36	7·36	18·92
Peppermint	27·40	46·72	3·30	8·50	17·38
Messmate	24·90	47·00	3·00	9·62	18·48
Brittle-gum	27·60	46·82	2·70	7·10	18·48
Spotted-gum	24·60	46·70	3·20	9·52	19·18
Mountain ash	22·22	47·06	2·45	10·74	19·98
Blue-gum	27·06	48·32	2·35	6·14	18·42

Comparing these results with those obtained from European woods, the most notable difference appears to be in the smaller amount of acetic acid obtainable from our timbers.

It is of course to be borne in mind that this material (algal peat) is very much drier than a true peat would be, or than the samples of timber examined. This would also account for the high percentage of ash in the specimen of algal peat examined. The analysis of algal peat is interesting in other ways. As a rule algæ are high in nitrogen. In Thorp's "Dictionary of Applied Chemistry" (Revised Edition, vol. i. 1912), p. 73, there is given the analyses of about ten varieties of algæ in which the nitrogen content averages 2·5 per cent. in the dry matter. In the case of the algal peat under discussion, the nitrogen in the dry matter only amounts to 0·44 per cent., or about one-sixth of the above amount.

Another interesting point in which this substance differs from ordinary peat is in the composition of the ash. In nearly all the analyses of peat ash that we have access to the amount of lime is a striking feature, running from 20 to 40 per cent. In the case of the algal peat this ingredient is by no means dominant, whereas the sand, insoluble matter, and soluble silica accounts for nearly 80 per cent. of the ash. In other analyses of peat these ingredients are either quite low in most cases, or amount in exceptional cases to about 20 per cent.

The name peat is somewhat of a misnomer, as this material is practically dried algæ, in which the organic structure is still apparent, and which does not possess the density and fineness of structure associated with peat. In true peat the woody fibre has undergone decomposition by the action of air and water. This is not the case in this sample, which is simply a desiccated sample of the plant.

The general appearance and mode of occurrence of the deposit is shown on Plate XC. Fig. 2, and the details of the peaty ice are shown on Plate XC. Fig. 3, and on Fig. 65.

Algous Deposit near New Harbour.

One of us (R. E. Priestley) observed an algal-like substance growing as a thick layer on the black mud of the tide flats just above the present level of the water and well inside the region which must be covered either at ordinary high tide or during any unusual rise of the water. The peculiar point about the plant was the formation of a series of cones as much as 6 inches high, which were formed by the gas from the organic mud underneath collecting as large bubbles under the impervious skin of algæ.

So far none of these peat deposits observed by us are more than a few acres in extent, but it is quite probable that in the larger lakes, such as that of Dry Valley (which, as shown by Scott, is about 14 miles in length), deposits of much greater extent may accumulate. Thus under the rigorous conditions of the 77th to 78th parallel of south latitude peaty material, which later may form coal, is actually growing at the present time.

GUANO

Mr. F. B. Guthrie has also furnished us with the following analysis and interesting account of the guano sample submitted by us from Cape Royds :—

Adélie Penguin Guano, Cape Royds Rookery, Antarctica.

	Per Cent.
Moisture	16·57
Organic matter and ammonium salts	46·75
Insoluble matter (sand)	18·72
Phosphoric acid (P_2O_5)	8·32
Equivalent to $Ca_3(PO_4)_2$	18·16
Potash (K_2O)	0·72
Total nitrogen	11·65
Equivalent to ammonia	14·15
Nitrogen in form of ammonium salts	3·09
Equivalent to ammonia	3·75

Its approximate percentage composition will be :—

Moisture	16·57
* Organic matter and ammonium salts	46·75
Insoluble matter (sand)	18·72
Tricalcic phosphate	18·16
Potash	0·72
	100·92

* Containing 11·65 per cent. nitrogen, equivalent to 14·15 ammonia.

For the sake of comparison some analyses of other similar guanos are added.

Average Composition of Seventy-eight Peruvian Guanos.

	Per Cent.
Moisture	13·67
* Organic matter and ammonium salt	52·05
Alkaline salts containing 3·34 per cent. $P_2O_5 = 6·89$ phosphate of lime	9·67
Sand and insoluble	1·83
	100

* Containing ammonia, 16·52.

	Angamos.	Ballestas.	Ichaboe.	Patagonian.
Nitrogen	20	11	9	4
Phosphate of lime	10	23	26	40

COMMERCIAL VALUE OF THE ADÉLIE PENGUIN GUANO

The composition of a guano depends very considerably upon its age and the amount of weathering and leaching to which it has been subjected. As a general rule, unless the guano has been deposited in caves or sheltered places, the result is a gradual diminution of the nitrogen and a corresponding increase in the phosphoric acid. The sample of Adélie penguin guano compares very favourably with that of the best-known guanos, as far as its agricultural value is concerned. Compared with Peruvian guano, it will be seen that it is very little poorer in nitrogen, and contains nearly double the amount of phosphoric acid.

It approaches in composition the Ballestas guano, whose analysis is quoted above. Its commercial value on the local market calculated from the most recent unit-values for phosphoric acid and nitrogen (May 1912) would be about £5, 10s. per ton.

CHAPTER XIX

*CAINOZOIC PALÆOGEOGRAPHY

PART I. ANCIENT EXTENSION OF THE GLACIERS

M. H. Arçtowski was the first to record evidence of the glaciers of the Antarctic having formerly had a very much greater extension than they have at present.† He found in Gerlache Strait traces of former glaciers in the shape of moraines, erratic blocks, and roches montonnées. This strait was formerly occupied by an immense glacier, which has left behind it a moraine from 20 to 25 metres above sea-level. Arçtowski considers (p. 64, footnote *b*) that, inasmuch as the Gerlache Strait is 400 to 500 metres deep near where these moraines were observed, it is probable that this glacier did not fill the strait from top to bottom, but was floating. He considers that the dominant movement of this floating glacier was at first from south-east towards the north-west. When checked by the opposing islands of Anvers, Brabant, and Liége the ice was diverted chiefly towards the north-east. He also records that Gaston Islet, about 1 mile eastwards of Cape Reclus, shows evidence of having been strongly glaciated, and the direction of the quartz-porphyry erratics show that the glacier of this strait moved southwards, from south of Cape Anna, towards the Bay of Flanders. Thus it is assumed that the main gathering ground of this unknown ice-sheet was situated on Danco Land, and that near Cape Anna it parted into two streams going respectively to the north-east and south-west, with possibly a third stream passing outwards direct to the north-west through the De Schollaert Canal into the Bay of Dalmann. The glacier which formerly filled Hughes Bay belonged to the north-east stream.

Dr. J. Gunnar Andersson ‡ records the fact that Moose Island, an entirely ice-free rocky island at Cape Westspring in the Bay of Brialmont on the *Belgica* chart, shows strong traces of ice-grooving right up to its summit; the furrows are directed towards the north-east. He concludes that this island was once over-ridden by an

* Cainozoic is here used in the sense of including all time from the close of the Cretaceous to the present.

† C. R. Acad. Sc., Paris, 27th Août, 1900. Sur l'ancienne extension des glaciers dans les régions des terres découvertes par l'Expédition Antarctique Belge.

Expédition Antarctic Belge. Voyage du S.Y. *Belgica*, 1897–98–99. Rapports scientifiques, Géologie, Les Glaciers, 1908, pp. 59–64.

‡ Otto Nordenskjöld, Antarctic, Zwei Jahre in Schnee und Eis am zud Pol, Bd. ii. p. 217.

immense mass of ice moving powerfully in a direction from south-west to north-east. This must have entirely filled the whole of the Orleans Channel. Some idea of the thickness of this ice stream may be formed from the fact that while the height of the adjacent island is at least 200 metres, soundings were obtained near by in the channel of 620 metres, consequently this ice stream must have been at least 800 metres thick.

The same author * also states in regard to the maximum glaciation of Graham Land that in bygone time the glaciation of these tracts was much more extensive than to-day. For example, he states that in regard to the past glaciation of Moose Island, "A single glance at our maps (Plates IV. and V.) will suffice to show that such a direction of the movement of the ice was here possible only in case the ice stream filled Gerlache Channel in all its breadth, and was forced to the north-east by the pressure against the island range that forms the north-west side of the channel" (p. 55). He adds, "Also in Hope Bay I found very clear evidence of the earlier maximum glaciation. This is in the form of a rocky hill, 100 metres high, once over-ridden by the adjacent valley glacier, the summit of which is now only 20 metres above sea-level." He also notes, "On the southernmost point surveyed by our expedition the Borchgrevink Nunatak, in 66° S. lat., Nordenskjöld found, by means of erratic boulders, that the island ice once rose 300 metres higher on the sides of the nunatak than it does to-day." Thus in Recent, or at least Post-Pliocene geological time, a vertical decrease in altitude of the ice has been proved to the amount of 300 metres in King Oscar Land, and 200 metres in the neighbourhood of the Orleans Channel. E. Gourdon, Geologist to Dr. Charcot's Expedition, records † "Les moraines que j'ai rencontrées dans le chenal de Roosen, tout au pied du pic Jabet que dans l'île Doumer, temoigment également d'une ativité que ne correspond pas à celle des glaciers actuels, et les blocs erratiques qu'elles renferment indiquent nettement une extension plus grande." In the neighbourhood of Kaiser Wilhelm II. Land, Drygalski has shown that erratic blocks cover the slopes of the volcano of Gaussberg, built up of leucite basalts, to a height of 370 metres above the sea and some 350 metres above the level of the surrounding land ice. Thus near Gaussberg the inland ice was formerly fully 350 metres thicker than it is at present. ‡ These erratics of biotite gneiss, gneissic quartz felspar hornblende rock, hornblende biotite granite, all suggest the existence of continental rocks inland from Gaussberg.

Similar evidence of recent retreat of the ice is everywhere noticeable in South

* Bulletin Geol. Instit. Upsala, vol. iii., "On the Geology of Graham Land," by J. Gunnar Andersson, pp. 53–57.

† Expédition Antarctique Française (1903–5), Géographie Physique, Glaciologie, Pétrographie, par E. Gourdon, p. 117.

‡ Dr. E. Philippi, Ueber die Landeis-Beobachtungen der letzten funf Sudpolar Expeditionen, p. 7. Deutscher Sudpolar Expeditionen, 1901–3, Bd. ii., Kartographie, Geologie, heft 1, p. 51, pp. 59–60.

Victoria Land. Captain Scott * records the fact that on the slopes of Mount Terror morainic material was traced up to a height of 240 metres above the present level of the ice surface, while near Cape Royds and at Cape Armitage the presence of erratics, and general shape of the hills, showed that the whole of that region had recently been over-ridden by an ice-sheet. On p. 273 the fact that some sixty years before Scott's Expedition Sir James C. Ross found the front of the Ice Barrier in McMurdo Sound some 30 miles in advance of where it proved to be at the time of the *Discovery* Expedition in 1900 obviously points to an immense recent recession of the Great Ice Barrier.

H. T. Ferrar, the Geologist to the *Discovery* Expedition, similarly records † that in the Ferrar Glacier Valley there is evidence of morainic material some 3000 feet above the present level of the glacier now occupying that valley. Similar evidence is afforded by the numerous erratics from the mainland perched on top of Black and White Island to the south of the *Discovery's* headquarters.

We may now briefly summarise the evidence collected by the Shackleton Expedition of the former greater extension of the Antarctic glaciers of South Victoria Land. Details have already been given earlier in this Report.

Conclusive evidence is afforded as to the former greater height of the ice of the outlet glaciers by the strongly glaciated and grooved character of nunataks, rocky promontories, coastal hills now more or less ice-free, and summits of low ranges adjacent to the outlet glaciers. Similar evidence is afforded by the glaciation of islands and deposition on them of moraines at altitudes now considerably above the level of the present glaciation.

If we commence at the northern end of the area examined by our expedition we find that in the case of the Reeves Glacier, between Mount Nansen and Mount Larsen, there rises a bold nunatak, the Hansen Nunatak.‡ This rises to an altitude of 2600 feet above sea-level, and about 1600 feet above the level of the adjacent glacier ice. The general appearance of Mount Larsen, Mount Gerlache, and Mount Crummer suggests that they have all been recently over-ridden by a heavy ice-sheet. The summit of Mount Larsen rises over 1400 feet above the level of the adjacent glacier ice. At Backstairs Passage, between Mount Crummer and Mount Gerlache, strongly glaciated terraces of granite, now completely ice-free, are exposed to view at levels of 500 to 600 feet above the adjacent glacier ice. The group of mountains between the Larsen Glacier and the David Glacier, Mount Bellinghausen and Mount Neumayer, have also obviously been over-ridden by the old ice-sheet. The great wall of granite, the D'Urville Wall, which bounds the David Glacier on the north, has most obviously been due to the action of glacier ice.

Cape Irizar, 600 feet above sea-level, shows evidence of having been intensely

* Captain Scott, Voyage of the *Discovery*, vol. ii. pp. 271–273.

† Royal Geographical Society's Journal.

‡ Called the Reeves Nunatak by the members of Scott's last expedition.

glaciated and grooved by an ice-sheet coming from the west, apparently an overflow from the David Glacier towards the E.N.E. In fact the whole of the coast-line from Cape Irizar for about 12 miles south, which now rises from 600 to 800 feet above the sea, is probably an island, Lamplugh Island, the whole of which has recently been enveloped in the glacier ice of the outlet glaciers and piedmont glaciers. Prior Island, between Cape Irizar and the Cheetham Ice Barrier Tongue, about 300 feet high, has also obviously been over-ridden by glacier ice. It may be added that Cape Irizar is strewn with a great variety of erratics.

Next, the formation of the terraces to the north and south of the Mawson Glacier show that the ice of that glacier has formerly occupied the greater part of the upper terrace which lies at an altitude of 700 to 1000 feet above the surface of the present glacier. Depot Island, and the adjacent coast-line near Cape Ross, were also found to have been powerfully glaciated. Depot Island is about 200 feet above sea-level. At Granite Harbour, the Mackay Glacier, like the Mawson Glacier, lies in a well-marked, over-deepened valley. (See Plate XVI. of Chapter IV.) A wide upper valley, or alb valley, excavated during the ice flood,* is now from 700 to 1000 feet above the level of the adjacent glacier. Dunlop Island, which is now quite ice-free, rises to a little over 100 feet above sea-level. The hills on either side of the Ferrar Glacier, both in North Fork and East Fork, show evidence of having been formerly intensely glaciated up to heights of from 2000 to 3000 feet above the level of the present glacier.

The grandest and most convincing evidence of this kind afforded by any feature as yet known in the whole of the Antarctic regions is that supplied by the glaciated surfaces and wonderful moraine deposits around the western, southern, and eastern sides of Ross Island. These remarkable moraines, containing an assortment of nearly all the rocks, except those of very soft and friable nature, which are to be found on the mainland to the south and west, attain an altitude of a little over 1000 feet above sea-level to the east of Cape Royds on the foothills of Erebus, while on the south-eastern slopes of Mount Terror, as already stated, they reach an altitude of about 240 metres above the level of the adjacent glacier ice. It is most fortunate that such a magnificent gauge of the former height of the Ross Barrier as Ross Island already existed at the time of maximum glaciation. It is interesting to note that, in the glaciation of the Cape Royds region, in spite of the powerful thrust from the west of the ice of the Ferrar Glacier, the ice of the Ross Barrier was able to keep direct on its northerly course without showing the influence of this north-easterly component of ice movement. This persistent northerly movement of the former Ross Barrier past Cape Royds is perhaps due in part to the protection afforded by the high massif of the Royal Society Range lying to the south-west.

* It is still doubtful how far this upper wide valley has been formed by "ice flood" glaciers, and how far they have been formed and modified by cirque glaciers. We consider that they are mostly of ice flood origin.

The Dellbridge Islands, as well as Inaccessible Island and Tent Island, rising to heights of respectively 500 feet and 400 feet, have obviously been heavily glaciated, and the summits, at all events that of Tent Island, strewn with erratics. Observation Hill, now about 700 feet above the level of the neighbouring Great Ice Barrier at Pram Point, has obviously been glaciated over its summit. It would be a matter of great interest and importance to ascertain the exact height of the old moraines distributed along the great promontory of Minna Bluff, and around the flanks of the extinct volcanoes, Mount Discovery and Mount Morning.

The excellent drawings of the late Dr. E. A. Wilson when on the *Discovery* Expedition, together with the photographs by himself and Shackleton of the coast-line south of Minna Bluff as far as Shackleton Inlet, show obvious traces of waning glaciation in the shape of ice-free hills and promontories exhibiting roches montonnées structure.

Another fine piece of evidence of this kind is that supplied by Mount Hope at the entrance of the Beardmore Glacier. Mount Hope rises 2760 feet above sea-level, and fully 2000 feet above the horizon of the Beardmore Glacier Ice. The summit of this great nunatak is still partly covered with moraine material, which must have travelled down the Beardmore Glacier for a considerable distance. Amongst the erratics, fragments of limestone, diabase, arkose, and a specimen of a new type of mineral, an iron phosphide, have been found. Mount Hope itself is entirely formed of granite. Like the Mawson, the Mackay, and the Ferrar Glaciers, the Beardmore Glacier lies in an over-deepened valley, with a much wider valley lying at an altitude of over 3000 feet above the surface of the present glacier. (See Plates XXVIII. and XXIX. of Chapter V.)

The great terraces of granitic rock with their roches montonnée surfaces, the foothills near Lower Glacier Depot, between Mount Ida and Mount Hope, now ice-free, were obviously produced by the glacier when its surface was fully 1000 feet higher than it is now. At the foot of the Cloudmaker mountain the recent lateral moraines rise to heights of fully 200 feet above the level of the adjacent glacier ice. Even at the head of the Beardmore Glacier, Mounts Darwin, Buckley, and Bartlett show evidence of having been enveloped in ice almost, if not quite, to their summits. Here again further evidence is much to be desired as to the exact height up to which undoubted traces of past glaciation extend on these mountains. (See Plates XXXI. and XXXII. of Chapter V.)

The whole of this evidence shows conclusively that the level of the outlet glaciers, during the maximum glaciation or ice flood epoch, was from 2000 to 3000 feet higher than it is at present, while the general level of the Ross Barrier in the neighbourhood of Ross Island was from 850 to 900 feet above its present level. It will be seen that in this connection the question as to whether the elevated marine muds of Ross Island are true "raised beaches," or upthrust portions of the sea floor, is of great importance. If it can be shown that the whole of the western side of Ross Island has been raised, since the time of maximum glaciation, to a height of fully 600 feet, the old moraines of the Ross Barrier at 850 feet above the present level of the ice vertically, may imply a decrease in the former altitude of the Ross Barrier of 250 feet as compared with 850 feet. But for reasons already adduced in the description of the raised marine muds, it is considered now to be almost certain that the bulk of the Ross Island upraised marine muds owe their present position to upthrust by the tongue of the Ross Barrier formerly occupying McMurdo Sound. Moreover, evidences of deglaciation are so widespread in this region of the Antarctic, extending as they do from 85° S. lat. to at least as far north as Mount Larsen in 75° S. lat., that it cannot all be explained away by a recent considerable elevation of the land. It may be safely assumed that the minimum amount of deglaciation from 85° S. to near Mount Nansen amounts to approximately the order of about 1000 feet in the case of large ice masses like the Ross Ice Barrier, and to from 2000 to 3000 feet in the case of the ice of the outlet glaciers. Fig. 46 of Chapter VI. shows the probable approximate limit of the old Ross Barrier during the maximum glaciation.

As already stated, the evidence in the American Sector of the Antarctic shows a recent deglaciation amounting to from 600 to 700 feet (183–213 metres) near Graham Land and Danco Land, and as much as nearly 1000 feet (305 metres in King Oscar Land). At Gaussberg the decrease in level of the inland ice in Recent Geological time amounts to nearly 1150 feet (350 metres).

It may be concluded, therefore, that it may be assumed at present that the average amount of deglaciation in recent times, in such parts of the Ross region as have recently been explored, amounts to approximately from 300 to 320 metres (984–1050 feet).

It will be a matter of great interest to decide whether or not the deglaciation has been differential in different localities. Much more extended observations will be needed in order to throw light on this question.

As regards the interesting question as to the maximum thickness of glacier ice during an Ice Age, we think that its maximum thickness was attained at the outlet glaciers either at their heads, just west of the Antarctic Horst, or in their lower portions near their junction with Ross Sea. This maximum thickness of ice at the climax of an Ice Age was probably of the order of from 4000 to 5000 feet (1219–1524 metres) at the outlet glaciers, and about 3000 feet to 3500 feet (914–1066 metres) in the case of the Ross Barrier along the latitude of Ross Island. Information is as yet lacking as to the amount of deglaciation of the inland ice since the time of the latest ice flood.

PART II. PROBABLE PRE-GLACIAL HISTORY OF SOUTH VICTORIA LAND IN CAINOZOIC TIME

The important question naturally suggests itself, if the whole of the ice and snow were cleared off from the surface of the Antarctic continent, what would be the nature of its present physiography? And next, what was the probable physiographic relief of the land in early Miocene time when, as the evidence collected by Dr. Otto Nordenskjöld's Expedition suggests, the whole continent was probably ice-free?

Before any guess may be made at the answer, the further question has to be considered as to when did the main faulting take place which produced the great Antarctic Horst. In the absence of direct stratigraphical evidence, further than that the faulting is Post-Beacon Sandstone, that is, most probably Post-Gondwana, probably Post-Cretaceous, we have to rely chiefly on the amount of dissection which the horst has undergone subsequent to the epoch of faulting. Some important conclusions follow from the considerations of the probable answers to the above questions. The great depth to which the transverse valleys of the great horst have been excavated, such excavation probably for the most part subsequent to the faulting, suggests that the faulting has taken place at some epoch ante-dating the Post-Pliocene. It has been shown that in the Auvergne valleys have been excavated to a depth of about 1500 feet (457 metres) since late Pliocene time; but the transverse valleys of the horst, like the Beardmore Glacier Valley, have been eroded to a depth of fully 6000 feet (1828 metres). Perhaps more than Post-Pliocene time is needed for such a vast amount of erosion.

If, as Mr. Allan Thomson, in this Memoir, supposes, the widespread injection of quartz-dolerites, in the Southern Hemisphere, was connected with the breaking in and foundering of large areas of Gondwana Land, then the major part of the faulting which produced the Antarctic Horst may be ascribed to some late epoch in the Cretaceous Period, for the evidence in Tasmania and South Africa shows that these quartz-dolerites, while they strongly intrude the Trias-Jura rocks, are themselves capped by later deposits, probably of Eocene age. In South Africa, according to Rogers, the date of their injection lies between Upper Jurassic and Upper Cretaceous. It may, therefore, be provisionally assumed that the principal tectonic movements which gave rise to the Antarctic Horst date for their beginnings to about the commencement of the Cainozoic Era. The existence of this long, comparatively narrow, elevated strip of the horst would probably give rise to a system of drainage much like that of the northern part of South America. It is doubtful whether, even in the long time that has elapsed since the Cretaceous, the rivers draining into the Ross Sea, and that southern part of it now occupied by the Ross Barrier, would have had time to cut back their valleys completely through the great horst so as to encroach on the region of westerly drainage on the other side. It is possible that, previous to the last great glaciation, a divide existed, within the limits of the horst itself, which shed short rivers, from 80 to 100 miles in length, eastward into Ross Sea, and large rivers, like the Amazon and the La Plata, perhaps towards Kaiser William II. Land and Weddell Sea respectively.

An alternative is to suppose that previous to the late Cainozic glaciation of the Antarctic the eastward flowing rivers of the Antarctic Horst had actually cut through the horst and encroached on the sandstones of the down-faulted area of the Beacon Sandstones in the neighbourhood of the present Ice Divide. This is situated on the South Magnetic Pole plateau area, at about 200 miles inland, and near Shackleton's Farthest South in lat. 88° 23′ S. and long. 162° E., also a little over 200 miles inland from the coast-line of the Ross Barrier area. In either case we are faced with the almost certain fact that there were a series of very short rivers draining eastwards, with very long ones draining westwards and northwards. If at the time immediately preceding the commencement of the Cainozoic glaciation the main divide was still situated within the horst itself, we are forced to a very interesting conclusion as regards the development of the modern transverse valleys, now occupied by the outlet glaciers. It must be assumed that as the ice accumulated on what had formerly been the western watershed of the horst, it gradually rose so high that it was able to overflow the cols in the main divide, and so discharge into Ross Sea as well as in the direction of Adélie Land, Kaiser Wilhelm II. Land, Enderby Land, &c. Thus the drainage may have gradually been reversed by the ice of the western portions of the outlet valleys becoming converted into obsequent streams. This, of course, would not be the case if the Divide, previous to the coming on of the Cainozoic glaciation, had already been driven back as far westward as 100 miles west of the western side of the horst, the position of the present Ice Divide. Even if it be conceded that many of the transverse valleys were originally partly tectonic in character, partly of fluviatile origin, it must become apparent that their present valley walls, so smooth, straight, and spurless, have been so extensively modified by the sculpturing of glacier ice, by frost-weathering, and by fluvio-glacial action, that all traces of former possible river action have now been effaced. (See Plate LVIII. of Chapter X.)

Another view, which seems to be more probable, is that the formation of the horst did not much ante-date, if at all, early Pliocene time. Previous to the faulting mature valleys of fluviatile origin may have drained across the area where the horst was about to rise. This is suggested by the oblique angle at which the Beardmore Valley, the Barne Inlet Valley, &c., meet the trend line of the horst. This is suggestive of a former radial drainage ante-dating the formation of the Ross Sea, as, if the valleys entirely post-dated the formation of the horst and were purely of glacial origin, the ice would probably have short-circuited to Ross Sea, producing valleys at right angles to the trend of the horst. Then the Antarctic Horst became developed, in a refrigerating climate. As a consequence the north-eastward flowing rivers were betrunked, in their lower courses, through the formation of the Ross Sea *senkungsfeld*, and were dammed back in their upper courses by the horst. Thus lakes probably gathered to the west of the horst, overflowing to north and west of the horst in the direction of Oates Land, or bending eastwards through the low gap between Mount George Murray and the Drygalski Glacier Tongue. Later, as glaciation developed, the ice rose high on the inland side of the horst, until it poured down the old shallow river valleys and swept bodily over all the wide low sags in the horst, especially between the Royal Society Range and Mount Nansen. During the prolonged glaciation that followed the old mature river valleys were cut down by the ice-flood to their present vast depth, and perhaps all traces of former river action, except that of the original trend of the mature valleys, became obliterated.

Still another view, advocated by T. Griffith Taylor, is that the horst was not at all notched by rivers, but that the cutting of the outlet valleys was the work of cirque recession on either side of the horst, the cirques incising low cols over which, later, the swelling ice-flood swept.

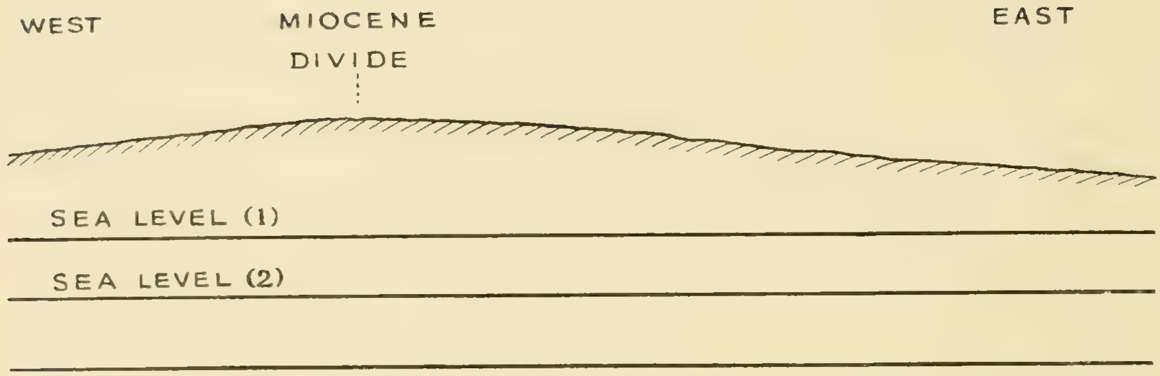
This question of the past physiography of South Victoria Land, in Pre-Pliocene glacial times, is also of considerable interest in relation to any estimates of the probable area of concealed coalfields to the westward of the Antarctic Horst. The almost meridional trend of the horst, combined with a general steady slope from near Shackleton's Farthest South to the coast nearly due south of the Balleny Islands, suggests that probably a large subsequent river eroded a wide channel following a subsequent course parallel to the Antarctic Horst, and entering the sea perhaps between Cape North and Adélie Land. If such a valley with its tributaries were eroded in Eocene, Miocene, and early Pliocene time, it would obviously have made great inroads on the former area of the Beacon Sandstone coalfield lying to the west of the horst. As the productive coal seams lie at some height up in the series, these seams would have suffered much from erosion.

This consideration shows how futile it would be to attempt anything more than an extremely rough estimate as to the possible areas of productive coal under the concealed part of this coalfield, where it is overlaid by a thickness of probably from 2000 to 3000 feet of glacier ice.

Fig. 66 illustrates the possible shifting of the position of the main divide of the Antarctic continent, in the South Victoria Land region, since the formation of the Antarctic Horst, probably in Early Tertiary, possibly in Miocene or even in Early Pliocene time, in regard to the latest of the tectonic movements.

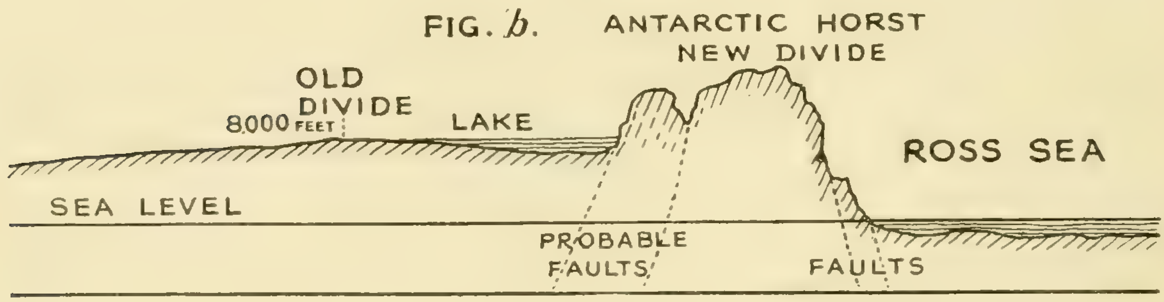
If the Ross Barrier were to disappear, and we could see the surface relief of the floor of Ross Sea, we should probably see as many long submarine morainic mounds as there are glaciers of any importance emptying into Ross Sea. Probably these mounds would extend considerably more than 100 miles from the shore-line. Possibly the moraines of the Ross Barrier may now be in process of being

FIG. *a*.



POSSIBLE SECTION OF ROSS REGION IN MIOCENE TIME

FIG. *b*.



POSSIBLE SECTION IN EARLY OR MIDDLE PLIOCENE TIME

FIG. *c*.

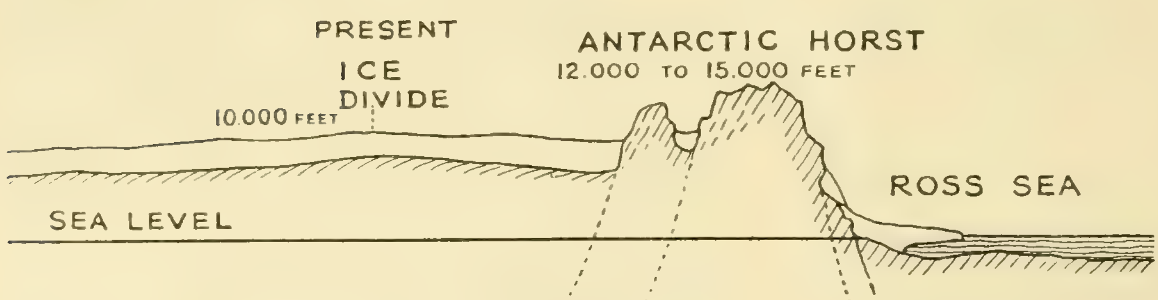


FIG. 66

dropped on to the bottom of the sea under the Barrier as the result of Sub-barrier thaw, at distances of even 300 or 400 miles seawards of the snouts of the Ross Barrier glaciers. Beneath them would lie the old delta deposits of perhaps Miocene or Early Pliocene time, except where the weight of the glacier ice, particularly

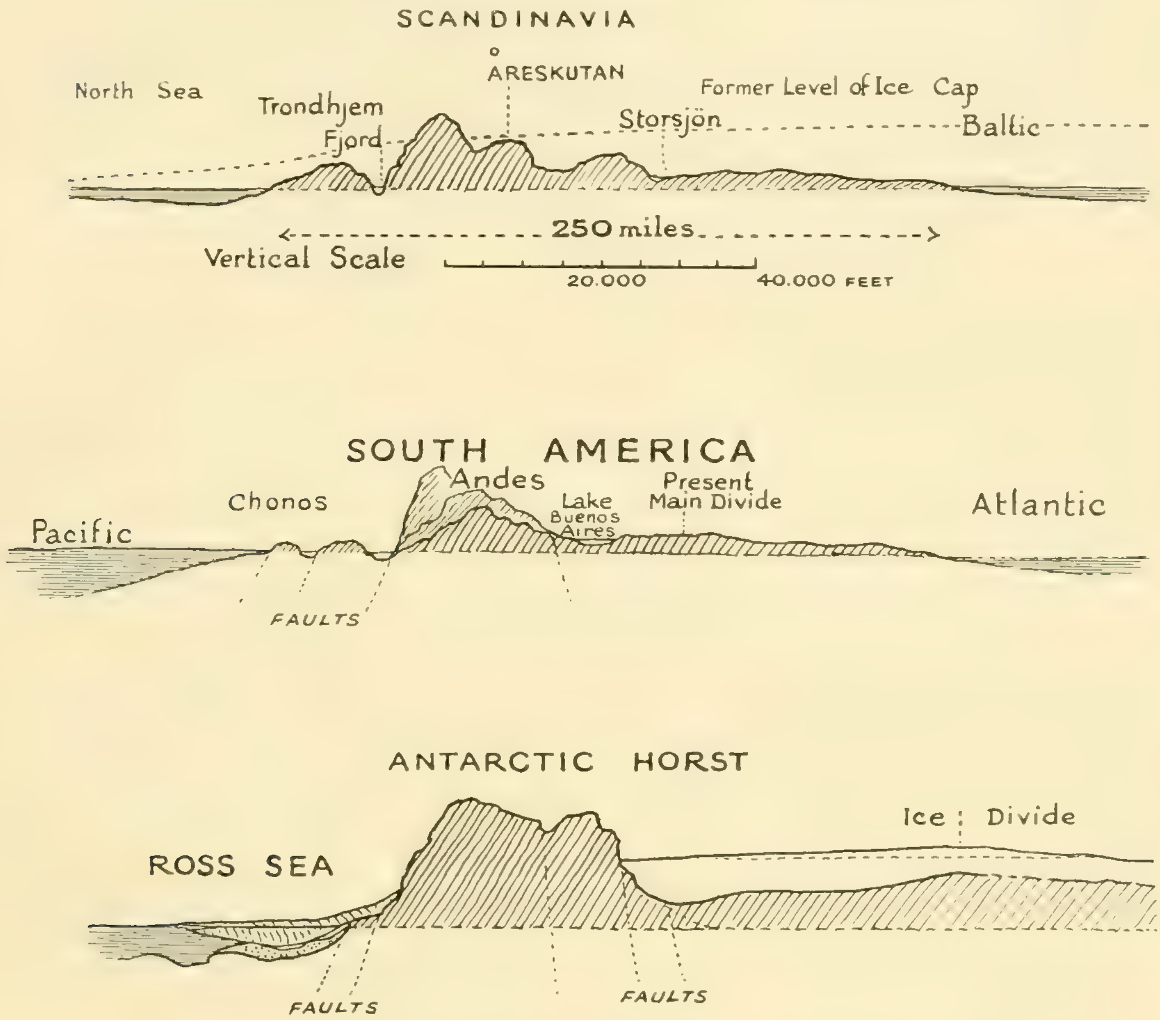


Fig. 67. Comparative Series of Sections showing Relief of Land in relation to former or present Glaciation

from the vast outlet glaciers, may have driven the old delta sediments somewhat seawards.

In relation to the subject of the probable relief of Antarctica in the neighbourhood of the horst in relation to the thickness of the covering of inland ice, it may be of interest to compare the sections respectively across Scandinavia, South America in the region of Patagonia, and the Antarctic Horst near Ross Sea. (See Fig. 67.)

It will be noticed that the section across Patagonia perhaps resembles that of the Antarctic Horst in that the present main divide between Chili and the Argentine Republic is in places far to the inland side of the Andes, and is lower in this case by as much as about 8000 feet than that of the old divide of the Andes. If Antarctica inland from Ross Sea has a relief like that of Patagonia or like that of Scandinavia, the thickness of the inland ice will be far thicker under the ice divide than our estimate of approximately 1500 to 2000 feet. In the case of Scandinavia, the fact that the ice sheet at one time heavily glaciated the summit of Areskutan, and moved from east to west, is good evidence, as pointed out to us by Dr. A. Strahan and G. W. Lamplugh, that the Scandinavian ice sheet near the Baltic formerly had a thickness in excess of 5000 feet. We think it unlikely that the inland ice of Antarctica is now, or ever has been, of such a vast thickness.

CHAPTER XX

NOTES ON GENERAL GEOLOGICAL RELATIONS OF ANTARCTICA TO OTHER PARTS OF THE WORLD

SUESS * in his monumental work has commented on certain points of resemblance between the tectonic lines of the American Sector of Antarctica, festooned with islands, and those of Central America, the Gulf of Mexico, the Caribbean Sea, and the Greater and Lesser Antilles, stating that (*op. cit.*, p. 495): "The resemblance of the South Sandwich Islands and the volcanoes of the Lesser Antilles has often been remarked upon." At the same time he cautiously concludes that "No connexion can be shown to exist between the widely remote volcanic indications of Burdwood Bank, the volcanic arc of the South Shetland Islands, and the Bransfield volcanoes (Bridgman, Deception, and others)." Arçtowski † has described the chief mountain chain of the American Sector as the Antarctandes, and has stated that these Antarctic ranges are not merely a pile of eruptive rocks, but that they are a folded range, in which perhaps the presence of eruptive rocks is accessory and of secondary importance. O. Nordenskjöld,‡ J. Gunnar Andersson,§ and M. E. Gourdon || have all insisted on the genetic affinity of the eruptive rocks of South America with those of the American Sector of Antarctica, and the two former authors emphasize other points of resemblance.

There can be no doubt that topographically and geologically Antarctica bears a remarkable resemblance to South America. On the west side of the American Sector of Antarctica lies an archipelago recalling the Chonos, Madre de Dios, and Magellanic Archipelagoes of Southern Chili and Tierra del Fuego. Just as is the case with these South American archipelagoes, the archipelago of the American

* "The Face of the Earth" (Das Autlitz der Erde). By Eduard Suess. Translated by Hertha B. C. Sollas under the direction of W. J. Sollas, vol. iv. pp. 470–473.

† Expédition Antarctique Belge. Voyage du S.Y. *Belgica* en 1897–9, Géologie, Les Glaciers, par Henryk Arçtowski. Anvers J. S. Buschman, 1908, p. 33.

‡ Petrographische Untersuchungen, aus dem westantarktischen Gebiete, Bull. of the Geol. Inst. of Upsala, vol. vi., part 2.

Die Schwedische Sudpolar-Expedition und ihre geographische Tätigkeit, von Otto Nordenskjöld, Stockholm, 1911, pp. 208–209.

§ "On the Geology of Graham Land," by J. Gunnar Andersson, Bull. of the Geol. Instit. of Upsala, vol. vii. p. 70.

|| Expédition Antarctique Française (1903–1905), commandée par le Dr. Jean Charcot, Géographie Physique, Glaciologie, Pétrographie, par E. Gourdon, Paris, 1908, pp. 206–208.

Antarctic Sector is separated from the mainland by longitudinal canals, such as Gerlache Strait and Orleans Channel. In fact this part of the Antarctic continent has dissolved itself in archipelagoes, which form a series of "panzer-horsts." This geographic condition perhaps persists westwards to King Edward VII. Land, but the recent discoveries of Roald Amundsen, together with the few observations of the Japanese Expedition under Lieutenant Shiraze, suggest that there are considerable land masses to the south of King Edward VII. Land. East of this fractured and sunken area in the Western Hemisphere and west of it in the Eastern Hemisphere rise the Antarctic Andes, as Amundsen holds, towering to heights of 15,000 feet (4572 metres) in Mount Frithiof Nansen, and to nearly 13,000 feet (3962 metres) in Mount Lister in the Royal Society Range. Beyond the slopes of the Antarctic Andes, facing the Atlantic and Indian Oceans, vast plateaux extend inland, in places for a distance of over 1000 miles (1610 kilometres) back from the ocean. This plateau for the most part rests on a foundation of crystalline rocks of Pre-Cambrian age. In South Victoria Land the Pre-Cambrian Complex is followed by Cambrian limestones, recalling the sequence in the eastern part of the Cordillera Real of the Bolivian Andes,* but not its structure, for in South Victoria Land no evidence of folding or overthrusting, like that which characterises the Bolivian Andes, has as yet been detected.

In South Victoria Land the Cambrian limestones and slates are followed by a vast sandstone formation, possibly of more than one geological age, mostly horizontally bedded, its higher strata containing coal seams, fossil wood and leaves, together with bony plates of some fish-like animal.† This plateau recalls that of Southern Brazil, with the coal-measures at the base of the Santa Caterina System, of Permo-Carboniferous age, the gneissic platform of the Falkland Islands with the Gondwana beds of Speedwell Island, or possibly the Rhætic plant-bearing beds of the Pre-Cordilleras of South America, and the Trias-Jura Coal-measures of Tasmania. It is even possible that the topmost sedimentary beds of the Antarctic Horst, in the Ross region, may ascend as high as the freshwater Puca Sandstones of South America, which with their Deinosaur remains are classed as Cretaceous.‡

Like the Permo-Carboniferous and Trias-Jura Coal-measures of Tasmania, those of South Victoria Land are invaded by huge sills and dykes of granophyric quartz-dolerite.

The affinity of the American Sector of Antarctica with the South American Andes is clear and obvious. Strata, chiefly of Mesozoic age, are there folded, mostly

* "The Face of the Earth," Suess, English translation by Sollas, vol. iv. p. 473.

† These were discovered by Messrs. T. Griffith Taylor, B.Sc., &c., and F. Debenham, B.Sc., of the British Antarctic Expedition of 1911–13 under Captain R. F. Scott, M.V.O., R.N. They were found in fragments of Beacon Sandstone at Suess Nunatak, inland from Granite Harbour, in the region of the Mackay Glacier. These have subsequently been shown by Dr. A. S. Woodward to be of Devonian Age.

‡ The chronological classification of these rocks will be made clearer when the fossil plant material obtained by Captain R. F. Scott's recent Antarctic Expedition is elaborated.

from west to east. Beds containing a rich Jurassic flora at Hope Bay rest on coarse conglomerates, which in turn repose on current-bedded sandstone with obscure plant remains. Cretaceous rocks, containing an abundant marine fauna, are followed by Oligocene or Miocene strata, partly marine, partly freshwater or estuarine, the probable equivalent of the Patagonian Molasse of Wilckens. A basaltic series follows, capped by the " pecten conglomerate," considered by J. Gunnar Andersson to be the equivalent of the Paraná beds of Cape Fairweather. In addition to these stratified rocks, the American Sector of Antarctica exhibits intrusive gabbros and granodiorites of most characteristic Andean affinities. While the relation of the American Sector of Antarctica to South America is thus extremely obvious, the problems presented by the great ranges of South Victoria Land are very perplexing, for while the fracture lines of the Andes appear to invade this region and to dominate its topography, all trace of Post-Mesozoic folding, so characteristic of the American Andes, is absent from the ranges of South Victoria Land, as far as is known at present. Petrologically also the South Victoria Land region differs almost wholly from the Andean type. The latter is of course typically of Pacific type, while the former is of Atlantic type. The relation of the ranges of South Victoria Land to the trend lines of the Andes on the one hand, and to those of Australasia, especially New Zealand, on the other, is one of the most interesting, and at the same time perhaps one of the most difficult of the tectonic problems presented to modern geology, and all we can presume to do under the circumstances is to offer a few suggestions very tentatively, referring readers to Suess' masterly summary (*op. cit.*, vol. iv.) for what is known about the relations of the South American and Patagonian Andes to the mountains of the American Sector of Antarctica, and to the original works of such writers as T. P. Moreno, R. Hawthal, O. Nordenskjöld, J. G. Andersson, O. Wilckens, H. Arçtowski, E. Gourdon, C. Darwin, C. Burckhardt, J. B. Hatcher, S. Roth, L. Wehrli, H. Steffen, G. Steinmann, Dr. Hyades, A. Reiter, Fonck, Halle, J. B. Scrivenor, and many others, references to whose works are given by Suess.

The following are the chief factors which may be employed in the correlation of the Antarctic regions with adjacent areas of the earth :—

1. The tectonic structure in reference to the chief earth trend lines.
2. The petrographical character of the eruptive rocks.
3. The palæontological evidence afforded by the fossil fauna and flora.

1. *The Tectonic Structure in Reference to the Chief Earth Trend Lines.*

In the chapter of this Memoir dealing with the physiography of the Antarctic, reference has already been made to the existence of the great horst, bounded by very heavy faults. This horst was proved by our expedition to extend from near Cape Adare for about 1000 statute miles, first south then south-east, far beyond the upper end of the Beardmore Glacier. On his recent brilliant march from the

Bay of Whales (Framheim) to the Pole, Amundsen reached the foot of the great horst in lat. 86° S. He found it to extend approximately for at least 100 miles farther in a direction S.S.E. and finally easterly, attaining altitudes of 15,000 feet above sea-level. The rocks of the horst, on the poleward side, drop sharply from these great elevations to an altitude of a little over 10,000 feet. Still farther polewards, to near 87° S., the surface of the inland ice rose to about 11,000 feet, after which it descended to about 10,260 feet (3127 metres) at the Pole. Captain Amundsen provisionally considers that this great horst is probably a continuation of the Andean Chain of South America. There can be no doubt that this horst is the dominant structure of the Antarctic continent.

In all probability this horst has a length of about 3200 miles. Its width, as already stated, from opposite the south-west portion of Ross Sea to the point where it was crossed by Amundsen, varies from about 50 miles to 100 miles. The interesting question suggests itself, are the rocks of the horst folded after the manner of those in the Andes? As pointed out by H. T. Ferrar, the massive Beacon Sandstone formation terminates in steep, and in places precipitous, slopes along the whole line of coast from beyond Cape North southerly to beyond the Royal Society Range. It is probable that Beacon Sandstone caps the range from that point to at least as far south as where Sir Ernest Shackleton's Southern Party, after ascending the granite and slate mountains of the horst in lat. 83° 33′ S., long. 170° E., reached the sandstone formation at an altitude of 6000 feet in 85° S. The sandstone formation there, containing seven seams of coal, thin portions of which at any rate are of economic value, were found to dip gently at an angle of about 6° to 8° towards the north-east.* There was no evidence at all of these rocks, which are provisionally classed as of Gondwana Age, having been folded. On the other hand, as described by Suess, the rocks of the South American Andes are strongly folded throughout a great part of Peru and Chili, including Patagonia, strata as new as Cretaceous being strongly involved in the folding. For example, at Staaten Island the Cretaceous strata are much altered by pressure, and dip at nearly vertical angles. At Depot Island, to the north of Granite Harbour, on the west coast of Ross Sea, the ancient gneiss platform is folded parallel with the coast-line, but this structure appeared to be the exception rather than the rule. At Mount Nansen, to the north of the Drygalski Ice Barrier Tongue, Beacon Sandstone strata appear to be almost horizontal. Recently Amundsen has exhibited photographs of the magnificent table-topped mountain, called by him Fridtjof Nansen, which make it almost certain that this mountain, like Mount Nansen of the Drygalski Barrier Region, is capped by gently inclined Beacon Sandstones. In the direction of Graham Land the end of this horst, near Terre Louis Philippe, at Hope Bay, is distinctly

* Only small pieces of coal about 2 to 3 inches long (50·8–76·2 millimetres) by about ½ inch thick (12·7 millimetres) were secured by Shackleton's party from this seam. Shortage of food prevented them from taking more. This was the first coal ever discovered in Antarctica.

folded, the strata, as described by Dr. Nordenskjöld and Gunnar Andersson, dip steeply in various directions. On the north-west coast of the American Sector of Antarctica folded quartzite-like beds, discovered in a group of small islands S.S.W. of Cape Roquemaurel, dip at 30° to north-west. At Cape Kjellman, half-way between Cape Roquemaurel and Cape Gunnar, sedimentary beds dip vertically with a trend from south-west to north-east, that is, parallel to the coast, but on the whole the dip appears to be in a general south-easterly direction.

The folded strata of Hope Bay contain well-preserved plants of Jurassic Age, such as *Cladophlebis*, *Alethopteris*, *Pterophyllum*, *Araucarites*, &c. (the full list is given a little later on). There is, therefore, clear evidence that here the Jurassic rocks are strongly involved in the folding.

At Snow Hill Island, also on the American side of the Antarctic, to the S.S.W. of Joinville Island, Cretaceous and Tertiary rocks have been described by Nordenskjöld and Gunnar Andersson. These dip towards E. and E.S.E. at gentle angles.

So far as the South Polar and Ross Sea end of the great horst is concerned, it would seem then to be a region of block faulting rather than a region of folding. By far the heaviest downthrow is towards the east in this area. In fact all that portion of the Antarctic continent, lying to the east of Ross Sea, and through to Charcot Land, appears to have undergone heavy inthrows. The Ross Sea itself is evidently a large *senkungsfeld*. The recent discovery by Amundsen of a range, from 2000 to 4000 feet in height, trending north-easterly from a spot some 30 or 40 miles to the south-east of where he struck the mountains of the horst in 86° S. lat., suggests that this important *senkungsfeld* does not extend across the horst itself to Weddell Sea.

In the next place, as regards the tectonics of Antarctica, one has to bear in mind the important fact that although the rocks of the horst, from near the South Pole to Cape Adare, are not known to have been faulted since Jurassic time, they are connected with an active volcanic zone which probably extends along the whole length of the great horst, and joins the active volcanoes of the American Sector and of the adjacent islands. No undoubted volcanoes have been identified as yet in the horst south of Mount Discovery, 78° 22′ S., and Mount Morning, 78° 30′ S. The mountains known as Goorkha Craters, in lat. 78° 50′ S., on the west coast of the Great Ice Barrier, are not known with certainty to be volcanic. The volcanic zone is known to extend at all events from Mount Morning to near Cape Adare, a distance of 450 miles, and if the Balleny Islands are situated on the same zone, the chain extends for a further distance of about 220 miles, in all 670 miles. On the American side of the Antarctic the volcanic zone is known to extend from the Seal Islands to Bridgman Island, a distance of about 300 geographical miles. No trace of volcanic action was observed on the western side of the American end of the great horst on the recent expedition of the Pourquoi Pass.

One of the greatest difficulties in correlating the trend lines of the great horst with those of South America is due to the enormous bend in the lines forming the long loop eastwards, connecting up Tierra del Fuego with the Falkland Islands, South Georgia, the Sandwich group, the South Orkneys, and thence with the South Shetlands and Graham Land.* A deep, Drake Strait, of over 2000 fathoms, as far as at present known, separates Cape Horn from the South Shetlands. Even at the Ross region end of the great horst there is a difficulty in correlating the trend lines with those of Australia and New Zealand. Towards the south-east of the southern island of New Zealand the trend lines swing sharply round, after having been near meridional, towards the S.S.E., so as to clear Campbell Island, leaving it to their west. There can be no doubt that the profound fracture of the Kermadec Deep prolonged south-south-westerly from the Tongan group is interrupted in its south-south-westerly course near the north-east end of New Zealand, and, as shown by the bathymetrical contours, swings around eastwards so as to pass to the east of the Chatham Islands, but then trends once more at first southerly, then S.S.W. in the direction of Ross Sea. Scott Island, on the 180th meridian, is a volcanic island lying near where a prolongation of these trend lines would reach the east and west trend lines, marking no doubt heavy faults, which run through the Balleny Islands. A study of the map (Plate II.) of the Australasian, Antarctic, and South American trend lines certainly suggests that the great horst is connected with the New Zealand plateau rather than with the eastern coast of Tasmania and Australia. If this view is correct, proof of such former connection should be afforded by submarine ridges at intervals, and possibly by submerged volcanic cones, in the neighbourhood of the 170th meridian of E. longitude. At the same time, in the Ross region, the general trend of the horst is somewhat interfered with by powerful cross faults trending east and west. In connection with the northward prolongation of the great horst towards Tasmania, it is of course possible that a parallel structure trends northerly from the deep indent in the coast to the east of Dr. Mawson's winter quarters at Adélie Land. This trend would approximately follow the meridian of 150° E. It is hoped that further light will be thrown on these two important questions, viz. the trends of the submarine ridges, respectively between Tasmania and the Ross Sea region, and between New Zealand and the Ross Sea, by the sounding expedition about to be undertaken by the S.Y. *Aurora*. It will be of special interest for this expedition to examine the area where the Royal Company Islands are considered to exist.†

We may now pass on to the petrographical evidence.

* Suess is cautious in the matter of considering this a continuous loop. "Face of the Earth," Sollas, vol. iv. p. 495.

† Recently a very important submarine bank has been discovered by Captain J. K. Davis of Dr. Mawson's Antarctic ship *Aurora*, 250 miles south of Tasmania. See the Geographical Journal, May 1913.

2. *Petrographical Character of the Eruptive Rocks.*

Petrographically Dr. G. T. Prior concludes that the volcanic rocks of Victoria Land "belong undoubtedly to the Atlantic group," while the late Dr. E. Philippi of the Gauss Expedition held that the coast of South Victoria Land is really of Atlantic type. Dr. Otto Nordenskjöld, J. Gunnar Andersson, Dr. J. Charcot, E. Gourdon, and Arçtowski are confident that Andean petrographical types are represented on the east coast of Graham Land. Gourdon * concludes that in the area examined by the French Antarctic Expedition of 1903–5, under the command of Dr. Jean Charcot, the whole area is occupied almost entirely by eruptive rocks, amongst which granitoid types greatly predominate. The group of these granitoid rocks forms a very homogeneous petrographical series, ranging as it does from granites to gabbros. He states that the continuity of the series is particularly clear in regard to the granites and the quartz-bearing diorites. Their community of origin is further emphasized by the character of the homogeneous basic enclosures which both contain in abundance. Both in chemical composition as well as in mineralogical characters these rocks are distinguished by certain clear characteristics. From acid granites to basic gabbros the series is characterised by the abundance of lime-soda felspars showing idiomorphic outlines, and as a rule well zoned. In the most acid varieties of granite the plagioclases always predominate over the orthoclase, a natural result from the poverty of the magma in potash and its richness in lime. Charcot after emphasizing these points remarks that these granites approach the monzonites. He adds that the ferro-magnesian constituent most widely distributed is green hornblende, almost always accompanied by biotite, and sometimes associated with pyroxene.

Arçtowski,† in his observations on the rocks collected in Gerlache Strait by the *Belgica* Expedition, considers it probable that these rocks resemble those obtained by the French Expedition. Dr. Otto Nordenskjöld and J. Gunnar Andersson conclude that the chains of mountains along the western coast of Terre Louis Philippe are formed of the same series of granular eruptive rocks exhibiting the same characters. Gourdon considers that, from the mineralogical point of view, the eruptive rocks of this quarter of the Antarctic constitute a family having general resemblances to one another in all their types, ranging from acid to basic, from volcanic to hypabyssal and to plutonic. He considers, therefore, that the American side of the Antarctic contains practically a well-defined petrographical province. This, he holds, shows a community of origin with that of the Andes of South America; and it is also related, in his opinion, to the dioritic rocks of the Cordillera of North America, the Sierra

* Expédition Antarctique Française (1903–5). Dr. Jean Charcot. Géographic Physique, Glaciologie, Pétrographie, by E. Gourdon, pp. 204–208.

† H. Arçtowski, Géographic Physique de la région Antarctique visite par l'expédition de la *Belgica* (Bull. Soc. Belge de Geographic, No. 1, 1900), pp. 40–42.

Nevada of California, Yellowstone National Park, Vancouver, and even certain particular granites in Alaska. One meets with almost similar rocks in the Lesser Antilles. This is the largest petrographical province in the world. This similarity was first emphasized by Dr. O. Nordenskjöld. Nordenskjöld specially studied the acid types, which are more of the nature of plagioclase granites than orthoclase diorites, and he has no doubt that the soda in these rocks predominates over potash. He considers these rocks to bear a close resemblance to those of Tierra del Fuego and Patagonia.

M. Gourdon (*op. cit.*, pp. 206–7) states that he has compared the rocks of the Charcot Expedition of 1903–5 with those collected at Cape Horn by Dr. Hyades in 1883, and finds the closest resemblance between the two groups. Quartziferous diorites, showing uralisation phenomena, are equally characteristic of both areas, but the predominance of zoned plagioclase is the most striking characteristic possessed by both groups of rock in common. Gourdon states that the Antarctic rocks are clearly granular, showing no tendency to develop into microgranular types, nor in the direction of the ophitic structure found in types poor in quartz. The microlitic rocks, according to Gourdon, can be divided into two groups; the one comprising very much older rocks is probably very old, the other, on the contrary, is remarkably fresh, and is certainly of volcanic origin. Although no trace of any volcano was observed by the French Expedition of 1903–5, Gourdon has no doubt whatever that these volcanic rocks are of recent age. He emphasizes the fact that Deception Island still shows traces of activity in the form of fumaroles, hot springs, &c., and Bridgman Island, an intermittently active volcano, may of course be included here. He also recalls that on the north-east of Terre Louis Philippe there are evidences of modern volcanic activity in Paulet Island and Mount Lindenburg. Gourdon's last paragraph is so important that we may be permitted to quote it in full (*op. cit.*, p. 208):—

"Enfin la découverte, parmi les blocs errants de l'île Wandel, d'un microgranite alcalin à amphibole et pyroxène sodiques, pose une question nouvelle.

"Les caractéristiques chimiques et minéralogiques de cette roche sont, en effet, tout a fait opposées à celles des autres roches éruptives de la région; elle est presque totalement dépourvue de chaus et très riche en alcalis. Ne serait-elle pas l'indice de l'existence plus au sud d'une province pétrographique nouvelle et, dans le cas où elle serait indigène, ne constitue-t-elle qu'une exception dont il serait en tout cas intéressant, au point de vue théorique, de préciser la portée? C'est ce que je vais m'efforcer d'élucider au cours de l'expédition nouvelle qui va parter dans quelques mois."

Dr. Alfred Harker in his work, "The Natural History of Igneous Rocks" * (p. 91),

* Atlantic.	Pacific.
Alkali-felspars form a large proportion of the more acid and intermediate rocks, and occur in many rocks of low acidity.	Alkali-felspars not abundant except in the more acid rocks, and wanting in the basic; soda-lime-felspars abundant.

has summed up the characteristics of the Atlantic and Pacific provinces respectively.

Iddings in 1892 noticed the remarkable geographical distribution of rocks of the Atlantic and Pacific type, but considered the distinction of alkali and sub-alkali groups too indefinite to be made a basis of classification. In 1896 Harker emphasized the vast importance of these two great world provinces of eruptive rocks, their distribution corresponding to the Atlantic and Pacific types of coast-line, as defined by Suess.

Becke in 1903 adopted a similar grouping. In Harker's map, showing the limits of the upper part of the Pacific petrographical region for the Tertiary and Recent igneous rocks, he draws the line of demarcation just to the north of Australia, leaving Australia in the Atlantic province, and New Guinea in the Pacific; thence carries it midway obliquely through the southern island of New Zealand, so as to include the alkaline rocks of Dunedin in the Atlantic province. He makes the following statement in regard to Antarctica :—

"Farther south characteristic alkali rocks appear in South Victoria Land, and the scanty data make it probable that the greater part of the countries within the Antarctic Circle should be attached to the Atlantic region. It is likely, however, that a tract about South Georgia, to the south of South America, should be separated and included with the Pacific."

Reiter * on tectonic considerations proposes to include "the Antarctic coasts and islands from the Balleny Islands to the South Orkneys with the Pacific type, relegating the remainder to the Atlantic."

Dr. G. T. Prior † states, "these volcanic rocks of South Victoria Land belong undoubtedly to the Atlantic group, although they occur along the coast which has been described as distinctly of the Pacific type." To which he adds this footnote :—

"While these pages were in the press Band ii., Teil 1, 'Deutsche Sudpolar Expedition, 1901–3,' was published; in No. 2, 'Geologische Beschriebung des Gaussberg,' by E. Philippi, the author brings forward arguments in favour of the view that the coast of South Victoria Land is really of Atlantic type."

Atlantic.	Pacific.
Microperthitic and crytoperthitic intergrowths frequent.	Zonary banding of felspars frequent.
Felspathoid minerals often found (leucite, nepheline, sodalite, primary analcime; also melilite).	Felspathoid minerals not found.
Quartz confined to the more acid rocks.	Quartz not only in acid rocks, but also in many intermediate ones.
Pyroxenes and amphiboles often include soda-bearing kinds.	Pyroxenes represented by augite, diopside, and the rhombic group; amphiboles by common hornblende.
Mica and garnets of common occurrence.	Micas not common except in the more acid rock.

* Die Sudpolarfrage und ihre Bedeutung für die genetische Gliederung der Erdoberfläche (1886).

† National Antarctic Expedition, 1901–4, Geology, p. 140

As already stated, the rocks of the great horst of Antarctica have not up to the present shown evidence of any marked folds, but are rather of the plateau type, with large broken segments characteristic of the Atlantic variety of coast-line.

Dr. P. Marshall,* in an able address to the Australasian Association for the Advancement of Science at Brisbane in 1910, has pointed out that in his opinion too much stress has been laid on these so-called Atlantic and Pacific types of petrographical provinces. He notices the importance and continuity of the Tonga Kermadec Deep, and in his map makes it clear that in his opinion the ocean deep to the east of the Chatham Islands is prolonged in a south by west direction parallel to the Tongan Kermadec Deep down towards Ross Sea. He states (*op. cit.*, p. 448):—

"The New Zealand coasts are not determined by fault planes, but their main directions are at least as old as the Miocene period. The main period of mountain formation in New Zealand was in the late Jurassic, and was possibly contemporaneous with rock folding in New Caledonia, but preceded the movement in the New Hebrides." "Much of the New Zealand coast-line is of the Atlantic type." "The occurrence of alkaline rocks in mid-Pacific goes far to negative the idea that alkaline eruptives are associated with the occurrence of the Atlantic coast type." In reference to this last statement, we may point out that Dr. Harker (*op. cit.*, p. 98) has already commented on this point and sought to explain it. He states "the case of the Galapagos Group, however, is instructive. These islands, situated some 800 miles west of the Andes, nevertheless have volcanic rocks of distinctly Atlantic phases." Now Suess makes this group of volcanoes a critical point in his syntaxis of the American mountain chains, and notes that it presents "the same formation and association as occurs elsewhere in the Atlantic region." In another place he says, "Wolfe rightly places these islands among the group volcanoes as opposed to the serial volcanoes of the mainland, and emphasizes the petrological contrast between them and the volcanoes of Ecuador. Here we see how the tectonic type characteristic of the Atlantic is associated with rocks of what we have styled Atlantic phases, even when it appears exceptional within the Pacific territory."

Marshall emphasizes the fact that there are many exceptions besides the Galapagos to the rule of the Pacific rock types existing within the Pacific area. Trachytes † occur at the Auckland and Campbell Islands of the Sub-Antarctic, as well as at Dunedin. Trachytes, bostonites, and phonolites rich in nepheline occur near Dunedin.

Basanites occur at Auckland, where they are widely distributed. Kleinschmidt

* Ocean Contours and Earth Movements in the South-west Pacific, by Dr. P. Marshall, M.A., D.Sc., F.G.S., Professor of Geology, Otago University, New Zealand, Rept. Aus. Assoc. Adv. Science, Brisbane, 1910, pp. 447–448.

† The Sub-Antarctic Islands of New Zealand, Article XXIX. The Geology of Campbell Island and the Snares, Wellington, N.Z. Gov. Printer, 1909. In this paper Marshall describes porphyries with oligoclase surrounded by anorthoclase, trachytes allied to pantellarites, and phonolites.

and Wichmann * have respectively collected and described alkaline rocks, such as syenite and foyaite, from Fiji. Nephelinite occurs at Raiatea, phonolite lava and scoriæ at Raratonga, and typical nepheline basalt at Itutaki. Alkaline plutonic rocks, such as nepheline-syenite, are also stated by Marshall, on the authority of La Croix, to occur at Tahiti. Marshall states (*op. cit.*, p. 445) that the classification of coast-lines as Pacific and Atlantic in type is not yet accepted by many authorities. He makes the very fair comment that the argument for considering the east coast of New Zealand to be of Atlantic type is at least as strong as that for classing it as Pacific. He considers (*op. cit.*, p. 446) that it appears somewhat heroic to regard such isolated islands as Raratonga and Tahiti as fragments of a fractured and shattered continent. Obviously Marshall concludes that there is no conclusive evidence to justify the coast structure of New Zealand being classed as wholly Atlantic or wholly Pacific, and he does not consider Pacific and Atlantic types of rock a useful classification as applied to the petrology of New Zealand.

Dr. H. I. Jensen has argued † that alkaline rocks are chiefly developed in areas where there has been heavy crust foundering as the result of great faulting. He considers that these serious displacements of the earth's crust may bring about a fusion and extrusion of extremely ancient portions of the earth's crust containing in them an excess of alkali derived from the heated waters of primæval seas. Certainly the neighbourhood of the great horst is one of very vast tectonic disturbances of the nature of block faulting. Dr. Jensen states that as the result of his study of the sequence of Australian alkaline lavas he infers that "basic lavas may rise along fractures and intrude themselves into the alkaline zone" of the earth's crust. "Here they will assimilate alkali and also help to bring about an elevation of the whole alkaline zone." He states, in the petrology of the alkaline rocks of Mount Erebus in this Memoir, "In this paper therefore the origin of basic alkaline rocks is ascribed to stoping, assimilation, and solution of alkaline sedimentary and metamorphic rocks by basaltic magma from the zone of basic igneous rock which is supposed to underlie the whole of the earth's crust."

Mr. J. Allan Thomson, in his chapter in this Memoir on the inclusions of the volcanic rocks of the Ross Sea, shows that the kenytes of Ross Island contain not only inclusions of Beacon Sandstone floated up from a strongly down-faulted, deep-seated area, but also fragments of the quartz-dolerites of the sills, presumably of Cretaceous Age. He states that "all the other inclusions (in the lavas of Mount Erebus) are of igneous origin, and genetically connected with the alkaline rocks of Ross Island. Many of them are types not met with at the surface as separate rocks,

* A. Wichmann, "Ein Beitrag zur Petrographie des Viti Archipels," Tocher. Min. und Petrog. Mitth., v. (1883).

† Proc. Linn. Soc. N.S.W., vol. xxxiii. part 3, 1908, "On the Distribution, Origin, &c., of the Alkaline Rocks."

viz. peridotites, gabbros, pyroxenites, orthophyric trachytes, sanidinites, microtinites, camptonites, and an orbicular augite syenite." The occurrence of these inclusions, he says, " gives some idea of the deep-seated rocks whose formation has accompanied the eruption of the lavas."

Professor W. G. Woolnough has, in his description in this Memoir of the erratics of Cape Royds, discovered several old plutonic rocks distinctly alkaline in character, so that this region was evidently alkaline in comparatively early geological times, perhaps as far back as late Palæozoic.

W. N. Benson, B.Sc., in his detailed description in this Memoir of the quartz-dolerites of the Ross Region, has specially commented on the very close resemblance of these to similar rocks forming the great sills of Tasmania, those of the Karoo of Natal and Zululand in South Africa, of Venezuela, Northern Brazil, British Guiana, the palisades of the Hudson River, &c.

Dr. D. Mawson has given a petrological description in this Memoir of the chief types of intrusive rocks met with in our expedition in South Victoria Land. He has not attempted to touch on the question of whether or not they show Andean affinities. Analyses of the typical granites from Cape Irizar show the rock to be very low in lime and magnesia, and high in potash and soda, the former being in excess of the latter. The granite near Mount Larsen, while still very poor in magnesia, contains nearly 3 per cent. of lime and 7 per cent. of alkalies, the soda slightly in excess of the potash. The intrusive dyke rocks of quartz- and felspar-porphyry from near Mount Larsen are poor in lime and magnesia, and contain over 8 per cent. of alkalies, the potash being in excess of the soda. The same feature is noticeable in the aplitic granite porphyry of Cape Irizar, with the exception that in this case the soda is in excess of the potash. This chemical composition of the older granites, granite porphyries, and quartz- and felspar-porphyries, is widely different from that of the Pacific type, and is essentially an Atlantic type of rock. On the other hand, the kersantite lamprophyre from Cape Irizar contains nearly $6\frac{1}{2}$ per cent. of lime and about $5\frac{1}{2}$ per cent. of soda and potash in the aggregate ; the rock thus approaches a Pacific type. This rock shows a distinct relation to the sphene-bearing diorites ; the latter contain over 7 per cent. of lime, and about $5\frac{1}{2}$ per cent. of alkalies. Thus the rock is intermediate between Pacific and Atlantic types. In their frequent large homogeneous inclusions of basic rocks, the gneissic granites, like those of Depot Island, resemble the granodiorites of the Andes. In the presence of micropegmatite and nearly uniaxial enstatite-augites the granophyric quartz-dolerite sills of South Victoria Land show a great resemblance to the Konga type of diabase so well known in Sweden.

As already stated, the quartz-dolerites of South Victoria Land, with their interstitial granophyric patches, are petrologically so extremely like the dolerite sills of Tasmania, that it is highly probable that the intrusions in these two widely separated countries were synchronous.

In conclusion, it may be said that in its kersantites, sphene-bearing diorites, and granophyric quartz-dolerites with rhombic pyroxenes, the rocks of the Ross Sea region bear some resemblance to the Andean types, but the whole of the granites, the granite porphyries, the quartz- and felspar-porphyries, as well as the old Tertiary and Post-Tertiary alkaline lavas containing anorthoclase, leucite, nepheline, &c., the typical kenyte, with associated trachytes, phonolites, sanidinite, leucitophyre, trachy-dolerite, tephrite, &c., are distinctly alkaline, and not therefore Andean. Dr. Jensen considers that the basalts without olivine, the olivine basalts, the limburgites, magma basalts and magnetic basalts of Ross Island, are all to be regarded as extremes of basic differentiation of a magma of the composition of intermediate kenyte. Such kenytes, constituting by far the greater proportion of the eruptive masses of Ross Island and South Victoria Land, are distinctly of Atlantic type.

We, therefore, quite agree with Dr. Philippi and Dr. Prior in regarding the type of eruptive rock represented in the western mountains of the Ross Sea region as essentially Atlantic.

In reference to the rocks so far recorded from King Edward VII. Land the case appears different. A specimen of granite collected and presented by Lieutenant Shiraze from this region is rich in biotite and plagioclase. Roald Amundsen records * that Lieutenant Prestrud of his expedition obtained from this region at Scott Nunatak specimens of white granite, micaceous granite, granodiorite, quartz-diorite, diorite and quartz-diorite schists. The diorite rocks appear to resemble, petrologically, the Pacific type.

In discussing the general relations of Antarctic to other parts of the world, after giving a short sketch of recent observations, we naturally turn to the master of earth tectonics, Suess.

In his chapter dealing with the oceanides and their relations to the south,† Suess makes the following important statement in regard to South Victoria Land :—

"These characters, notwithstanding the number of recent volcanoes, do not indicate a Pacific structure. The horizontal position of the sandstones, the wide distribution of gneiss and granite, and all the contours show that this plateau belongs to the Atlantic type. As regards South Victoria Land, we must agree that the coast is broken off. It recalls the fractures of East Africa rather than a Pacific arc, and this comparison is in complete accordance with the conclusions of Prior based on the nature of the rocks. Whether or not King Edward VII. Land, which is situated farther east (lat. 76°–78° S., long. 100°–150° W.), and has furnished loose fragments of ancient rocks, must be referred to the same type, can hardly be determined at present. It is certain that the regions lying still farther east, such as Graham Land, possess a different structure."

* The South Pole, vol. ii. p. 396.

† "Face of the Earth" (Das Antlitz der Erde), by Eduard Suess, translated by Hertha B. C. Sollas under the direction of W. J. Sollas, vol. iv. pp. 293–294.

Recently Professor Gregory * has made some very important suggestions in regard to a re-classification of coast types. He states ("Scientia," *op. cit.*, p. 7), "I proposed in 1908 to subdivide the Pacific type into two varieties—the primary Pacific type along the outer edge of the fold mountain chains, and the secondary Pacific or sub-Pacific type, where the coast is less directly connected with the border chains of the Pacific, but is due to subsidences within the mountain chains."

He next states (p. 48): "Primary Pacific coasts are determined by the proximity of long lines of fold mountains, to the trend of which the coast is in general parallel. The mountains bounding them are of comparatively young geological age. Overthrusts and overfolds, if present, are mostly directed towards the ocean.

"Secondary Pacific or sub-Pacific coasts are due to the subsidence of basins on the inner side of mountain chains along coasts of the primary Pacific type.

"They are frequently bordered by active or recent volcanoes. The oldest rocks usually occur along the coast, and are followed by younger rocks farther inland; except where horsts project into the sea, the coast-line is approximately parallel to the grain of the adjacent country."

Gregory states further (p. 52): "Professor Suess, however, in his last volume,† remarks that the coast of South Victoria Land recalls the fractures of East Africa rather than a Pacific arc. The points on which he lays stress are the horizontal position of the sandstones, the wide distribution of gneiss and granite, and the contours. I fail, however, to see any particular resemblance between this coast and that of the fractured area of Eastern Africa. There the land is a high plateau, composed mainly of Archæan rocks; it was flanked at intervals along the coast by marine Mesozoics; its volcanoes are inland upon the plateau, and not at its foot; and there are no representatives along the coast of the lower Palæozoic slates of Cape Adare or of the Archæocyathus limestone of the Beardmore Glacier. The coast of South Victoria Land seems to agree both in the character of its rocks and their arrangement with Eastern Australia, and should accordingly be assigned to the secondary Pacific type."

On page 54 he concludes: "The information now available shows that South Victoria Land is more similar in structure to Eastern Australia than to New Zealand. Hence it appears most probable that the continuation of New Zealand and of the primary Pacific coast lies through King Edward VII. Land towards Graham Land. Hence I should be disposed to classify the coasts of Antarctica as shown on Fig. 8, South Victoria Land being of the secondary Pacific type, the line from King Edward VII. Land to Graham Land of the primary Pacific character, and the remaining coasts of the Atlantic type."

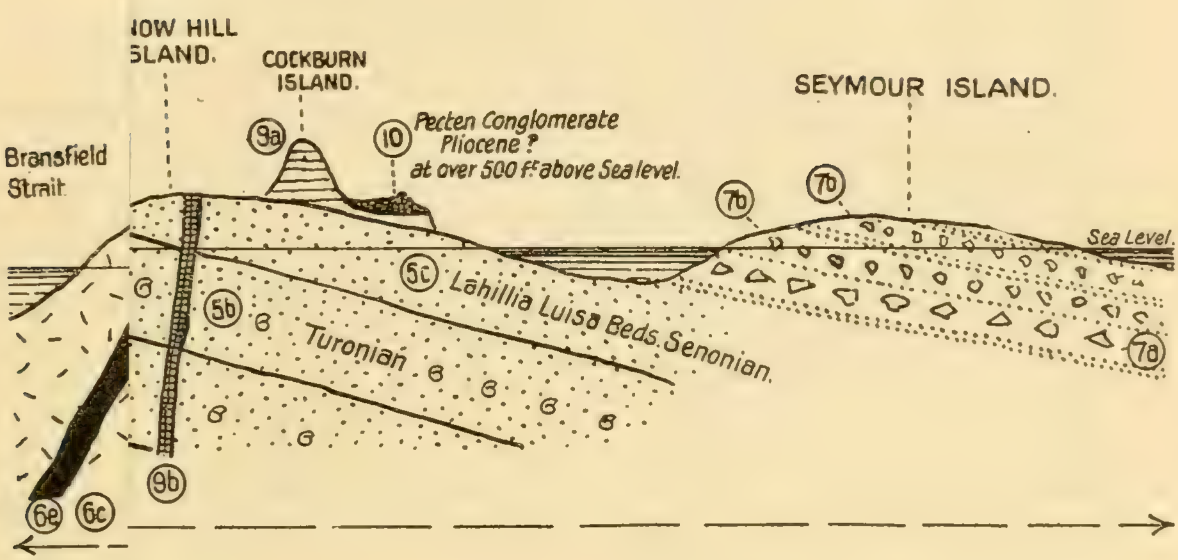
* Structural Geography, 1898, p. 61, § vii.

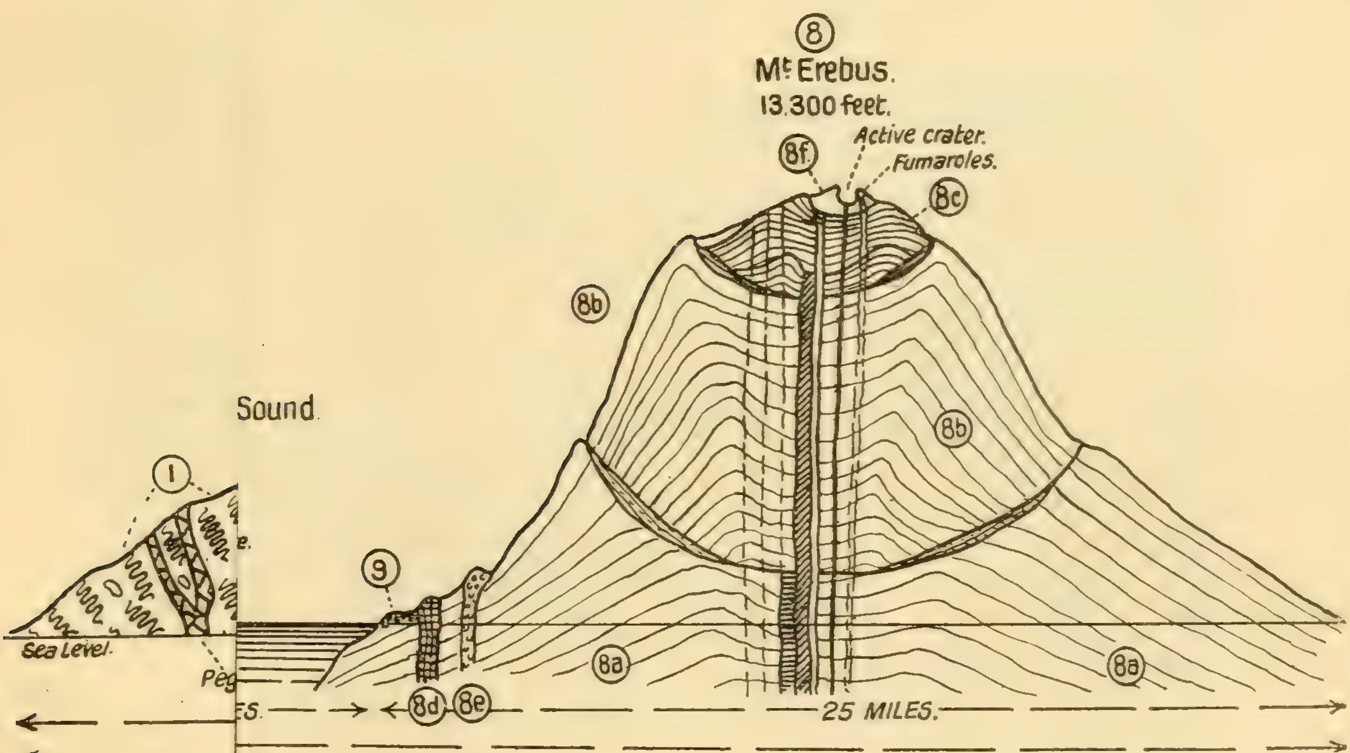
Scientia, vol. xi., sixth year (1912), xxi. pp. 36–63. "The Structural and Petrographic Classifications of Coast Types." J. W. Gregory.

† "The Face of the Earth," vol. iv. pp. 293–294.

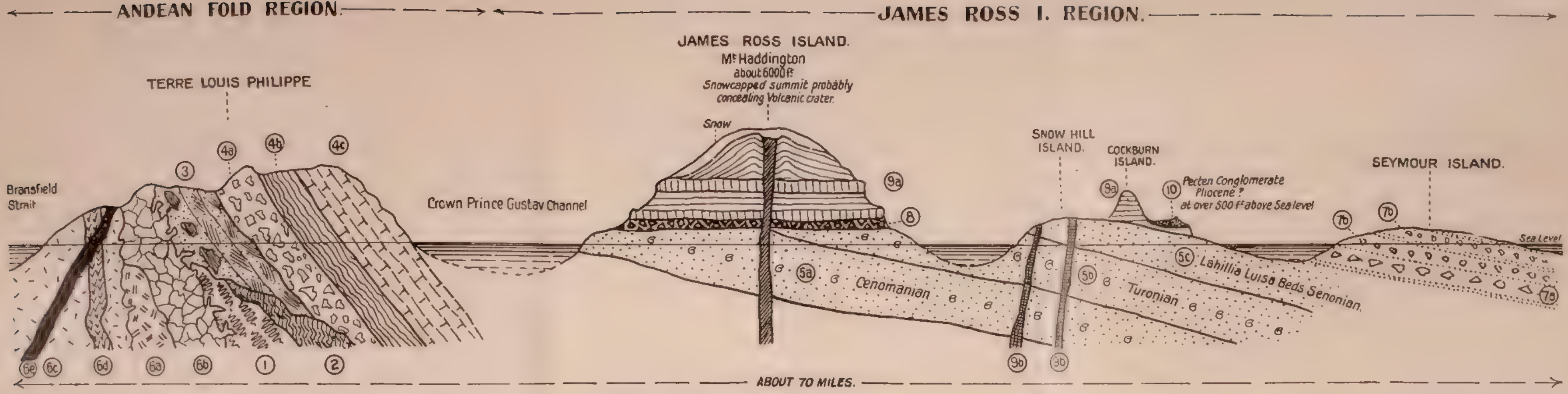
PLATE XCII

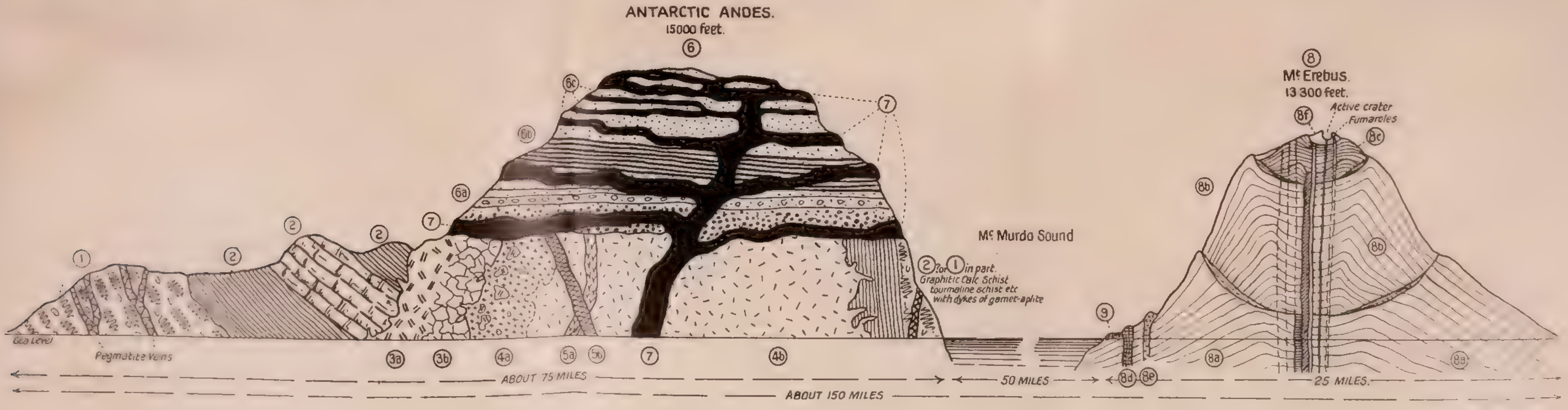
. REGION.





[To face p. 310


ANDEAN FOLD REGION
JAMES ROSS I. REGION.
JAMES ROSS ISLAND.
Mt Haddington
about 6000 ft
Snowcapped summit probably concealing Volcanic crater.
Snow
TERRE LOUIS PHILIPPE
Bransfield Strait
Crown Prince Gustav Channel
SNOW HILL ISLAND.
COCKBURN ISLAND.
Pecten Conglomerate Pliocene ? at over 500 ft above Sea level
SEYMOUR ISLAND.
Sea Level
Cenomanian
Turonian
Lahillia Luisa Beds Senonian.
3
4a
4b
4c
9a
8
10
7b
7a
5a
5b
5c
6e
6c
6d
6a
6b
1
2
9b
3b
ABOUT 70 MILES.


ANTARCTIC ANDES.
15000 feet.
6
6c
6b
6a
7
Mt Erebus.
13 300 feet.
8
8f
Active crater
Fumaroles
8c
8b
Mc Murdo Sound
2 or 1 in part.
Graphitic Calc Schist tourmaline schist etc with dykes of garnet-aplite
9
1
2
Sea Level
Pegmatite Veins
3a
3b
4a
5a
5b
7
4b
8a
8d
8e
ABOUT 75 MILES
50 MILES
25 MILES.
ABOUT 150 MILES

In Fig. 8, above, Professor Gregory produces a sketch map of Antarctica, which is in opposition to that published by Dr. Douglas Mawson,* and that given by Dr. W. S. Bruce.

In the same paper Gregory contends that the Atlantic and Pacific cannot be regarded as distinct petrographical provinces excepting in a broad, loose way, the exceptions being almost as numerous as the rule.

3. *Palæontological Evidence afforded by the Fossil Fauna and Flora.*

As regards the fossils obtained so far from the Antarctic regions, by far the most important remains which have been discovered, or at all events the most complete, are the plants. A fine collection of these were secured at Hope Bay, on Terre Louis Philippe, by Dr. J. Gunnar Andersson and other members of Dr. Otto Nordenskjöld's Expedition. A valuable series of fossils has also been obtained, first by Captain Larsen of the *Jason*, and later by Dr. Nordenskjöld and his staff at Snow Hill Island. At the latter locality there is an abundant Cretaceous marine fauna followed on higher horizons by plant beds of perhaps Miocene age. These in turn are succeeded by late Tertiary marine beds, which can be correlated with similar strata in Tierra del Fuego and Patagonia. Plate XCII. Fig. 1 is a diagrammatic section across the American end of the Antarctic continent, showing the approximate relation of these fossiliferous beds to one another, and their approximate sequence in connection with the eruptive series.

The information is taken chiefly from the memoirs of Dr. J. Gunnar Andersson, as well as from those of J. Charcot, E. Gourdon, and Dr. W. S. Bruce.

As the palæontological record is so far very much more complete on the American side of the Antarctic than in the Ross Sea region, we may briefly review the evidence in the former quarter, and then pass on to consider the probable palæontological relations of the rocks of the Ross region.

Suess has shown that a strong trend line nearly concentric with the lines which pass through Southern Patagonia, Tierra del Fuego, and Staten Island runs through the Falkland Islands. This has a general W.N.W. to E.S.E. trend. At the Falkland Islands there is an extensive development of marine Devonian sandstone resting on older granitic rocks; this in turn is succeeded by a Permo-Carboniferous formation which is developed, as described by J. Gunnar Andersson, in both islands, and particularly in a small island known as Speedwell Island. Halle has described *Glossopteris* from the latter locality. Drift fragments of kerosene shale, as we are informed by the Governor of the Falkland Islands, have been obtained, transported from inland, on the banks of rivers. These have been proved

* Geogr. Journ., vol. xxxvii., June 1911, p. 612, "The Australasian Antarctic Expedition," by D. Mawson, D.Sc. In his map D. Mawson shows the mountains of the Antarctica of South Victoria Land continuous with the ranges of "Westantarctis," and not divided by Professor Gregory's "Hypothetical Antarctic Rift Valley," extending from Ross Sea to Weddell Sea.

by Mr. F. Chapman, of the National Museum, Melbourne, to contain *Reinschia australis*. Further, glacial beds have lately been found near the *Glossopteris*-bearing strata.

This shows these strata to be obviously of Permo-Carboniferous age. In South Georgia, which appears to rise from the submarine ridge along the E.S.E. trends from the Falkland Islands and from Staten Island,* the rocks are formed chiefly of old schists, from which hitherto no determinable fossils have been obtained. The Sandwich group of islands, which lie at the eastern bend of the loop where it has curved first southwards, then south-westwards, trending in the direction of the South Orkneys, are geologically almost unknown. They are considered to be partly volcanic. Bellinghausen in 1819 witnessed an eruption of Sawadowski, the most northerly of these islands.† In the South Orkneys Dr. W. S. Bruce has discovered Ordovician fossils, graptolites, and phyllocarids at Laurie Island. These Ordovician fossils occur in dark sills. Recently Dr. W. T. Gordon has discovered well-preserved *Archæocyathinæ* in a lump of limestone dredged by Dr. W. S. Bruce to the south-east of the South Orkneys. This large block was obtained from a depth of 1775 fathoms in lat. 62° 10′ S., long. 41° 20′ W.

The trend lines from the South Orkneys are directed towards the South Shetlands, but from the latter group no fossils have yet been recorded. At Dundee Island loose fragments of red jasper, determined by J. J. H. Teall to be of radiolarian origin, were obtained in 1893 by Captain Robertson. ‡

We now reach the mainland of Terre Louis Philippe. At Hope Bay a rich Jurassic flora has been collected.

J. Gunnar Andersson § enumerates the following fossils as identified by Professor Nathorst: ||—

Species of the *Equisetaceæ* closely related to *Equisetum* (*Equisetites*)—

Columnare, Brongn.

Sagenopteris, closely related to, or possibly identical with, *S. Phillipsi*, Brongn.

Cladophebis, the type *C. denticulata-nebbensis-whitbyensis* is represented by several species.

Todites Williamsoni, Brongn. (sp.).

Scleropteris.

Stachypteris.

* Suess, however, does not consider that South Georgia lies in a continuation of Burdwood Bank to the east of Staten Island.

† Quoted by Suess, vol. iv. p. 488.

‡ Proc. Roy. Soc., Edinburgh, vol. xxii., 1898, pp. 66–70, "Notes on some Specimens of Rocks from the Antarctic Regions." By A. Geikie.

§ Bull. Geol. Instit. of Upsala, vol. vii. pp. 26–27, "On the Geology of Graham Land." By J. Gunnar Andersson.

|| Comptes Rendus, June 6, 1904, "Sur la flore fossile des régions antarctiques."

Thinnfeldia indica, Feistm. (*Salicifolia*, Oldh., sp.).
Pachypteris.
Sphenopteris hymenophylloides.
Sphenopteris Williamsoni.
Otozamites, several species, allied to those of the Upper Gondwana of India.
Williamsonia pecten, Phill. (sp.).
Nilssonia (?), or *Oleandridium* (?).
Pterophyllum Morrisianum, Oldh., of India.
Araucarites cutchensis, Feistm.

Also conifers allied to—
Taxites tenerrimus, Feistm.
Cheirolepis gracilis, Feistm.
Brachyphyllum mammillare, Feistm. (*non* Lindley).
Palissya.
Elatides.

Mr. W. S. Dun, Palæontologist to the Geological Survey, New South Wales, and Sydney University Lecturer in Palæontology, has kindly supplied us with the following list showing the distribution of the chief genera of this Antarctic flora in Jurassic time: *—

	Antarctica.	S. Africa.	India.	Argentine.	Australia.
Sagenopteris . .	×	—	×	—	×
Thinnfeldia . .	×	×	×	×	×
Cladophlebis . .	×	×	×	—	×
Pterophyllum . .	×	—	×	×	×
Otozamites . .	×	—	×	—	×

The close affinity of the flora to that of Australia and of India, shown on this list, implies a land connection between Antarctica and Australia in Jurassic or Trias-Jura time.

At Snow Hill Island abundance of Cretaceous fossils, including numerous Ammonites, were collected by Dr. Nordenskjöld's Expedition. These fossils imply the existence of a mild climate, with comparative warm ocean currents in the neighbourhood of Snow Hill Island in Cretaceous time. The fossil plants Araucaria, Fagus, &c., near to *A. braziliensis*, unearthed by the Nordenskjöld Expedition at Seymour Island, adjoining Snow Hill Island on the north-east, prove that these mild weather conditions were further prolonged into some part of Tertiary time, probably Oligocene or Lower Miocene. In marine strata, also of Tertiary age, and considered by Wilckens † to belong to Upper Oligocene or Lower Miocene, this

* Further details may be gained from Dr. White's able Memoir on the Santa Caterina Permo-Carboniferous and other rocks of Southern Brazil, as well as from Memoirs on the Argentine Republic.

† Die Meresablagerungen der Kreide- und Tertiarablagerungen in Patagonien. Neues Jahrb. f. Min., Beilage, Bd. xxi., 1905.

expedition found numerous bird bones, since referred to five new genera of penguins,* besides two vertebræ of a big mammal referred to the genus Zeuglodon. It is very interesting to note that remains of a large penguin have been obtained in New Zealand in the Oamaru beds, which are considered to be of Eocene age.

At Cockburn Island, to the north of Seymour Island, Andersson describes a pecten conglomerate 160 metres above sea-level. He considers this to be probably of Pliocene age, and the equivalent of the Paraná beds to the north of the Argentine Republic, or of the Cape Fairweather beds of Southern Patagonia. The stratigraphical sequence from the Pliocene to the present in the Graham Land region is admirably summarised by Andersson.† This concise summary is so important for the purpose of the question now being discussed, that we transcribe it here in full :—

Development of Southernmost S. American and Graham Land.

Epochs.	S. America, mostly after Wilckens.	Graham Land.	Facies of Oscillations.
Quaternary	Raised beaches. Magellan Clay. Maximum glaciation.	Raised beaches. Clay with *Thracia meridionalis.* Maximum of glaciation.	Regression. Transgression. Regression.
Pliocene	Formation of lakes and channels. East of the cordillera. Paraná-formation.	Formation of eastern channels. Pecten-conglomerate.	Transgression.
Upper and Middle Miocene	Basalt beds and craters. Santa Cruz beds.	Basalt-tuff formation.	Regression.
Lower Miocene	Patagonian molasse.	Younger Seymour Island beds.	Transgression.
Oligocene and Eocene	Pyrotherium-Notostylops beds. Mountain-folding.	Hiatus. Mountain-folding.	Regression.
Senonian	San Jorge series.	Older Seymour Island beds. Snow Hill beds.	Transgression.

It is of special interest to note that Andersson considers that the mountain-folding takes place in the Graham Land regions after the close of the Senonian and in Pre-Eocene or early Eocene time. It is also a matter of great interest to note that the Cretaceous rocks lie on the eastern side of Graham Land. If, therefore, Graham Land, as seems now very probable, represents the extension from the Devil's Glacier, south-east of the great horst of the Ross region, the newer rocks of Andean type lie on the western side of the horst in the American Sector, and might be expected to occur in the Australian Sector somewhere to the east of the horst either faulted down in Ross Sea, or lying to the east of King Edward VII. Land. In the North and South Islands of New Zealand, the Cretaceous and Jurassic rocks of that Dominion, also more or less of the nature of a horst, lie on the east side, and are folded.‡ It would be a matter of great interest to decide, if the fold is

* *Anthropornis Nordenskjöldi, Pachyteryx grandis, Eospheniscus Gunnari, Delphinornis Larsenii,* and *Ichthyopteryx gracilis.*

† Bull. Geol. Institut. Upsala, vol. vii., 1906, "On the Geology of Graham Land," p. 70.

‡ Obviously the west side of the horst in the Western Hemisphere becomes the eastern side in the Eastern Hemisphere. (See Plate C. of this chapter.)

asymmetrical, from what direction the thrust has proceeded. As far as can be judged from Andersson's sketch section (*op. cit.*, p. 25), the folding force at Hope Bay has come from a general north-west direction.

We can now pass on to the Palæontological evidence of the Ross area. The oldest rocks which have so far yielded fossils in that area are the *Archæocyathinæ* limestones of Cambrian age, found as fragments in an extensive limestone breccia at the foot of the great granite monoliths of Lower Glacier Depot near the mouth of the Beardmore Glacier. These limestones are considered by Mr. C. S. Wright of the late Captain R. F. Scott's Expedition to be probably *in situ* near Mount Adams, on the Beardmore Glacier, and in the opinion of Professor Skeats, also at Buckley Island, on the same glacier. These have been described by Mr. T. Griffith Taylor early in the Memoir. Taylor draws attention specially to the geographical position of the *Archæocyathinæ* horizon, stating that hitherto the occurrence nearest the Poles of these fossils had been that of Waigatch Island, to the north of Russia in lat. 70° N. Adopting Professor Skeats' determinations of the limestone at Buckley Island as containing *Archæocyathinæ*, they would have ranged in Cambrian time in the Antarctic from at least 83½° to about 86° S. In this summary Taylor concludes that of the five families of the *Archæocythinæ* alliance (*vide* p. 105 of his Memoir), two are certainly represented in the Antarctic, viz. the *Archæocyathinæ* and the *Spirocyathidæ.* He considers that *Archæocathus* and *Protopharætra* are certainly represented, and show close affinities with the South Australian forms.

Associated with these fragments of the *Archæocyathinæ* is the abundant dendritic organism which Mr. F. Chapman classes with the supposed calcareous plant *Solenopora.**

No fossils were obtained by the Shackleton Expedition on any higher horizon until that of the Beacon Sandstone is reached. Here only one determinable fossil was found, and even that in a somewhat imperfect state of preservation. As determined by Professor Goddard it proves to be a true wood, showing medullary rays. Professor Lawson of Sydney University is of opinion that the wood may possibly be angiospermous, but this is doubtful. The formation having been extensively intruded by the diabase sills may be considered to be Pre-Upper-Cretaceous, if the sills there, as in Tasmania, are Post-Jurassic to Upper Eocene. At present we provisionally class the Beacon Sandstone as Gondwana.

While admitting that some of the sandstones below the coal-measures may be older than Gondwana, and some of the highest sandstones possibly newer than Gondwana, the fossil plants recently collected by the late Captain R. F. Scott and Dr. E. A. Wilson, from the top of where Shackleton and Wild discovered the coal-measures at the head of the Beardmore Glacier, and those obtained by one of us (R. E. Priestley) from the Priestley Glacier, as well as the fossil fish plates found by

* A very important and interesting paper on *Solenopora* and allied fossil algæ, chiefly from the Carboniferous, has recently been published by Professor Garwood.

Messrs. Taylor and Debenham from the Beacon Sandstone of the Mackay Glacier, inland from Granite Harbour in South Victoria Land, will no doubt fix the geological horizon more precisely. This great plateau coal-measure formation has, tectonically at all events, no representative in New Zealand, but is extensively developed in Tasmania, and on the Australian continent. The horizon, however, is represented in New Zealand, but the rocks there instead of lying in broad flat strips, as they do in the great horst of South Victoria Land, are very steeply inclined, folded, and much altered by metamorphic agencies. So far then as relates to structure, South Victoria Land is, in regard to its coal-bearing sandstone formation, closely related to Tasmania and South-eastern Australia.

No fossils have been found as yet in the Ross region above the horizon of Beacon Sandstone until the raised beaches are reached. A possible exception to this rule occurs in the case of some soft fragments of a rock which has the appearance of a glauconitic sandstone found in the moraines of the Nansen-Drygalski Piedmont. These contain traces of radiolarian shells, but the latter are too imperfect to admit of a chronological sequence being based upon their evidence.

SUMMARY

We may now attempt to sum up the evidence in regard to the question as to whether the great horst of the Ross region is, or is not, part of the tectonic unit of the South American Andes.

At the outset the question presents itself, what are the essential characteristics upon which one may depend for determining the unity and continuity of any particular mountain chain? For example, is one to rely mostly on a continuation of the trend lines, on the similarity of tectonic structure, on the similarity of date of formation of the range, on that of the sedimentary rocks composing the range, on that of the eruptive rocks, or on that of the physiography of the range? There can be no doubt that all these factors help to determine the question as to whether a mountain mass in one part of the world may be considered to be referable to the same unit as that of another mass at some more or less remote distance.

We have seen that, tested by its petrological characteristics, the horst of South Victoria Land shows more points of divergence than of resemblance when compared with the South American Andes, and even with the Antarctic Andes of the American Sector. In its general absence of folding, as far as at present examined, the Antarctic Horst does not resemble the South American Andes or the Antarctic Andes of West Antarctica. At the same time it must be admitted that in West Antarctica the folds, as described by J. Gunnar Andersson, appears to be mostly of the nature of gentle anticlines and synclines.

In reference to similarity of sedimentary rocks, we miss in South Victoria Land the considerable development of Cretaceous and Tertiary rocks met with in James

Ross Island, Snow Hill Island, Seymour Island, &c.; but the fact must not be overlooked here that the above-mentioned localities occupy a comparatively small superficial area, and that if the Antarctic Horst is a continuation of the Graham Land Antarctic Andes, and if these Cretaceous rocks are developed on its western side, that is, on the side of the horst nearest to Africa, they would be faulted out of sight, in South Victoria Land, under the thick covering of the inland ice on the west side of the great horst. It is possible that some outcrop of them might occur along the coast-line recently discovered by Lieutenant Pennell in the *Terra Nova* of the British Antarctic Expedition of 1910–12.*

If now we examine the points of resemblance between the horst of South Victoria Land and the Andes of West Antarctica, the following features at once enforce themselves on our attention :—In the plan of the earth, as a result of the tendency of the earth's crust to contract in two directions, more or less at right angles to one another, the dominant type of fold and fracture is S shaped. An S-shaped fold of this kind on a grand scale is formed by the Carpathians, Alps, Apennines, Tunisian, and Atlas Mountains, with the trend lines which cross the Straits of Gibraltar, and terminate in the Betic Cordillera. Again in the Burmese arcs, in relation to the great folds of the Himalayas, those of the Salt Range, the Suliman Mountains, and the ranges of Beluchistan, Iran, and the Zagros Hills, we have another example of gigantic tectonic features built on an S-shaped plan.

As pointed out by one of the authors † in a recent paper, the main trend lines of Australia are distinctly S shaped. The same structure is to be seen in Central America and South America, and from Patagonia and Tierra del Fuego one sees possible evidence of an immense loop swinging far to the east from near Cape Horn towards South Georgia, and perhaps even the Sandwich Group, returning westwards through the South Orkneys to Graham Land.‡

As regards Graham Land, all the great authorities on the structure of that region —tectonic, petrographical, and palæontological—are agreed that the rocks of that plateau, which constitutes Terre Louis Philippe, Palmer Land, Danco Land, Graham Land, Terre Loubet Bay, Terre Fallières, and King Oscar II. Land, show that it is undoubtedly part of the same unit as the South American Andes. These Antarctic Andes of West Antarctica show evidence of very heavy downthrow faults towards the north-west, in the direction of Bransfield Strait, Gerlache Channel, and the archipelago recently discovered and described by Dr. Charcot's Expedition to the north and south of Baie Marguerite including Terre Charcot. There can be little doubt that the South Shetlands, the Palmer Archipelago, the Biscoe Islands, together with

* Mr. C. T. Madigan, of Dr. Mawson's Australasian Antarctic Expedition, has lately discovered sandstones and coaly shales about 250 miles east of Dr. Mawson's headquarters in Adélie Land. These rocks are probably to be referred to the Beacon Sandstone.

† Jour. and Proc. Roy. Soc. N.S.W., vol. xlv. pp. 1–60, Presidential Address by T. W. E. David.

‡ Suess cautions us against necessarily considering this to be a continuous loop.

Alexander I. Land, Charcot Land, &c., represent the structure which Suess terms a "panzer-horst." Along the north-western lines of fracture lie the partly active or dormant volcanoes of Bridgman Island and Deception Island. On the other side, that is, on the south-east side of West Antarctica, is another series of powerful fractures that separate the mainland along Crown Prince Gustaf Channel from the James Ross, Snow Hill, Seymour, Vega I. Islands, and the Hope Bay region. J. Gunnar Andersson has already suggested the existence here of powerful faults having a downthrow towards the south-east. Along this line of fractures, where seen, there have been extensive outflows of basaltic lava, and there is evidence of definite points of eruption here, such as Paulet Island, Mount Haddington, and Mount Christensen in Robertson Island. We thus see that West Antarctica is in effect a horst flanked by a volcanic zone on either side, with evidence of the heaviest fracturing on the side which faces the Pacific Ocean.

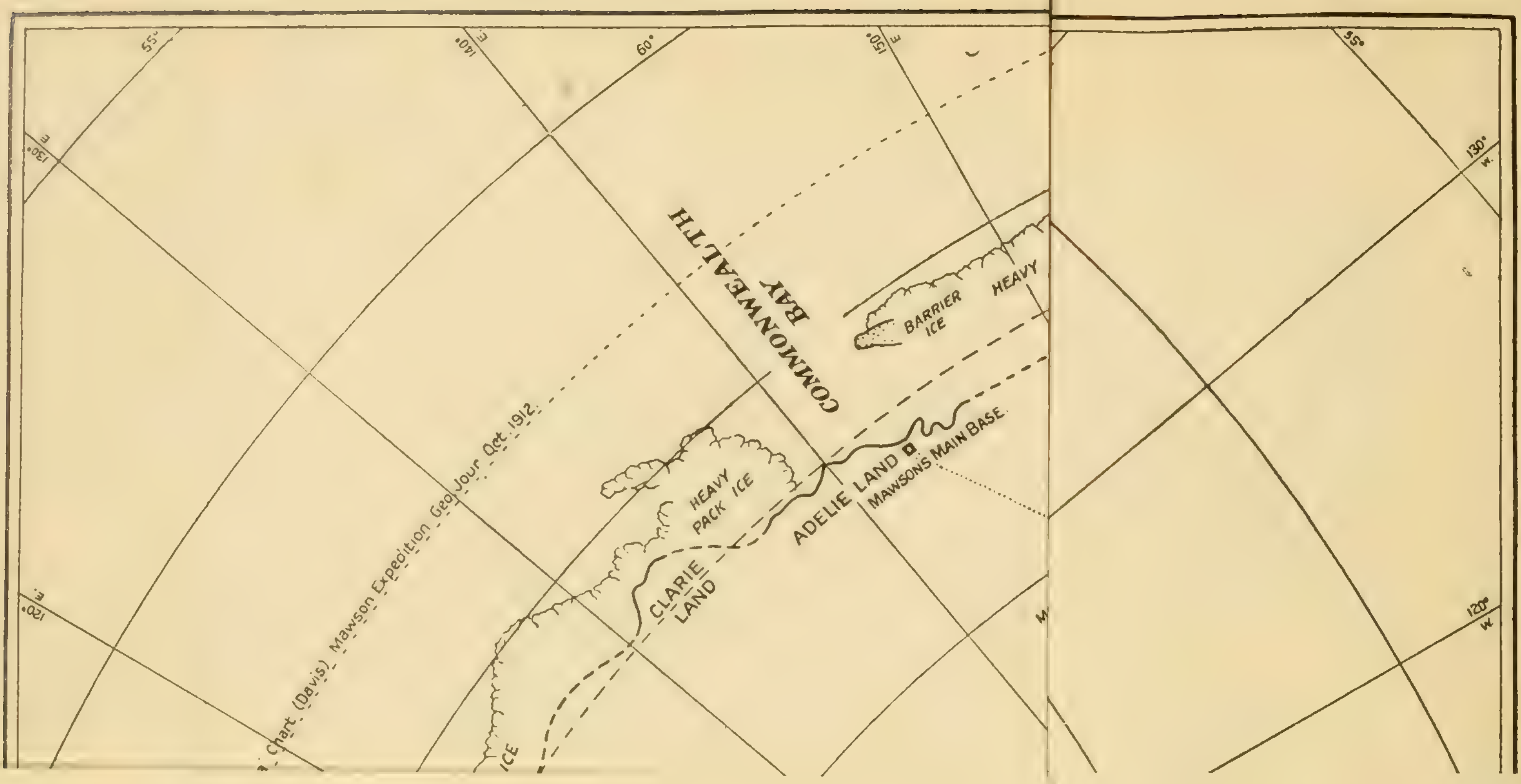
As regards the probable trend of these Antarctic Andes southwards from Graham Land, if we may judge from experience of trend lines in other parts of the world, we should expect that, after describing the big loop between Weddell Sea and the Falkland Islands, the trends would return to approximately their former bearing, which is nearly meridional. This direction would carry them right into the high ranges recently traversed by Captain Amundsen. If we study the structure of the great horst from near the South Pole up to South Victoria Land we see that tectonically it much resembles in its broad features the Antarctic Andes of West Antarctica. The heaviest fracture, amounting in this case to 6000, probably 8000, feet lies on the side nearest to the Pacific. This too is a zone of active or extinct volcanoes, such as Mount Morning, Mount Discovery, Mount Erebus, Mount Terra Nova, Mounts Terror, Bird, Melbourne, Cape Jones, and probably several of the high peaks, such as Mount Herschell, &c., in the Admiralty Range.

The continuity of the horst is somewhat interrupted in South Victoria Land by cross faults running approximately east and west, so that it is somewhat uncertain as to whether the Balleny Islands lie on the west or on the east side, respectively, of the horst. The appearance of mountains of very black rock, such as Mount Mackintosh, seen by the Magnetic Pole Party of the Shackleton Expedition on the western side of the horst, suggests that there is probably a volcanic zone in this region corresponding with that of the Paulet and Mount Haddington belt. A study of the bathymetric chart shows that it is very possible that the Tongan Deep, which traced southerly bends eastwards to avoid the New Zealand-Chatham Islands plateau, still farther south trends in the direction of Ross Sea. It seems equally probable that Tasman Sea describes a deep loop southwards towards the Macquarie Islands, and is still farther prolonged southerly by the deep indent in the Antarctic coast between Cape North and Adélie Land.

If the correlation of these broad tectonic features is correct, New Zealand obviously forms a prolongation equatorwards of the horst of South Victoria Land. It will be


Antarctic Circle
SCOTT I
BALLENY IS
COMMONWEALTH BAY
KING GEORGE V LAND
C North
C Adare
ADELIE LAND
CLARIE LAND
SOUTH MAGNETIC POLE AREA
VICTORIA LAND
ROSS SEA
ROSS ISLAND
PROBABLY DENSE PACK ICE
KING EDWARD VII LAND
ROSS ICE BARRIER
BEARDMORE GLACIER
KING HAAKON VII PLATEAU
SOUTH POLE
10250 ft
KAISER WILHELM II LAND
PLATEAU
ANTARCTIC
WEDDELL SEA
ALEXANDER I LAND
ADELAIDE
BELLINGHAUSEN SEA
Antarctic Circle

PLATE XCIII

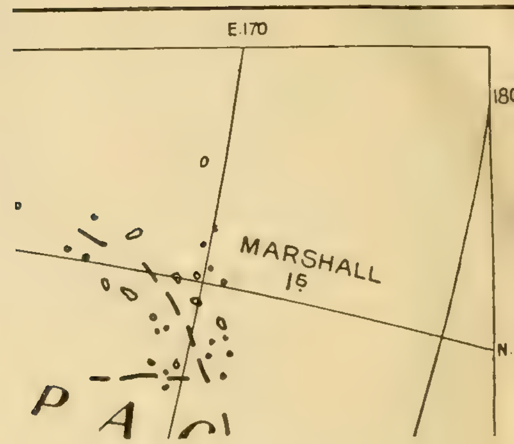


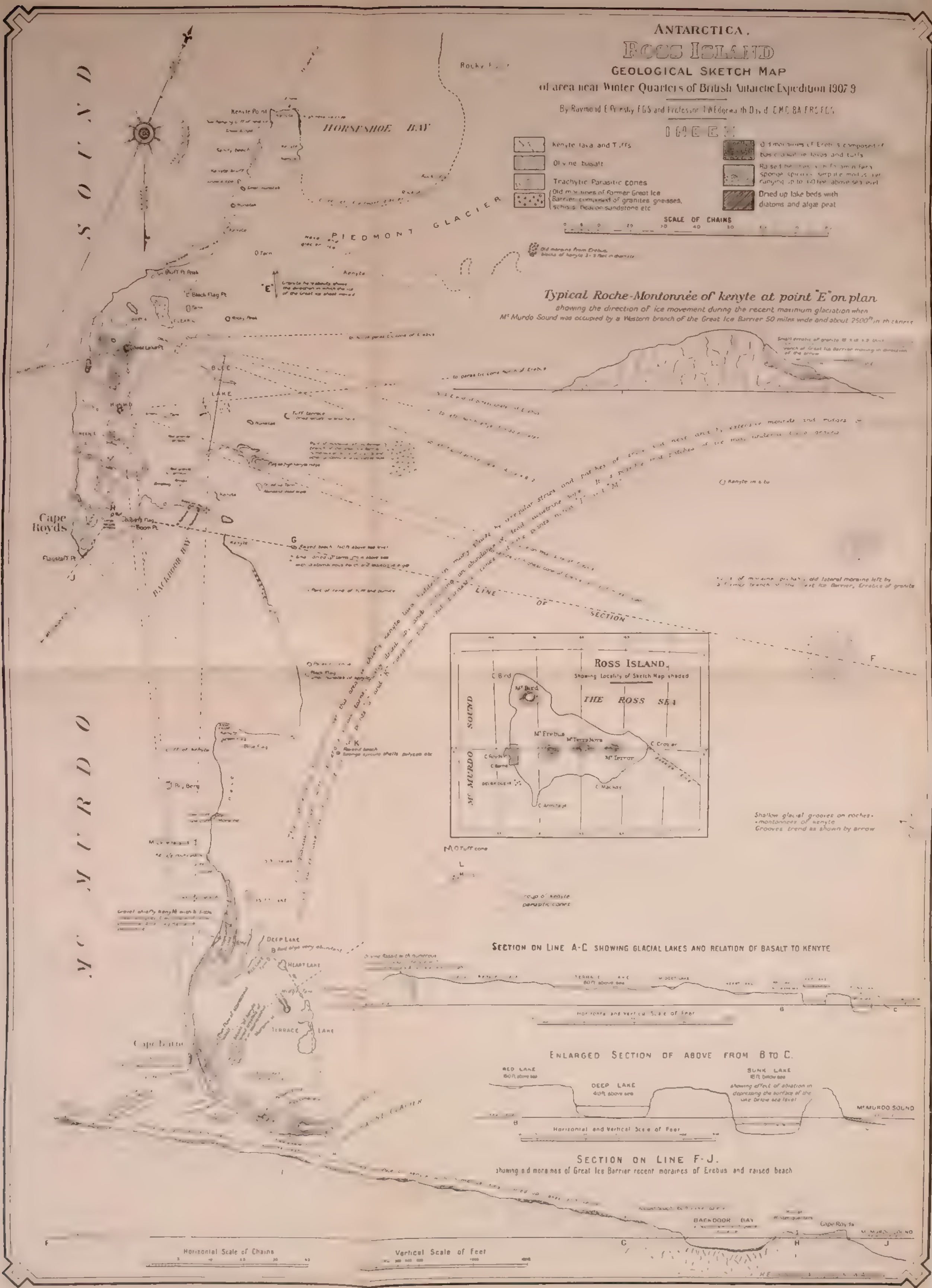
COMMONWEALTH BAY
BARRIER ICE
HEAVY
HEAVY PACK ICE
ADELIE LAND
MAWSONS MAIN BASE
CLARIE LAND
ICE
Chart (Davis) Mawson Expedition Geo. Jour. Oct. 1912
55°
60°
140° E
150° E
130° E
120° E
130° W.
120° W.

Map showing chief trend lines from Australasia & Oceania across Antarctica to South America

[To face p. 319

PLATE XCIV





ANTARCTICA,
ROSS ISLAND
GEOLOGICAL SKETCH MAP
of area near Winter Quarters of British Antarctic Expedition 1907-9
REFERENCE
Kenyte lava and Tuffs
Olivine basalt
Trachytic Parasitic cones
Dried up lake beds with diatoms and algae peat
SCALE OF CHAINS
HORSESHOE BAY
PIEDMONT GLACIER
Typical Roche-Montonnée of kenyte at point "E" on plan
M^c MURDO SOUND
Cape Royds
Flagstaff Pt
BACKDOOR BAY
LINE OF SECTION
ROSS ISLAND,
Showing Locality of Sketch Map shaded
THE ROSS SEA
M^t Bird
M^t Erebus
M^t Terra Nova
M^t Terror
C. Crozier
C. Bird
C. Royds
C. Barne
C. Mackay
C. Armitage
DEEP LAKE
TERRACE LAKE
SECTION ON LINE A-C SHOWING GLACIAL LAKES AND RELATION OF BASALT TO KENYTE
ENLARGED SECTION OF ABOVE FROM B TO C.
DEEP LAKE
SUNK LAKE
M^c MURDO SOUND
Horizontal and Vertical Scale of Feet
SECTION ON LINE F-J.
showing old moraines of Great Ice Barrier recent moraines of Erebus and raised beach
BACKDOOR BAY
Cape Royds
Horizontal Scale of Chains
Vertical Scale of Feet

noticed that, as shown on the map (Plate XCIV. of this chapter) illustrating the main trend lines of the South Polar regions, that the main axes of fold in New Zealand are also S shaped, the trend lines swinging round in the South Island towards the south-east, so as to clear Campbell Island and leave it somewhat on the west. This sharp south-easterly bend of the trend near Invercargill suggests that the Macquarie Islands, as well as the Balleny Islands, probably belong to the western side of the great horst. Possibly the great Te Anau fault, which so profoundly affects the geology of the South Island of New Zealand, with its enormous throw eastwards, is connected with the faulting on the west side of Ross Sea.

As regards direction of horizontal movement, the Antarctic Andes of the American side appear to have been tilted chiefly towards the Atlantic, but the evidence is as yet too meagre for us to generalise upon it. We have as yet insufficient evidence to say in what direction the strata of the horst in South Victoria Land have been tilted, if they have been tilted at all. In New Zealand the strata have been folded towards the Pacific Ocean. On the whole therefore, tectonically as regards faulting but not as regards folding, the evidence seems favourable for considering the great horst of South Victoria Land, in spite of the dissimilarity of its eruptive as well as of many of its sedimentary rocks as compared with those of the American Andes, to be partly related to that great range, and possibly its fractures are not only continuous with those of the South American Andes on the one hand, but also with those of the sub-Antarctic islands, like the faulted area of Campbell Island, and with those of the Alps of New Zealand, on the other. A second possible view is that the horst of East Antarctica swerves around to Prince Luitpold Land and Coats Land, a quite possible structure. A third view is to correlate, as Professor J. W. Gregory has done, the horst of South Victoria Land with the coasts of Tasmania and Eastern Australia as secondary Pacific or sub-Pacific coasts, while King Edward VII. Land and Carmen Land may be correlated with the primary Pacific coast of New Zealand. It is obvious that whichever, if either, of these correlations may be adopted, the coast of South Victoria Land belongs to the Atlantic type, as defined by Suess.

The expeditions which are now being fitted out for further Antarctic exploration this year should go far towards solving this great problem.

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