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Rottnest Island: The Rottnest Biological Station and Recent Scientific Research

Edited by E. P. Hodgkin and K. Sheard

Foreword

The Rottnest Biological Station is an institution of which the State of Western Australia should be truly proud. To Professor H. Waring and Dr. E. P. Hodgkin of the Department of Zoology, University of Western Australia, and Dr. K. Sheard of the Division of Fisheries and Oceanography, C.S.I.R.O., belong the credit for bringing it into being. They deserve the thanks, not only of scientific workers but also of the people of the State as a whole, for their timely recognition of the need and for the enthusiasm and vigour which they brought to bear in its fulfilment.

The station was established primarily to enable research to be carried out on the marine and terrestrial fauna and flora of Rottnest Island, and for the training of undergraduate and post graduate students in essential field disciplines.

Until now all research has been directed by University personnel, with the exception of certain quokka population studies undertaken by the Wildlife Survey Section of C.S.I.R.O. It is our desire, however, that as trained personnel become available, some part of the research programme of the Fisheries Department will be undertaken there.

I am particularly happy that as chairman of the controlling committee I am able to keep my Department in such close touch with the work as well as the progress and development of the station. In a State the size of Western Australia, with myriad scientific problems but only a small population and somewhat slender financial resources, it is of paramount importance that the most economical use be made of all available personnel and finance. The only real way of doing this is by the closest co-operation between all agencies engaged in similar kinds of research. I believe that in the Rottnest venture this desideratum is being achieved.

A. J. FRASER,
Director of Fisheries, W.A.

9.—Introduction

Broadly speaking, biological advance comes from either development of new techniques with which to attack classical problems or the exploitation of a previously inaccessible fauna using classical and other techniques. In the latter case the developments usually proceed on a well-defined pattern. The forerunners are the collectors and taxonomists who move in to catalogue and list the animals in the hitherto unknown field; this is a continuing process which broadens into ecological studies of various kinds. It is a phase of describing what there is and what occurs. Sooner or later people want to know "why?" and "how?" Then the physiologists and biochemists of various sorts take up the story.

The potential attraction of academic biological work in Australia is its rich, little explored fauna. This potential has never been fully realised, chiefly because the distances to be travelled from central laboratories to field areas are prohibitive, particularly to University staffs tied to teaching and administrative routines. The existence of a local site such as that on Rottnest Island with its attractive fauna, free from predators and protected by statute from man's destructiveness, offers a way out from this frustration if living quarters and simple laboratory facilities are available.

The various interim reports in this series show how such a station has been established and indicate the number and kind of programmes that have been set in motion on ecological and physiological themes. These reports not only concern the work that has been attempted (chiefly on the marsupial, *Setonix brachyurus*, the quokka) but outline also a number of fields where detailed work is worth while. The marine problems are little touched at present, a limitation in this regard being the absence of sea-water aquaria for fish and crayfish work; so far these have been beyond our financial resources.

The choice of the quokka as a subject for intensive multipurpose research was a logical one. I had come to Australia with the express purpose of working on marsupials, but quickly realised the rarity within easy reach of the metropolitan area of the numbers of individual animals necessary for modern biological work. In this context Rottnest Island as a research area was a gift from heaven. As can be seen from these reports, its large population of quokkas provided not only a simple opportunity for introducing techniques of modern biology to students, but some very worthwhile problems in vertebrate biology. The opportunities presented by the Island for work in many other biological fields are also evident, so that the Department of Zoology is in the happy position on the one hand of being able to cater for a wide range of specialist activities, and on the other of maintaining varied and worthwhile field courses for its students.

Students and staff have reacted to these opportunities with enthusiasm. At this point it is important to emphasize that the station and its facilities were not taken over ready-made for research workers to walk into and use as a base. Credit is given elsewhere to those who translated an idea into a site and buildings. There were many others whose enthusiasm and labour made the building usable in the early stages of the Rottnest studies. The present day student and research worker likewise helps where he can, but he should be aware that there were others before him. A list of workers contributing to Station activities (research and otherwise) is given at the end of these reports. Of these the following (in alphabetical order) were forerunners who should be doubly mentioned: J. Barker (neé J. Buttle), S. Barker, George, Hodgkin, Lee, Littlejohn, Main, Malcolm (and Mrs. Malcolm), Milward, Rudeforth, Sharman, Shield, and P. Woolley.

The form of these reports has been dictated by the necessity of fitting a large amount of different kinds of information into the one small Journal part. Accordingly all references concerning Rottnest Island have been collected in a separate Bibliography and only those outside this scope, but necessary to a particular report, have been included with that report. Also, information with regard to individuals named in these reports has been given separately. There has been some duplication but only where this is necessary for clarity. Perhaps some helper may have been overlooked in the rush of preparation. If so I tender my apologies in advance.

In conclusion I would like to offer my personal thanks to all who have co-operated in this most rewarding venture. Elsewhere the financial contributions of the University, State Fisheries, and Australian Academy of Science are acknowledged. It is pleasing to me personally to here acknowledge the moral support and generous financial backing of the C.S.I.R.O. Executive in the carrying out of our marsupial research programme.

H. WARING,
Professor of Zoology.

10.—Rottnest Island as a Location for Biological Studies

The choice of Rottnest Island as a research centre arises from certain obvious advantages, e.g., the ease of access and the abundance of the quokka, the marsupial around which so much of the research has centred. The titles of the accompanying papers could suggest that there is nothing further to be said on the problems inherent in an insular situation. This may be so, yet, as will be mentioned below, the solutions of problems attacked on Rottnest have a potential application to continental situations which would not usually be considered as having anything in common with an island fauna. It thus seems desirable to give the general background and aspirations of the research a little more discursive treatment than will be given in other papers of this series in order that the full implications of the work can be appreciated.

Even a superficial acquaintance with the terrestrial fauna of the western portion of Australia poses a number of problems all of which centre around the distribution of animal species at the present, during the historical, the prehistorical and geological past. Many of the extant terrestrial animals especially the mammals have disjunct or restricted distributions which give every impression of being relicts of wider ranges. Perusal of the records of occurrence in the historical past confirm their relict nature for one soon discovers not only the wide extent of the former range but also the number of species which have become entirely extinct. Commonly such range restriction and extinction are ascribed to habitat destruction following the advent of European-type culture in Australia as well as the impact of introduced predators such as foxes or herbivores such as rabbits. However, this cannot be the whole story for some species of mammals apparently became extinct before settlement was extensive and certainly before foxes and rabbits were present. The suspicion that European man with his associates was not the sole agent of extinction is strengthened when one studies the cave deposits along the Western Australian littoral. Here, in extensive deposits (mostly originating from owl pellets though there are many remains of larger animals), are an immense number of specimens of species which are either no longer found in the vicinity or are entirely extinct.

Glauert was (1910, 1912, 1914, 1948) the first to work these deposits and more recently Lundelius has surveyed caves over a much wider geographical area and, although this latter worker has as yet published no C14 dates, there is every indication that faunal changes have proceeded throughout the deposits to the superficial zone and these must be considered as within historical times. Many of the bones collected by Glauert and Lundelius (1957) are con-specific with species now restricted to the wetter south-east of Australia. The pre-historic and geological evidence thus suggests that environmental factors, as opposed to man-made habitat changes, have perhaps played an important part in the range reductions and extinctions witnessed in the past 100 years or so.

Students of climatic change have proposed this mechanism repeatedly to account for disjunct or relict distributions in the Australian fauna. Some workers suggest a great aridity at about 5,000 years ago while others disagree and Tindale points out that because of the uniqueness and sensitivity of some relict populations the climate could not have been much more arid in the recent past than it is at present. The apparent continuity of the process of species extinction from Pleistocene time to the historic past might be taken as supporting Tindale (1955). The question is open. However it is quite clear that we will gain no real understanding of the faunal depauperisation until something is known of the way species react to deteriorating environmental conditions. As the accompanying papers show, it is as a deteriorating environment that Rottnest offers such a valuable experimental "laboratory."

But Rottnest is not the only such "laboratory"; there are a number of other islands along the W.A. coast extending from the vicinity of Shark Bay to south of Esperance. These contain relicts of Pleistocene faunal assemblages which were cut off from the mainland with the eustatic rise of the seas at the close of the Pleistocene. Some of these islands, e.g., the Abrolhos, contain fauna which is unknown on the adjacent mainland but is found several hundred miles to the south. Others, e.g., Rottnest, contain a fauna which is represented on the immediately adjacent mainland. It is the presence of a similar fauna on the adjacent mainland that affords one of the great research assets of Rottnest and this, plus the fact that the Island is large enough for local island populations to be developed, has meant that, potentially, both intra-island populations as well as island versus mainland populations could be compared.

Clearly if Rottnest has been isolated since the close of Pleistocene we might expect to find some changes in the fauna. The headings under which changes might be expected can be listed as follows:—

(a) Those related to survival in a deteriorating environment.
  - i. No change but wide individual tolerance which has not yet been exceeded by island environment, i.e., Rottnest animals similar to mainland.
  - ii. A significantly different range of tolerance in the island animals; this presumably produced by natural selection.
  - iii. A significantly different set of ranges of tolerance within the island population; this again presumably produced by selection.

(b) Those related to evolutionary differentiation in geographical isolation.
  - i. Morphological differentiation.
  - ii. Genetic isolation, e.g., sterility in island x mainland matings.
  - iii. Behavioural differences, e.g., male call differences in frogs.

For a profitable analysis in terms of the foregoing we need rather idealised animals which are amenable to morphological, physiological and experimental analysis. Fortunately, Rottnest contains four vertebrate species which, in varying degrees, fulfil the ideal, these are:—

The quokka (*Setonix brachyurus*) and the frogs *Heleioporus eyrei*, *Hyla raniformis* and *Crinia insignifera*. The last mentioned species affords a good illustration of the kind of population changes which are possible. This species is polymorphic with a phenotypic frequency of the morphs on the mainland of: Striped, 0.37; lyrate, 0.37; and patternless, 0.26. On Rottnest patternless animals are not found and the remaining two morphs are equally frequent. In this case, if we assume that individual morphs and morph frequencies in the population have an adaptive significance then we have a measure of the magnitude of the changes which may be expected in other non-polymorphic populations. Nevertheless the principal research target has been the quokka which offers an opportunity for investigating the possible causes of marsupial extinction which had been so widespread during Quaternary time. There is no doubt that the study has lived up to expectations and it is now possible to use the data in hand as a basis for analogous reasoning when studying other macropod marsupials.

So much for theorising and speculation. The results, though not yet applicable directly to studies of faunal extinction generally have application to other fields, viz.: (i) Conservation and (ii) Pest Control.

(i) *Conservation.*—Many fauna reserves are of necessity "islands" in the sense that they are areas of country usually unwanted for either agricultural or pastoral pursuits. Because of their size and insular nature most will deteriorate as areas containing representative natural habitats. To these situations the information that is coming from the Rottnest studies, especially as that relates to marsupials, has an application far wider than might be expected when it is viewed simply as a study of an island population (Main, 1956).

(ii) *Pest Control.*—From the inception of European settlement various marsupial species have been regarded as pests. Usually this has meant an active policy of extermination which in most cases has been successful from the settlers' point of view, with the result that the offending species has become totally or locally extinct. However, there are a few exceptions to this state of affairs, especially under pastoral conditions, where pest species have prospered even under widespread hunting and poisoning as well as in the presence of environmental changes caused by gross pastoral over-grazing. These successful species are the other side of the problem of extinction and require as much study as the threatened species. As a result of the Rottnest work on a small amenable species it is now possible to proceed in these studies on the less amenable species knowing that there are sufficient data from which general research programmes can be formulated. Such work has begun on the mainland.

A. R. MAIN.

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11.—History of the Rottnest Biological Station

The Rottnest Biological Station had its origin in a visit that Professor Waring and I paid to the Island in May, 1948, shortly after he arrived in W.A. on first appointment. He at once recognised the potentialities of the Island for biological studies and especially the research asset represented by the large quokka population. We talked then about the possibility of establishing a field station. The Island had been the scene of active biological study before, as evidenced by the Bibliography, and there had been student camps under Professor G. E. Nicholls. The last of these, in November, 1945, was my first introduction to Rottnest. On that occasion we used two bungalows in the settlement, both as living accommodation and as laboratories. I vividly remember the untidy array of microscopes and other apparatus that cluttered the kitchen table, the smelly collections of marine animals we examined, and the happy friendly relations between students and staff.

Physiological research on the quokka started almost immediately in the Zoology Department and another student camp was held in 1951. However no further action was taken to establish a field station until 1953. In this year Dr. K. Sheard undertook successful personal negotiations with the Naval Officer-in-Charge, W.A. for the lease of the naval barracks and signal station near the central lighthouse. In September the Navy agreed to lease the buildings to the State Department of Fisheries at a nominal rental. This was finalised by the Department of the Interior and a ten year lease commenced on 21st December at an annual rental of £1.

A committee of management, the Rottnest Biological Station Committee, was set up under the Chairmanship of Mr. A. J. Fraser, Superintendent of Fisheries for Western Australia. This held its first meeting on 11th January, 1954. The other members at that time were the Hon. Mr. L. F. Kelly, M.L.A., Minister for Fisheries and Chairman of the Rottnest Island Board with Dr. K. Sheard of the C.S.I.R.O. Division of Fisheries, Professor H. Waring representing the University, and Mr. B. K. Bowen of the Fisheries Department as Secretary. Subsequently Dr. J. M. Dunnet, of C.S.I.R.O. Wildlife Survey Section, joined the Committee (October, 1955 to July, 1956), Mr. T. Sten replaced Mr. Kelly as a representative of the Rottnest Board, I took Professor Waring's place, and in September, 1958, Mr. R. W. George was appointed to represent the W.A. Museum. The Committee meets quarterly. One meeting a year is held at the Station.

When they were first leased the buildings were little more than shells and, although in fair condition, had had no maintenance since they were vacated after World War II. Even before the lease had been formally signed parties of volunteers had started to put the building in order, to paint them outside and to install essential furnishings and fittings. Since then a great deal has been done to maintain and improve the buildings, much of it by the voluntary labour of those using the Station, their friends and relatives, those attending annual student camps, and by some of the technical staff of the University who have spent part of their holidays at the Station. Officers of the State Department of Fisheries have assisted also.

Rottnest Island is a Reserve for recreation, and is under the control of the Rottnest Island Board. It is primarily a holiday resort and each summer large numbers of visitors occupy the bungalows of the settlement on Thompsons Bay. There is no private ownership of land and no private transport is allowed. Lack of transport would have severely handicapped work at the Station and permission of the Board was sought to use a vehicle. A second-hand Land Rover was purchased and transported to the Island in April, 1954, by the Army. It has recently been replaced with a new vehicle. Throughout the development of the Station we have had the friendly co-operation of the Board members, of its employees, and especially of its Secretary, Mr. Jim Stark. Good relations were cemented recently (February, 1959) when Board members and Island residents were entertained at the Station and told about research conducted on the Island by the Zoology Department. At the outset the Lighthouse Department helped with transport; throughout we have drawn on their supply of bore water, and successive Light Keepers have acted as caretakers to the Station.

All research projects are separately financed (through University Research Grants, C.S.I.R.O. Scholarships, Nuffield and Rockefeller Grants), and hence this is not a worry to the Committee, which has no funds directly at its disposal.

Development and maintenance have been financed by the participating organisations. On the recommendation of Mr. E. M. Barker, at that time Chairman of the Senate Finance Committee, the University made an initial grant for the purchase of the Land Rover, a small lighting plant and essential furnishing and now makes an annual maintenance grant. Annual grants from the State Fisheries Department have been used to provide floor coverings, for the recurrent expenditure on painting and for other outside facilities. C.S.I.R.O. has made available a 32/250 volt lighting plant and for two years supplied petrol to the Station. Mileage is charged for the use of the vehicle but at present no other Station charge is made.

From its inception the Station has been in frequent use. During 1954 the principal users were Sharman and Barker in their pioneer work on quokka biology. In 1955 and early 1956, Dunnet and his assistants spent much time there making population studies of the quokka. In 1957 and 1958, Shield and his team made repeated visits to conduct their studies of quokka nutrition. While these have been the regular users of the Station many others have made constant use of it for their investigations, as will be evident from succeeding articles. The first student camp was held in November, 1954, and since then undergraduate training has been a regular feature of the Station.

The Station has no resident staff: permanent facilities are at present limited to ordinary domestic requirements and a laboratory fitted with light, power and water, but to which equipment is brought from the mainland according to the needs of particular work. The proximity of the Station to Perth and the University and the accessibility of Rottnest by boat and aeroplane, has thus made it possible to conduct much valuable research at a relatively insignificant cost. The policy of the management committee is to facilitate in every way the academic study of fauna and flora and the study of economically valuable organisms within the purview of State Fisheries and C.S.I.R.O. The concern of the Committee for the preservation of this unique habitat led to an approach to the Australian Academy of Science for funds to extend the fenced enclosures. A grant was made and two fences have been erected. In addition to workers from the sponsoring bodies, a number of visiting biologists have used the Station for short periods and it is hoped that more may be welcomed in the future.

E. P. HODGKIN.

12.—Geology of Rottnest Island

Introduction

Rottnest Island lies on the continental shelf along the western flank of the Perth Basin. It forms the northern termination of two parallel chains of low islands and shallow reefs that strike in a north-north-westerly direction from the vicinity of the mainland south of Perth. Both chains are composed mainly of Quaternary aeolianite and represent major series of calcareous sand dunes which formed close to the shore line when the sea-level was considerably lower than at present. The eastern chain consists of the Murray Reefs, Seal Island, Bird Island, Point Peron, Garden Island, Carnac Island and the Stragglers Reefs; the second chain lies approximately two miles to the west of the first and includes Coventry Reef, Hawley Shoal and Casuarina Shoal. Gravity surveys (Vening Meincsz 1948; Thyer and Everingham 1956) show Bouguer Anomalies of between -65 and -70 milligals in the vicinity of Rottnest Island and suggest that a thickness of about 20,000 feet of sedimentary rocks separates the surface exposures from the underlying crystalline basement complex.

Recent contributions to our knowledge of the geology of Rottnest Island have been made by Teichert (1950) and Fairbridge (1954). The present authors wish to acknowledge the valuable assistance of Mr. B. E. Balme, Dr. E. P. Hodgkin, Mr. P. E. Playford and Miss M. E. Redman in the compilation of this review. Two of us (C.W.H., E.W.S.K.) are currently engaged in a study of the geology of Rottnest Island.

Succession

All rock exposures on Rottnest Island are thought to be of Quaternary age, but Tertiary and Cretaceous strata were penetrated in the Rottnest Island Bore. This bore was drilled near the Rottnest Cemetery at a surface elevation of approximately 10 feet above mean-sea-level. It reached a total depth of 2,582 feet. A Lower Cretaceous sequence of dark grey, sandy, glauconitic claystone and shale and dense sandstone was penetrated between 2,185 feet and 2,582 feet; this interval is correlated with the South Perth Formation, known from bores in the Perth Metropolitan Area. The overlying Kings Park Shale is a marine formation which extends from 933 feet to 2,185 feet. It consists of impure sandstone, grey sandy shale, and thin beds of impure limestone. Numerous fragmentary invertebrates were recovered from the available cores. Spore and pollen studies confirm the correlation with the Middle to Upper Eocene Kings Park Shale of the Perth bores. Coarse-grained, red, brown and yellow sandstone occupies the interval between the base of the "Coastal Limestone," at 233 feet, and the top of the Kings Park Shale, at 933 feet. Samples of this part of the section are not available for study, but the unit may represent part of an ancient delta of the Swan River. A thin unnamed formation of late Tertiary or Pleistocene age occurs below the "Coastal Limestone" in the Public Works Department Swan River bores directly to the west of the Fremantle Traffic Bridge. It is perhaps of similar age and origin to the sandstone beneath the "Coastal Limestone" in the Rottnest Island Bore. Sandy limestone extends from the top of the unnamed sandstone formation, at 233 feet, to the surface of the bore.

The Rottnest Island Bore, which is the second deepest hole drilled in the Perth Basin, penetrated the thickest known section of the Kings Park Shale. Comparison of the depths of formations in the bores of the Perth area suggests that the Mesozoic and Tertiary sections in this area are faulted.

Exposures

All lithified strata exposed on Rottnest Island are referred to the "Coastal Limestone." They consist predominantly of coarse-grained, cross-bedded aeolianite and include minor developments of marine limestone. Fossil soils of limited areal extent are fairly common in the cliff sections west of Narrow Neck.

The aeolianite of the "Coastal Limestone" is similar in composition to the sands on the present day beaches of the island. It is composed mainly of comminuted shells, calcareous algae, Foraminifera and other calcareous microfossils, but includes rounded quartz grains and minor amounts of heavy minerals. Quartz grains are usually only minor constituents of the aeolianite, but in some bands within the fossil dunes they reach a high concentration.

An emerged coral reef in Salmon Bay, lithified shell deposits at Geordie Bay, and the shell beds around the margins of the salt lakes represent marine incursions into the "Coastal Limestone" during periods of higher sea-level. The fossil soils are characterised by their massive structure and the presence of the terrestrial gastropod *Bothriembryon*. They formed fairly rapidly in flat interdunal areas and do not exhibit signs of soil maturity.

Soils forming at the present time are shallow and immature. They show the initial stage in soil formation, namely the accumulation of organic matter near the surface.

Physiography

Rottnest Island is characterized by rolling sand dune topography, and reaches a maximum elevation of only 154 feet. Permanent drainage channels are absent, but a number of swamps form in favourable interdune locations during winter (see p. 85 herein). The system of salt lakes represents shallow arms of the sea which were isolated in recent times, by bar and dune formation near the present coast.

A striking physiographic feature of the Island is the ubiquitous occurrence of narrow marine benches situated a few feet above mean-sea-level along the present coastline and around the margins of the salt lakes. Previous authors (Teichert 1950; Fairbridge 1954) have interpreted these features as remnants of low-water-level marine benches formed during recent eustatic still-stands or slow retreat of sea-level. Benches at 10-11 feet above the present mean-sea-level have been related to the "Flandrian" sea-level of Europe, those at 5-6 feet to the "Calaisian" and those at 2-3 feet to the "Dunkirkian." Emerged coral reefs at Salmon Bay and Stark Bay and shell beds around the lakes yield unmistakable evidence of higher sea-levels. However, studies in progress suggest at least some of the low-water-level benches formed during these periods of higher sea-level have been either drastically remodelled or obliterated by rapid erosion. Some of the benches around the present coastline appear to owe their form to surface induration of the aeolianite near the upper limit of the splash zone, and it therefore seems that they are unrelated to eustatic phenomena.

A fall in present sea-level of approximately five fathoms would link Rottnest Island to the mainland as a peninsula extending through Garden Island to Point Peron. Fossil pollen and radiocarbon studies (Churchill 1959) indicate that, approximately 5,000 years B.C., sea-level stood five fathoms lower than at present. The separation of Rottnest as an island is thus a young geological event.

BRIAN F. GLENISTER, C. W. HASSELL and E. W. S. KNEEBONE.

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13.—The Vegetation of Rottnest Island

Our earliest record of the vegetation of what is now Rottnest Island comes from fossil pollen and megascopic remains in swamp sediments and dunes of late Pleistocene age. Apart from species still found on the Island, the past occurrence of *Eucalyptus gomphocephala*, *E. marginata*, *E. calophylla*, *Agonis*, *Casuarina*, *Banksia*, *Macrozamia* and *Xanthorrhoea* indicates that a tuart woodland similar to that of the present mainland once existed here. Since then, rising sea-level and erosion have reduced the area to an island, 7 miles long and 3 miles wide. Consequent increase in wind exposure and deterioration in rainfall have played their part in rendering former habitats unsuitable for tuart woodland. Thus the present vegetation consists solely of elements of a *coastal complex*.

Supralittoral Vegetation

In comparison with the mainland, the strand plants *Cakile maritima* and *Arctotheca nivea*, and the fore-dune species *Spinifex hirsutus* and *Tetragonia zeyheri*, are rare on the island. The dominant plant of Rottnest fore-dunes is *Spinifex longifolius*; associated with it are *Atriplex isatidea* and the introduced *Anthericum divaricatum*.

An entirely different suite (mostly of succulents) occupies rocky shores: *Carpobrotus aequilaterus*, *Threlkeldia diffusa*, *Tetragonia implexicoma*, *Sporobolus virginicus*, *Eremophila glabra*, *Nitraria schoberi*, *Enchylaena tomentosa*, *Arthrocnemum halocnemoides*, *Salicornia australis* and *Atriplex paludosa*. Many of these species are now abundant only on offshore stacks and islets. Except at Cape Vlaming, excessive browsing by quokkas in summer has exterminated or impoverished most of the succulent-dominated communities on the main island coast.

Coastal Dune Vegetation

This is a fairly open formation of low, generally microphyllous, shrubs, 1 to 5 feet high. Composition and height depend on wind exposure and depth of sand over the consolidated dune. The succession from sandy shores is usually through *Scirpus nodosus, Scaevola crassifolia* and *Calocephalus brownii* to *Olearia axillaris.* The stony phase is pioneered by the dwarf shrub *Frankenia pauciflora*, which, with decreasing exposure, is replaced by taller shrubs: *Westringia dampieri, Leucopogon insularis, L. parviflorus, Acrotriche cordata* and *Boronia alata*. On leeward slopes most of these give way to *Acacia cuneata, Olearia axillaris. Myoporum insulare, Diplolaena dampieri, Melaleuca pubescens*, and *Acacia rostellifera*.

Interdunal Vegetation

In sheltered valleys and slopes, where the sand is deep and the accretion of silt has enhanced its water holding capacity, a scrub develops, almost exclusively of *Acacia rostellifera*. Typically the formation is closed and from 10-20 feet in height. The liana *Clematis microphylla* is common here. Undergrowth is sparse and usually restricted to *Stipa variabilis* and *Acanthocarpus preissii*.

This scrub was once far more extensive than it is at present. As recently as the end of last century, visitors could describe the vegetation of Rottnest as "impenetrable" beyond the confines of the eastern settlement. Today all that remains of the scrub in the western half of the island are a few isolated thickets of *Acacia rostellifera*.

Where the scrub has gone, there now occurs a low dense formation consisting almost exclusively of sclerophyllous monocotyledonous plants. The most characteristic species is *Acanthocarpus preissii*, a fruticose, pungent-leaved perennial, 1-3 feet high. It is usually associated with a tussock grass, *Stipa variabilis*. Less common are two other tussock grasses *Poa australis* and *Danthonia caespitosa*, the sword rushes *Lepidosperma gladiatum* and *L. resinosum, Conostylis candicans* and a small grass-like sedge, *Carex preissii*. Apart from annuals, dicotyledonous species are uncommon and are usually found (1) in disturbed areas (e.g. *Thomasia cognata*), (2) where the scrub has recently disappeared (e.g. *Didiscus caeruleus* and *Guichenotia ledifolia*), or (3) where the limestone is near the surface (e.g. *Stackhousia pubescens* and *Oxalis corniculata*).

Recent research has shown that the status of the *Acacia* depends on quokka grazing pressure. Where the animals are abundant, the *Acacia* is eaten out and replaced by communities of herbs and low shrubs that are resistant to fire and generally unpalatable to quokkas. Where quokkas are excluded by fences or where their density is low, as in the Stark Bay hinterland, *Acacia* thickets expand into the surrounding *Acanthocarpus-Stipa*.

Thus *Acanthocarpus-Stipa* and *Acacia* scrub are the end-points of a single sere, whose direction is controlled by the intensity of quokka grazing. The present trend over most of the Island is for *Acanthocarpus* to replace scrub, which implies a recent increase in the abundance of the quokkas The evidence for such an increase and the factors responsible for it, have been discussed by Storr (1957).

Limestone Ridge Vegetation

In the western two-thirds of the Island, the consolidated dunes are usually covered by shallow calcareous sands. At the eastern end of the Island the dunes are frequently covered by finer sands relatively rich in organic matter, which support a closed formation comprising several species of shrubs 5-15 feet high. *Templetonia retusa* occasionally occurs in pure stands. More often it is mixed with one or more of the following: *Pittosporum phillyrioides, Spyridium globulosum, Beyeria viscosa, Alyxia buxifolia, Acacia rostellifera* and *Melaleuca pubescens*. Most of these species reappear on limestone cliffs in sheltered bays. Undergrowth is sparse and confined usually to *Phyllanthus calycinus, Acanthocarpus preissii, Stipa variabilis* and *Guichenotia ledifolia*.

Swamp and Salt-lake Vegetation

The various marsh communities form concentric zones around the lakes and swamps. Except where the limestone is bare, the innermost zone is dominated by the samphires, *Arthrocnemum arbuscula, A. halocnemoides*, and *Salicornia australis*. During winter and spring this zone is largely under water. In early summer after the water has receded, certain low creeping perennials renew their growth, viz.: *Hemichroa pentandra, Wilsonia humilis, Samolus repens* and *Suaeda australis*.

The next zone is dominated by the large tussocky sedge, *Gahnia trifida*. Sometimes it is mixed with or replaced by the erect sedges and rushes, *Scirpus nodosus, Hypolaena* sp. and *Juncus maritimus*. Less frequently it is interspersed with bushes of *Arthrocnemum halocnemoides, Atriplex paludosa* or *Myoporum viscosum*. Wherever the soil is less saline and richer in organic matter, a mat of grasses and herbs covers the bare spaces between tussocks of *Gahnia*. The mat is dominated by the perennial grass *Sporobolus virginicus*.

As the land rises, the *Gahnia* is replaced by *Melaleuca pubescens*, an erect or umbrageous tree up to 40 feet high. It forms the only dominant of a closed community in which undergrowth is rare apart from the ascending succulent, *Threlkeldia diffusa*, and occasional tussocks of *Stipa variabilis*. If the flats surrounding the lake are extensive there is a correspondingly broad zone of *Melaleuca pubescens*, but where the land continues to rise it gives way to *Acacia rostellifera* or *Pittosporum phillyrioides* according as the soil is deep or shallow over the limestone.

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14.—Physiology of the Quokka

Investigations of physiological processes operating in the quokka have been carried out during the last 10 years by a number of people in various capacities and of different interests. As a result, these studies have not followed a systematic sequence but are linked by the common interest of the investigators in the marsupial group. Therefore, rather than give a chronological account of the work done on the quokka, the following summary uses broad headings which group together investigations of related physiological processes.

Digestion

Few animals and no mammals form their own alimentary cellulase to digest the cellulose which encases plant cells. Consequently, those mammals which use plant material as food rely on unicellular organisms, which live in the digestive tract, to digest the cellulose portion of their food so that this substance can be made available for the animals' needs. This is particularly important in the case of grazing herbivores. Mammals can be divided into two groups by the manner in which micro-organisms assist them in this respect: the ruminants, in which the stomach is divided into four pouches, the first of these (the rumen) being the major site of predigestion of food by micro-organisms, and the non-ruminants, in which the stomach is a single compartment, digestive micro-organisms being contained in a relatively large caecum and in the colon.

The quokka, like other macropods, is an herbivorous animal of grazing habit. Moir, Somers, Sharman and Waring (1954), and Moir, Somers and Waring (1956) showed that in this animal the problem of digesting plant material is largely overcome by a type of "pregastric digestion" which is similar, in many respects, to that which occurs in ruminants. Thus, the stomach is large and sacculated, has an oesophageal groove and the proximal pouch contains bacteria which attack and ferment the food. As in ruminants, this bacterial action results in production of volatile fatty acids which are absorbed mainly from the fore-stomach. However, the stomach of the quokka does not exactly resemble that of the ruminant; it is not known if the oesophageal groove functions as in ruminants and the functions of the distal pouches of the quokka stomach are unknown.

Two related characteristics of digestion in ruminants are the slow rate of passage of food through the alimentary canal and the small proportion of fibrous food that remains undigested. In investigating these processes in the quokka, Calaby (1958) observed that the rate of passage of food through the digestive tract in this animal is faster than in the ruminant but slower than in the horse; also that the percentage of dry food digested by the quokka is less than in ruminants but greater than in rabbits. Thus, digestion of plant material in the quokka is less efficient than in the domestic ruminant although probably more efficient than in non-ruminant herbivores.

Little is known of the essential food requirements of the quokka. In nitrogen balance trials, using a mixture of equal parts of oaten and lucerne chaff and ground sheep nuts, J. H. Calaby (personal communication) obtained a preliminary figure for crude protein requirements for maintenance of adult animals, of approximately 3.5 grams per kilogram live body weight per day. Further information on this subject awaits future investigation.

Metabolism

General

The trend towards the specialised ruminant type shown by studies on digestion in the quokka are paralleled by some aspects of the metabolism of this animal.

Moir *et al.* (1954, 1956) recorded that blood volatile fatty acid (V.F.A.) and glucose levels in the quokka are similar to those found in ruminants, V.F.A. levels being higher and glucose levels lower than those normally found in non-ruminants; also V.F.A. was shown to be removed from the circulation by the liver and other tissues. These facts indicate that quokka tissues may be like those of the ruminant in utilising relatively large amounts of V.F.A. as an energy source. However the relative importance of V.F.A. and glucose in this respect are not yet known.

Further studies by J. Barker (unpublished) have shown that while normal blood glucose values for the quokka are similar to those for ruminants, feeding increases the blood glucose level to a rather greater extent than occurs in ruminants. However, intravenous injections of insulin in the quokka depress the blood glucose to very low levels which would not be tolerated by non-ruminants, this without apparent effect on the animal. This response is similar to that which occurs in ruminants. On the other hand, glucose tolerance times for the quokka are similar to those for non-ruminants and much shorter than those for ruminants. Finally, the ability of the quokka to convert injected propionate to glucose is considerably less than that of the ruminant although relatively greater than that of the rabbit.

Thus, although the quokka is like the ruminants in that it tolerates blood levels of V.F.A. and glucose that would not be tolerated by non-ruminants, some aspects of cell metabolism in this animal must differ from that of the ruminant, and full investigation of intermediary metabolism in the quokka should be of great interest.

Trace Elements

Cobalt and Copper.—Ruminants require cobalt for the synthesis of Vitamin B_{12} by micro-organisms in the rumen. A higher intake level of cobalt is necessary in ruminants than in non-ruminants due to their poor faculty for absorption of Vitamin B_{12} and to their requirement of a high level of cobalt in the rumen liquor to maintain a normal population of micro-organisms. In cobalt deficiency, rumen levels of cobalt are depressed. As a result, changes occur in the population structure of the resident micro-organisms and Vitamin B_{12} production falls below the minimal requirements of the host. Thus the need for cobalt in ruminants is indirect and cobalt deficiency is in fact a deficiency of Vitamin B_{12}. Ruminants become cobalt deficient when grazing light land low in cobalt and particularly when grazing coastal sand dune country consisting largely of wind born shell fragments.

After Moir *et al.* showed that the quokka had "ruminant-like" digestion, it was of interest to determine whether cobalt deficiency plays a part in limiting the numbers of quokkas on Rottnest Island, an area which consists entirely of sand dune formations and which has, in the past, proved an unsuitable area for grazing sheep. S. Barker (unpublished data) has attempted to produce experimental cobalt deficiency in quokkas. The basic diet used had a cobalt level of 0.02 p.p.m. (dry weight basis). This level is slightly lower than those found in the few Rottnest plants that have been analysed for cobalt. Although the liver cobalt levels in the quokkas were, after several months, significantly lower than those of control animals, serum levels of Vitamin B_{12} did not approach the lowest levels found by Shield (1958) in the Rottnest population during spring months. No symptoms comparable with those exhibited by Vitamin B_{12} deficient sheep were produced in quokkas on these low cobalt intake levels. It is therefore tentatively concluded that the quokka is more efficient than ruminants with respect to conversion of cobalt to Vitamin B_{12} and/or to absorption of Vitamin B_{12}.

Copper deficiency occurs in ruminants under two types of circumstance—

(1) a simple deficiency occurring in animals grazing on copper deficient pastures; and

(2) an induced deficiency occurring in animals grazing pastures with normal copper levels but also with high molybdenum and inorganic sulphate levels—in this case an interaction between these three ions reduces the availability of copper to the animal.

By analysis of plants eaten by the quokka, S. Barker (unpublished data) has shown that Rottnest pastures are low in copper—the mean level being less than 5.0 p.p.m. (dry weight basis)—but field studies indicate that this in itself is adequate for the quokka. Also, in certain areas of the island, plants have a high molybdenum and inorganic sulphate content, and field studies have shown that during the summer, blood copper levels of animals in these areas fall below the winter levels. It therefore appears that when local population numbers build up during the summer, reduction in blood copper occurs in animals eating plants of high molybdenum and inorganic sulphate content. Preliminary experiments have indicated that a Cu-Mo-SO_4 interaction does exist in the quokka and further work on this problem is in progress.

Iron.—The mechanism of iron transfer from the female quokka to the suckling joey is being investigated by Kaldor. In eutherian mammals that have been studied, uterine embryos obtain iron for haemoglobin manufacture and iron storage as a result of placental transfer and such animals are born with a relatively high blood haemoglobin concentration. After birth the young are, for a time, dependent on the maternal milk for further iron supplies but eutherian milk has a low iron content. Therefore, the young are largely dependent on their own iron stores during the lactation period and as these are not fully adequate for their needs, a characteristic decline in blood haemoglobin and in iron stores of the young occurs during this period. Blood haemoglobin and iron stores do not rise again until foods other than milk are taken.

Preliminary studies on the quokka have shown that the blood haemoglobin concentration is low in the young joey but rises throughout pouch life and towards the end of this period it is almost as high as the adult value. Storage iron in the liver is maintained at a constant high concentration during the corresponding period. These findings indicate an unusually high concentration of iron in quokka milk and this was confirmed by analysis. How this high output of iron in milk is maintained is the subject of work in progress as this is of great theoretical interest since there is no known mechanism for active secretion of iron into milk.

Water

Since Rottnest Island is an area where summer conditions are fairly prolonged and are coincident with a limited natural water supply, the quokkas living on the island might be expected to have some means of physiological adjustment to varied water availability.

Bentley (1955) described the ability of the quokka to concentrate its urine so as to maintain a positive water balance when drinking salt solutions as concentrated as 2.5% NaCl. (However, most of his animals were not able to maintain a positive water balance when drinking sea water (equivalent to 3.3% NaCl).) Therefore, animals living on Rottnest Island should be able to satisfy their summer water requirements by drinking any available brackish water, but while they may occasionally drink sea water, it is unlikely that they could survive over long periods with no other source of water. This is borne out by Bentley's field observations: urine samples collected from animals on the island during the winter were dilute while those collected during the summer were more concentrated, but the degree of concentration of summer field samples did not indicate any severe dehydration or show electrolyte concentrations that would indicate that the animals were drinking strong salt solutions. Therefore, animals which survive the summer are able to obtain sufficient water from their food and available fresh or brackish drinking water to maintain a positive water balance.

The structure of the quokka kidney was also described by Bentley and his observations indicated that the relative volume of reabsorptive tubule tissue exceeds the normal value for most other species. This may have physiological significance in relation to the wide seasonal variation in kidney secretory function observed in quokkas living in their natural habitat.

The possibility has been envisaged that if some seasonal fluctuation in the state of hydration of island animals does occur, this might be demonstrated by measurement of total blood volume at different times of the year. Preliminary work to test this was done by Ho (1958) and further work is being carried out by Shield and Woolley, but no definite information regarding seasonal changes is yet available. The method used to assess total blood volume is the Evan's Blue (T1824) Dye method. Ho found that the time for complete mixing of injected dye in the circulation of quokkas is longer than is usual for other mammals and that the plasma volume per kilogram body weight is lower in the quokka (as in other marsupials that have been tested) than in eutherian mammals.

Temperature Regulation

Another important aspect of quokka physiology in relation to their environmental conditions is that of temperature regulation. Homoiothermy is a general feature of eutherian mammals and is largely attained by evaporation of water from the skin and/or lung surfaces in hot ambient conditions, and by peripheral vasoconstriction and shivering in cold conditions. It was at one time thought that many marsupials, including the quokka, were not able to maintain a constant body temperature under conditions of gross changes in environmental temperature. That this is not true of the quokka has been clearly shown by Bentley (1955) and Bartholomew (1956) who observed very efficient homoiothermy in quokkas subjected to high and low environmental temperatures.

Under hot conditions, the animals' respiration rates rose considerably, and Bentley observed that these increases were of the same order as those that occur in eutherian mammals of similar size such as the cat and the rabbit. He also described considerable sweating from the fore and hind paws, which he showed to be the only skin areas containing sweat glands. Both workers also described obvious salivation of quokkas in hot conditions and Bartholomew considered that evaporation of saliva, which the animals spread over their limbs and tail as a result of a "licking response to heat stress," was the major cooling factor. However, it is difficult to distinguish the relative roles of sweat and saliva in this respect since the behavioural licking response would spread both sweat and saliva to increase cooling by surface evaporation. Bentley (unpublished data) has shown that the licking response to heat stress is not essential for maintenance of the homoiothermy exhibited by these animals, by using circular perspex collars that extended out from the neck, to prevent licking. Under hot environmental conditions, collared quokkas showed no increase of body temperatures compared to quokkas without collars; the paws became soaked with sweat which spread up the limbs and evaporation of this, together with the increased respiration rate, provided adequate cooling for the animals. It thus seems likely that the adjustable methods for heat loss in the quokka under natural conditions are largely a combination of panting and evaporation of sweat and saliva from parts of the body. These effects are enhanced by the behavioural pattern of licking. The licking response is acquired early in life (it was observed by Bartholomew in pouch young) and this worker also showed that homoiothermy develops in the quokka during pouch life.

Bartholomew demonstrated that furred quokkas are also able to maintain their deep body temperature at normal levels when subjected to cold conditions with ambient temperatures as low as −10 C. This ability was accompanied by shivering and widespread peripheral vasoconstriction.

No data are available on metabolic rate changes in quokkas under hot or cold conditions.

Blood

Blood Groups

Blood group systems have been demonstrated in several mammalian species and provide interesting material for genetical studies. An investigation of naturally occurring blood group antigens and antibodies in the quokka was carried out by Saunders (1958). The preliminary findings indicate that differences occur between individuals in this regard but further work is necessary to elucidate the genetic mechanisms involved.

Haemoglobin

It has been shown that differences between individuals with respect to the type of haemoglobin in the erythrocytes, occur in several mammalian species. Such differences are genetically controlled. From electrophoretic analysis of quokka blood, Kirk has so far been unable to demonstrate haemoglobin differences between individuals of this species (unpublished data).

Erythrocyte Electrolytes

In most mammalian species, potassium is the predominant cation, sodium being present in only small concentrations. However, in carnivores sodium is the predominant cation in erythrocytes and in sheep, goats and possums, different individuals have either high sodium or high potassium erythrocytes.

Eadie (unpublished data) showed that quokka erythrocytes are unusual in containing roughly equal concentrations of sodium and potassium and that pouch young are not different from adults in this respect; J. Barker (unpublished data) confirmed this in studying the variation of erythrocyte sodium and potassium distribution between individual quokkas and is at present investigating other properties of these cells.

Endocrinology

Adrenal Physiology

The adrenal cortex produces hormones that are essential to life in a wide range of vertebrate species that have been investigated. When these animals are adrenalectomised, they die after varying periods of time (which are fairly characteristic for each species) during which they exhibit typical symptoms resulting from disruption of electrolyte, water and carbohydrate metabolism. However, the North American opossum, *Didelphis virginiana*, has been shown to be unusually resistant to adrenalectomy and there was thus the possibility that this might be a characteristic of the marsupial group. This hypothesis is not substantiated by the observations of Buttle, Kirk and Waring (1952) who reported that adrenalectomised quokkas have a short survival time (approximately two days) during which typical symptoms of adrenal insufficiency, such as loss of appetite, muscular weakness, depression of blood glucose and plasma sodium levels and elevation of plasma potassium, occur.

Animals living under conditions of environmental stress are very dependent on their adrenal cortex secretions which aid the body cells to cope with the additional functional requirements imposed upon them by the stress conditions. In such situations, the rate of secretion of adrenal cortex hormones is increased above normal and if the stress is severe and/or prolonged the animals suffer from exhaustion of adrenal function. A concommitant effect with increased adrenal activity under conditions of stress is depression of the ascorbic acid content of the adrenal cortex. These facts were used by Herrick (unpublished data) in an investigation of variation of adrenal function in quokkas at different seasons, in relation to dehydration stress. Herrick's results indicated that there was an increase in adrenal cortex secretion in quokkas subjected experimentally to severe dehydration. However, he obtained no evidence of unusual adrenal activity or of dehydration in wild animals caught on Rottnest Island during summer or winter months.

The various investigations bearing on water metabolism which have been mentioned provide no evidence that dehydration stress is an important factor in population limitation among the quokkas on Rottnest Island (and see the report on Rottnest field studies in this part). It may, of course, account for death of a small number of animals which were not represented in the samples obtained by the various workers.

Reproduction

Valuable contributions to the field of comparative reproductive physiology have been made by extensive investigations of reproduction in the quokka, particularly since there is remarkably little information of this nature concerning the marsupial group.

Sharman (1954) commented on, and Waring, Sharman, Lovat and Kahan (1955) described the anatomy of the reproductive tract of the female quokka, which is similar in all important respects to that of other marsupials, and of the pouch, which contains four nipples, and recorded some observations on the birth and pouch life development of the young. Thus, the animals appear to be exclusively monovular, since multiple births have never been recorded. New born quokkas (which weigh approximately half a gram) move into the pouch and attach to one of the nipples which hypertrophies, along with the mammary gland that supplies it, as the foetus grows. Only the one nipple is used by any one young during lactation. The sexes are externally indistinguishable at birth and remain so for about three weeks after which either pouch or scrotum can be distinguished. The young are born in an undeveloped condition, but by the time they are about five months old, their eyes are open and they are well covered with fur. They remain permanently in the pouch for a total period of about six months after which they leave it for increasing periods of time until they are finally too large to enter it Even though no longer resident in the pouch, they continue to feed from the elongate nipple which often protrudes from the pouch, until they are about 9-10 months old.

Sharman (1955*a*) studied the oestrus cycle of the adult female quokka. He observed that the non-breeding part of the year (period of anoestrus) for quokkas in the wild lasts approximately from October to January. Towards the end of January, the breeding season starts with the commencement of oestrus cycles—these animals are polyoestrus within the breeding season. As in many other species, domestication results in reduction and finally elimination of the anoestrus period, in which case oestrus cycles recur throughout the year and are only interrupted by pregnancy and lactation. Each oestrus cycle is about 28 days in length. The period of behavioural oestrus in each cycle lasts for about 12 hours and is followed, within the next 24 hours, by ovulation, whether or not copulation has occurred. Details of the changes in the ovaries, uterus and vagina during the oestrus cycle and the anoestrus period are given and similarities between the cyclical changes in the female quokka and those in *Didelphis*, *Bettongia* and *Dasyurus*, the only other marsupials for which detailed information is available, are described.

Details of pregnancy and embryonic development of the quokka were described by Sharman (1955*b*). This account shows that the quokka placenta is of the yolk sac type and that the gestation period is about 26 days. After parturition, the female develops an oestrus condition and ovulation occurs; copulation and fertilisation of the post partum ovum may occur at this stage, but development of this zygote normally proceeds only to the blastocyst stage. While the first young remains in the pouch, the blastocyst stays in a quiescent state, unimplanted in the uterus which remains in an undeveloped state of lactation anoestrus. If the pouch-young is removed, the blastocyst becomes implanted and starts to develop further, the uterus changes to the pregnant condition and a second young is eventually born.

This mechanism would account for the fact that *domesticated* female quokkas have occasionally been observed feeding two young at the one time—one no longer resident in the pouch, but still feeding from the exterior by the elongate nipple to which it was previously attached, and the other newly born and attached to a different nipple. In such a case, the blastocyst would have remained viable for at least five months. However, this mechanism of delayed birth is probably of value in the wild population on Rottnest Island only in cases where the first young of the season is, for some reason, lost during earlier pouch life. By the time the first young normally leaves the pouch, seasonal anoestrus would, in most cases, have commenced in the wild carrying female and under these conditions the quiescent blastocyst degenerates.

Nerve Physiology

Studies are in progress by Collin on the conduction velocity in nerves from quokkas of different size, in order to obtain data on the developmental aspect of nerve conduction.

Pharmacology

The effects of pitressin and pitocin (extracts of the posterior lobe of the pituitary gland) on blood pressure, have been studied in a wide range of vertebrate species. Both drugs affect blood pressure in all non-mammalian species that have been tested, although the effects of each varies in different species. The platypus, a prototherian mammal, also shows blood pressure changes with both drugs. No eutherian mammal has been shown to exhibit a blood pressure response to pitocin, while pitressin causes a rise in blood pressure in these animals. Similar responses to those of the Eutheria have been demonstrated in the only two marsupials—one being the quokka—that have been tested. That this is true for the quokka was first shown by Feakes and Waring (unpublished data) and was later verified by Woolley (unpublished data).

These effects are of interest in relation to the phenomenon of tachyphylaxis (or reduction of response to a drug when serial doses of the same amount are given over a period of time), which has been demonstrated by the above workers in relation to the effects of pitressin on blood pressure in the quokka. Woolley is at present investigating the mechanism by which this tolerance is brought about.

In summary, it can be said that these investigations on the quokka are of great interest in relation to comparative physiology, since relatively little is known of physiological function in the marsupial group. Several unusual mechanisms have been demonstrated and it is possible that some, at least, of these will prove to be characteristic of the macropod group.

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15.—Rottnest Field Studies Concerned with the Quokka

Rottnest Island is a study area of value to field ecologists interested in the dynamics of mammal populations. It is closed to recruitment by immigration and to loss by emigration such as occurs in continental populations in response to climatic or seasonal change.

Its area is 4,700 acres, i.e., not so small as to make it an extremely artificial study area. The single species of indigenous mammal, the quokka, is a herbivore with no carnivorous predator so that no complication in the way of predator-prey relationship obscures the direct relationship of the animals to the environment. The animals are small (adult: 3.5kg), easily caught, and relatively docile when handled. In captivity they domesticate easily for experimental work. Practically all the females have one young per year, there being no observable senescence in the population. Although accounts of the early days of the colony indicate that large numbers of the animals were shot for sport prior to 1914, since that date the Island has become a game reserve and with complete protection the population has become virtually a natural population with human checks removed. All these factors add up to the fact that this Island and its indigenous quokka population provide a relatively simple ecological situation. When it is realised that the search for such situations has in recent years driven ecologists to the simplified regions of the desert, tundra and the steppes, it is fortunate that we have so close at hand in Western Australia a study area capable of producing a growing body of fundamental research on a marsupial population.

One of the fundamental questions of population dynamics concerns the limiting factors of population growth. Starvation and disease are the causes most favoured by mammalogists. Prolonged seasonal adversity in the form of drought in hot deserts and blizzards in cold deserts decimates populations seasonally or periodically. Less frequently it can be demonstrated that the fertility itself is affected by adverse conditions of food, water or disease and this adjusts population numbers without the spectacular death rate associated with the three major limiting factors.

Since the original landing of Volckersen 300 years ago the journals of the various navigators and naturalists indicate that the population of the Rottnest Island quokka was dense enough to elicit comment. Today the quokka numbers are still large. The Island has been separated from the mainland some 7,000 years according to Churchill (1959) and one can speculate that over the major part of this period the density of the animals has been high.

What then are the natural limiting factors of this population? Initially an attempt was made to establish some correlation of death with season. If successful this would give a clue to the probable cause. As no recently dead or moribund animals are in evidence at any season no pathological evidence can be sought to give a lead to the immediate cause of death. In fact animals in this condition are rarely found, as the sick animals presumably seek shelter before becoming moribund and die unnoticed until destruction of the vegetation reveals their skeletons. These are common on the Island. Hence, as the only remaining evidence of natural deaths, a large (600) collection of crania was made in the hope that they would reveal some seasonal pattern of death. It seemed upon analysis that the major part, if not the whole of the population deaths, takes place in the late summer, i.e., March and April. This observation gave a valuable lead because any limiting factor had to be operative at or a little before this period.

With an established season of death further analysis of such a population could proceed on two parallel lines. Either the biotic environment of the herbivore could be studied for the effect of grazing, or the population of animals themselves could be studied by extended sampling, the knowledge of their clinical status providing an assessment of the factors contributing to morbidity. Both these lines of attack have been and are still carried on with the Rottnest Island quokka population. Initially the latter approach was used—an analysis of the physiological status of the population through a complete haematological survey extending over some two years, with large samples of animals, repeated periodically throughout the year. We knew that semi-starvation in general produced an anaemia and that this anaemia was probably of a special type—hyperchromic and macrocytic. Summer dehydration, acute or chronic was expected to produce the reverse picture—a haemoconcentration. Generalised disease has its own general indicators in raised white cell concentrations and high sedimentation rates of red cells whilst the evaluation of vitamin B_{12} deficiency is most easily determined by blood serum bioassay. B_{12} deficiency has not been demonstrated in animals other than the sheep, but seemed a possible limiting factor in this case.

Two study areas have been selected on the Island—one comprising the whole of the west end of the Island: an area of some 500 acres joined to the main island by a narrow isthmus, whilst the other is located adjacent to Lakes Bagdad and Pink and totals in all about 300 acres.

The West End study area contains no free fresh water and the animals presumably satisfy their water requirements from that contained in their food. The other study area—Bagdad—has an ample water supply all the year around as a number of seepages around the periphery of the salt lakes flow summer and winter. To use two areas so dissimilar in their available drinking water for a physiological evaluation of the animals in each could show whether dehydration operated as a limiting factor on the West End animals during the summer, when the mortality pattern appeared constant all over the Island on the evidence of the skull collections. Thus similarity of mortality incidence in West End and Bagdad could suggest that the lack of potable water on West End was not a contributory cause there. However, it is a well known phenomenom that thirsty animals will not eat, so that chronic water shortage leads to starvation which, rather than dehydration, then becomes the proximal cause of death. With this thought in mind the similarity of the seasonal pattern of death in the two study areas may relate to different causes, that of the West End being primarily mediated by dehydration. Inanition due to food shortage in the presence of water and inanition due initially to chronic water restriction, but a really secondary starvation, present clearly separable blood pictures.

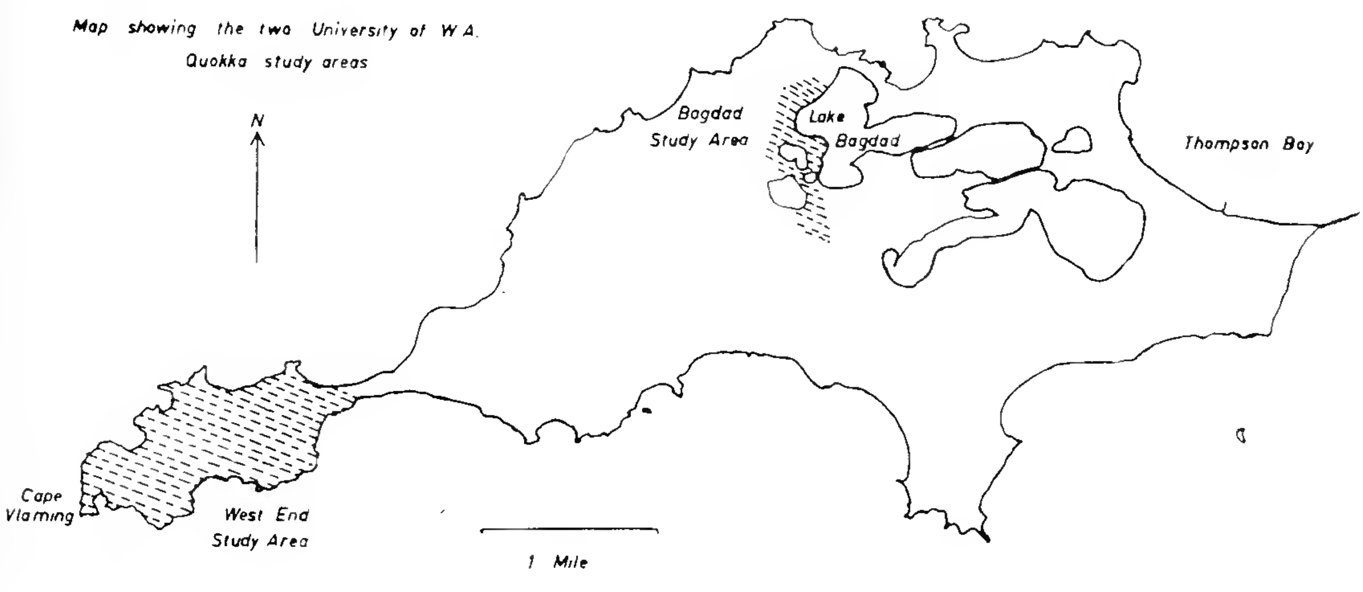
The necessary experimental evidence came from a colony of quokkas kept in the zoology yards which had been subjected to water restriction for a period of 6 or 7 months. The *chronic* dehydration of the experimental animals produced, after some months of continued water restriction, a blood picture which differed both from acute dehydration and primary starvation: on the one hand an anaemia in so far as the haemoglobin and red cell concentrations fell below the average of the control sample as did the haematocrit values, and on the other, an increase of the serum proteins, both albumin and globulin, over those values in the control animals which were maintained on a diet of food and water *ad. lib.*

In the field under summer conditions the blood picture was the same for both areas, giving no evidence that either acute or chronic dehydration supervened in the West End despite the total lack of free fresh water.

With the demonstration by Moir, Summers and Waring (1956) that the quokka was ruminant-like, possessing a large stomach, and an oesophagael groove very like that in the sheep the question arose as to whether low cobalt

ROTTNEST ISLAND

WESTERN AUSTRALIA



values which had previously prevented the establishment of sheep at Rottnest, also affected the macropod population; in particular could this act as a specific limiting factor to population growth? Experimental work with sheep had demonstrated that a drop in serum B_{12} values paralleled a progressively developing "coast disease," overt symptoms of the disease appearing at a definite low level of the serum vitamin concentration in the experimental animals. For this reason it was thought that a haematological survey of the quokka population over a complete season would reveal any deficiency comparable to that in sheep. We were fortunate in having the haematology department of the Royal Perth Hospital able to do all our B_{12} assays. The survey was conducted during 1956-57 and over the whole period for both study areas a total of some 450 animals were assayed. At no season did the Rottnest average B_{12} values fall as low as those in "coasty" sheep. Instead a seasonal variation in the quokka B_{12} level was evident such that the maximum occurs in the late summer, not the minimum which would be expected to correspond to the mortality peak. In addition statistical analysis revealed no correlation with haemoglobin or albumin levels with low B_{12} levels as in the case of experimental animals. Hence, taken together, the several aspects revealed by the serum B_{12} assay indicates that the soil cobalt deficiency (low enough to totally eliminate a eutherian ruminant, the sheep, from the area) does not affect its marsupial analogue, the quokka.

The extreme control of the Island's vegetation by the quokka has been demonstrated in several ways. In February 1955 fires burnt out the whole middle of the Island. Immediately afterwards the Zoology Department erected 25 animal exclusion quadrats on various burnt areas. After two years of subsequent regrowth the effect of the quokka grazing was amply demonstrated by the luxuriant growth inside a majority of the quadrats and the poverty outside. The immediate implication of this was that the animal population itself was being primarily controlled by starvation. Semi-starvation uncomplicated by disease has a fairly definite blood picture (Keys, Brozeck, Henschel, Michelson and Taylor, 1950). There is a rather profound anaemia of the order of 25 per cent. decrease in the haemoglobin, red cell count, and haematocrit. This anaemia is generally of the macrocytic, hyperchromic type. (Over a period of some two years the seasonal anaemia of the quokka during late summer has been of this type, the blood picture corresponding to what the World Health Organization (1951) regards for humans at least as a severe semi-starvation anaemia.) However, these figures are averages. Hence 50 per cent. of the population will be below this value and some smaller percentage will be in the pathological range of blood values indicative of severe starvation. Parallel to the decrease in formed elements of the blood was a decrease in plasma proteins, with this effect more marked in the albumin rather than the globulin fraction.

All the foregoing considerations taken together suggest that it is most probable that semi-starvation is the condition of the general Island population with starvation the fate for some proportion each year, as evidenced by the skull data.

Starvation in mammal populations is rarely unaccompanied by disease when population numbers are high. As previously mentioned no moribund animals were available for their pathology to be determined and so other measures of disease were required. White blood cell concentrations and the sedimentation rate of red cells are general non-specific indicators of disease. True, both these measures are affected by conditions other than disease, e.g., diet and pregnancy, but in general large variation in sedimentation rates indicate tissue destruction, whilst an increase in white cells indicates active increase in phagocytosis. As a result of the survey, cycles were found also in these two blood measures. However, the trends were the opposite to expectation on an hypothesis of seasonal disease in the late summer. The white cell counts on the average fell to low values during this period—this being expected in starvation. Similarly low sedimentation rate values were found in the summer, this probably reflecting the decrease in plasma proteins, which correlation is known to exist.

Rectal temperatures of all animals captured also follow a seasonal trend when plotted. An average drop of some 2.5°C. for the West End animals occurs in the late summer as compared to winter values. A control colony well fed and watered on the mainland shows no comparative drop during the summer. Studies on domestic ruminants have shown that the heat of fermentation as measured by body temperature rise is appreciable after a meal. The quokka being ruminant-like will have a digestion which will also contribute this heat of fermentation to its general metabolic heat. The relatively large drop in rectal temperature at the summer season possibly reflects the starvation, being the combined effect of recession of fermentation and the lowering of the metabolic rate consequent upon starvation.

From this field survey it is seen that positive indications exist only for starvation as the controlling factor of population increase for the Rottnest Island quokka (and see report on the Physiology of the Quokka in this part). Other factors either have contra-indications or no evidence can be adduced for their effect. These indications are over the study-years of 1955 through 1958, but no unusual seasonal or other conditions which could make the study-years non-representative have been discovered.

J. W. SHIELD.

References

Keys, A., Brozeck, J., Henschel, A., Michelsen, O., and Taylor, H. (1950).—"The Biology of Human Starvation" (Univ. Minnesota Press: Minneapolis, Minn.)

Joint F.A.O./W.H.O. Expert Committee on Nutrition (1951).—Prevention and treatment of malnutrition in times of disaster. World Health Organization Technical Report Series No. 45. World Health Organization, Geneva 21.

Fig. 1.—Exclosure in *Acacia* thicket burnt February, 1955, north of Biological Station. Strong regrowth of *Acacia* inside fence hides other species not seen outside. *Stipa* and *Thomasia* clumps in foreground.
Photograph, J. W. Shield

Fig. 2.—Exclosure at Barker's swamp. Note the dense regrowth of halophytes inside the fence. *Suaeda* is abundant inside the fence but rare outside.
Photograph, J. W. Shield

Fig. 3.—Quokka. Flash-light photograph of young adult.

Photograph, A. R. Main

Fig. 4.—Wilson Bay. Wide intertidal platform with outer part terraced. Small intertidal undercut. Note cross bedding in aeolianite rock.
Photograph, E. P. Hodgkin

Fig. 5.—Fish Hook Bay. Photograph taken through deep intertidal undercut at entrance to bay. Low tide. Pole height six feet.
Photograph, E. P. Hodgkin

1955, in centre of island between lakes and narrow neck.
Photograph by courtesy of West Australian Newspapers Ltd.

Photograph, A. R. Main, April, 1957

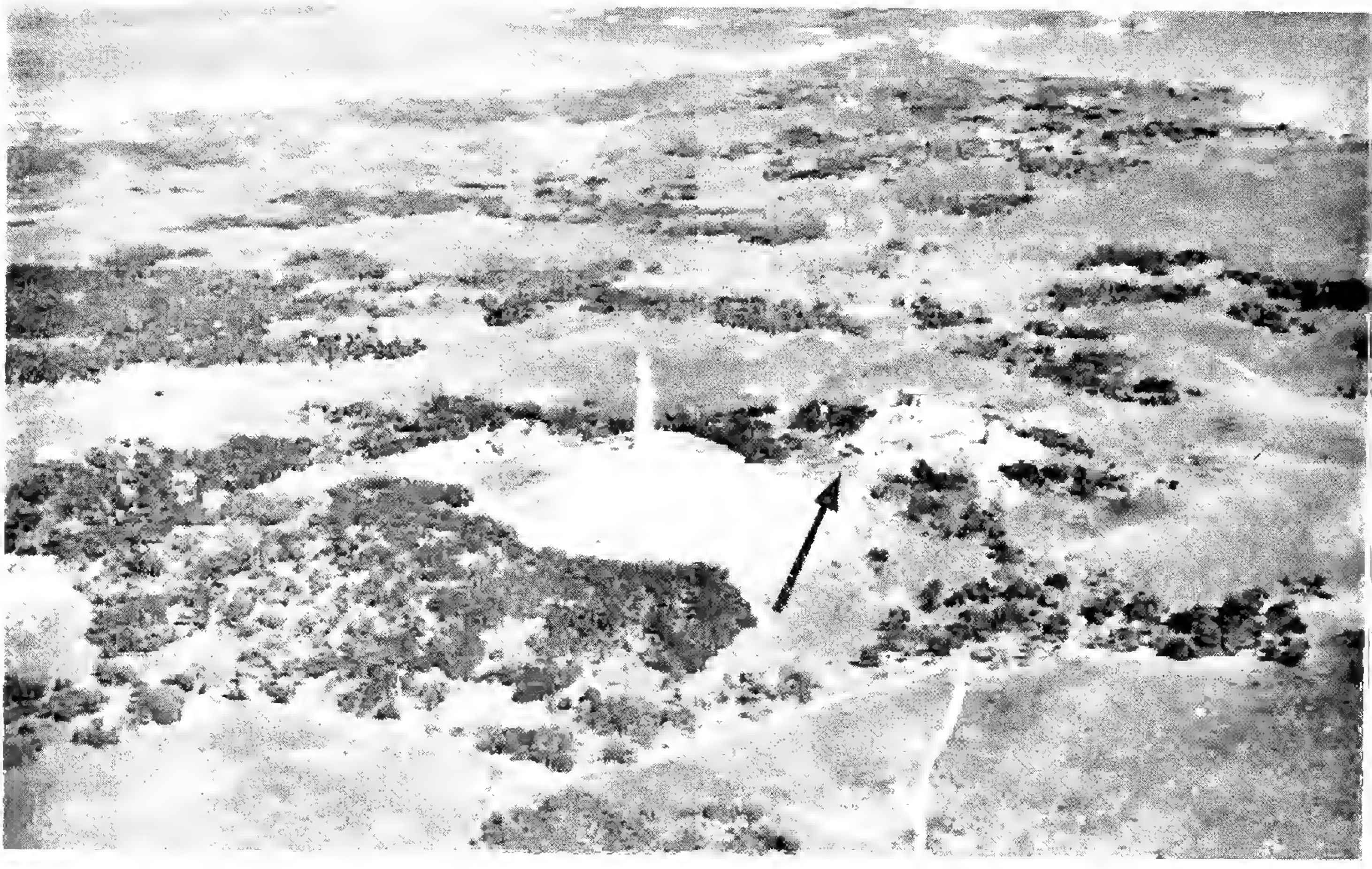


Fig. 8.—Central part of Rottnest Island, looking west, April, 1954. Shows vegetation before the 1955 fire. Arrow points to Biological Station.
Photograph, A. R. Main

Fig. 9.—Aerial photograph shows upper Serpentine and part of main Serpentine lakes. Note seepage area (top and right of upper lake, *Gahnia* clumps adjacent to these, *Melaleuca* copse in foreground, *Acacia* top left, *Tuart* plantation top right.
Photograph, A. R. Main

16.—The Birds of Rottnest Island

For its size (4,726 acres) Rottnest has a disproportionately varied and abundant avifauna, the reason for which is not hard to find. The outstanding feature of the Island is its multiplicity of habitats: steppe, dune scrub, tall scrub, samphire, salt-lakes, brackish swamps, fresh-water soaks, sandy beaches, rocky coasts and offshore islets and stacks. In addition there are the man-made habitats of tuart plantations and grassy clearings.

Systematic accounts of the birds of Rottnest have been written by F. Lawson [Whitlock] (1905), Glauert (1929), and Serventy (1938). In the present paper the birds will be discussed under headings of major habitats.

Open Country

Steppe (dominated by *Acanthocarpus* and tussock grass) is now the widest-spread plant formation on the island. Its chief bird inhabitants are the Pipit (*Anthus novaezeelandiae*), White-fronted Chat (*Epthianura albifrons*), Raven (*Corvus coronoides*), Kestrel (*Falco cenchroides*), and the introduced Pheasant (*Phasianus colchicus*). A surprising absentee is the Black-faced Wood-Swallow (*Artamus cinereus*), which occurs in similar situations along the mainland coast.

Scrub

As on the mainland, dune scrub (*Olearia axillaris* etc.) supports very few species. Only the Singing Honeyeater (*Meliphaga virescens*) is common here. The Spotted Scrub-Wren (*Sericornis maculatus*) is now quite rare.

A more varied fauna occupies the tall scrub (*Acacia rostellifera*, *Templetonia retusa*, etc.), but as this formation is being rapidly replaced by steppe most of its birds are declining. Indeed, two species, the Brush Bronzewing (*Phaps elegans*) and the Rufous Whistler (*Pachycephala rufiventris*) have already disappeared from the island, while the numbers of Golden Whistler (*P. pectoralis*) and Red-capped Robin (*Petroica goodenovii*) are steadily decreasing. The presence on Rottnest of the latter is remarkable, for the opposite mainland is occupied by the Scarlet Robin (*P. multicolor*), which is replaced by *goodenovii* only in the drier country north and east of the jarrah forest. The Western Silvereye (*Zosterops gouldii*) alone is abundant; significantly one of its major food items is the purple fruit of *Solanum simile*, a plant favoured by fire and disturbance generally. Largely confined to the *Templetonia* scrub west of the salt-works is a small colony of Peafowl (*Pavo cristatus*), descendants of birds liberated from the Zoological Gardens about 1912. The two introduced turtle-doves (*Streptopelia senegalensis* and *S. chinensis*) are not strictly scrub-birds: they favour isolated thickets and the contiguous grassland.

Woodland

Woodland is a minor component of the vegetation of Rottnest and accordingly few birds are found in it. The Fan-tailed Cuckoo (*Cacomantis flabelliformis*) is a common visitor in winter and spring to the groves of teatree (*Melaleuca pubescens*) on the eastern end of the island; whereas around Perth its status seems to be merely that of a passage migrant. The wooded margins of swamps and lakes are the principal habitat of the Sacred Kingfisher (*Halcyon sancta*). Large teatrees are the favourite roosting sites of pheasants and ravens, the latter commonly nesting in them. The widespread planting of tuarts (*Eucalyptus gomphocephala*) has provided a niche for the Western Warbler (*Gerygone fusca*), which has recently become established on the eastern end of Rottnest.

Lakes and Swamps

It is on or around the salt-lakes that one finds the greatest concentration of birds. Throughout the year certain of the lakes (especially Government House and Serpentine) support enormous numbers of brine shrimps (*Artemia salina*), which in turn provide abundant food for breeding Silver Gulls (*Larus novaehollandiae*) and Mountain Ducks (*Tadorna tadornoides*). The Banded Stilts (*Cladorhynchus leucocephalus*) that visit the Island in summer feed exclusively on these crustaceans.

The shores of the lakes are occupied in summer by huge flocks of birds that breed in northern Asia; they are composed of the following species (in order of decreasing abundance): Little Stint (*Calidris ruficollis*), Curlew Sandpiper (*Calidris ferruginea*), Turnstone (*Arenaria interpres*), Sanderling (*Crocethia alba*), Large Sand-Dotterel (*Charadrius leschenaultii*), Sharp-tailed Sandpiper (*Calidris acuminata*), Hooded Dotterel (*Charadrius cucullatus*), Greenshank (*Tringa nebularia*), and Golden Plover (*Pluvialis dominica*). The only resident shorebird is the Red-capped Dotterel (*Charadrius alexandrinus*). Exposed shell-banks are the chief nesting site of the Rottnest population of Fairy Terns (*Sterna nereis*). The ubiquitous Welcome Swallow (*Hirundo neoxena*) is most abundant in the vicinity of the lakes, where myriads of flying insects assure it of a regular supply of food.

Fresh and brackish waters support far fewer species. Outside the breeding season the White-faced Heron (*Notophoyx novaehollandiae*) is a common visitor to the Island. Grey Teal (*Anas gibberifrons*) are less frequent. Recently established on Rottnest, the Banded Plover (*Zonifer tricolor*) usually breeds on grassy flats beside fresh-water swamps. Rock Parrots (*Neophema petrophila*) drink at the soaks and obtain much of their food (e.g. samphire seeds) in the vicinity, but for nesting they resort to the offshore islets.

Coast and Islets

Much smaller numbers of limicoline birds are found on the coast than around the lakes. Sandy beaches are occupied by the Pied Oystercatcher (*Haematopus ostralegus*) and the Red-capped Dotterel, both of which are resident, and a few migratory species, especially the Little Stint, Sanderling, and Large Sand-Dotterel. The Turnstone, Grey Plover (*Squatarola squatarola*), and Whimbrel (*Numenius phaeopus*) prefer rocky shores. At low tide, Reef Herons (*Demigretta sacra*) may be seen on the fringing reefs.

Several marine species nest on offshore stacks and islets, viz: Osprey (*Pandion haliaeetus*), Silver Gull (*Larus novaehollandiae*), Crested Tern (*Sterna bergii*), Bridled Tern (*S. anaetheta*), Caspian Tern (*Hydroprogne caspia*), Pied Shag (*Phalacrocorax varius*), and Wedge-tailed Shearwater (*Puffinus pacificus*), though the largest breeding colony of the last-named is on the main island at Cape Vlaming. Non-breeding but regular visitors to the seas off Rottnest include the Gannet (*Sula serrator*) and Arctic Skua (*Stercorarius parasiticus*).

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17.—The Salt Lakes of Rottnest Island

The salt lakes cover some 500 acres at the eastern end of the Island and separate the settlement area from the main part of the Island. At their highest level in August the four main lakes and Garden Lake are continuous. However water lies over the bar between Bagdad and Herschell Lakes only very briefly, and in summer not only does a bar separate Serpentine from Government House Lake, but other smaller portions of the lakes are cut off. Water passes freely through the built up causeway between Herschell and Government House Lakes.

The seasonal change in water level is marked. The highest winter level (August) is 2.8 ft above zero on the Fremantle tidal datum (fixed at lowest low water). By March the level of Lake Bagdad has fallen to +0.5 ft ('57, '58, '59), Herschell and Government House Lakes to —0.5 ft and the main Serpentine Lake to +1.0 ft ('59). Monthly mean sea level varies from 2.8 ft in winter (June) to 2.1 ft in summer (October to January); the lakes are thus below sea level for most of the year.

The lakes have wide, gently sloping littoral fringes and are of no great depth so that the seasonal evaporation results in considerable concentration of the salts. Chlorinity figures for the 1958-59 season are thus shown below:—

Lake	Approx. Depth	Chlorinity, parts per thousand			
		14/9/58	26/11/58	9/2/59	22/3/59
	ft.				
Bagdad ...	8	43	51	67	63
Herschell	16	55	60	73	76
Garden		32	38	60	67
Govt. House	20	65	70	84	88
Pink ...	...	27	46	158	182

There is considerable seepage into the lakes and this shows as a film of water between high and low lake levels. The principal areas of seepage are shown on the map. Most are fresh, with chlorinities between 0.5 and 3.0 ‰, some are brackish and one, on the north shore of Lake Bagdad at its nearest point to the sea, approximates the chlorinity of sea water (19.0 ‰).

The three small western lakes are shallow and Negri and Sirius dry out each summer; from the biological point of view they are best regarded as brackish. The western part of Government House Lake becomes cut off and may also dry out; until recently the salt from this was harvested commercially.

There is no macroscopic plant life in the salt lakes apart from an algal film on the rocks and the spheres of *Botryococcus macropogon* (Xanthophyceae) that are washed up on the shores. *Lamprothamnion macropogon* (Charales) grows in the brackish lakes.

The fauna of the lakes is very restricted in number of species. *Artemia salina* is the principal planktonic animal. It is present in the three large lakes and Garden Lake but is particularly abundant in Government House Lake where the water on the leeward side is often coloured pink by the animals. Chironomid larvae (*Tanytarsus* sp.) and the larvae and pupae of an ephydrid fly are abundant in the algal film on the rocks round the lake margins and at times free in the water. Hydrophilid and dytiscid larvae and adults and the larvae of a trichopteran *Symphitoneuria wheeleri* occur seasonally. Isopods are common under loose stones.

The brackish water gastropod *Coxiella striatula* is abundant in lakes Negri and Sirius; Macpherson (1957) records the type locality of this species as "Lake Ursula," a name used by Mr. Glauert for the seasonal pool in Rifle Range swamp. The crab *Brachynotus octodentatus* occurs in brackish seepage at north Bagdad Lake; this species is common in brackish waters along the south coast of Western Australia. Chironomid larvae, amphipods and ostracods are common in the seepages.

There are extensive shell deposits round the lake margins, both consolidated in the littoral shelves and as unconsolidated material at up to 12 ft above lake level. They are composed largely of lamellibranchs; *Katelysia scalarina* and *Venerupis* sp. appear to be the most abundant, and *Hormomya* sp. nov. is also plentiful. Several species of gastropod are common, including *Notoacmea onychitis* and three species of the small *Diala*; *Eubittium lawleyanum* is abundant in the upper part of some deposits and this appears to have been mistaken for *Coxiella* by Teichert (1950).

In many places there are undercut cliffs near the lake edges similar to the intertidal undercuts of the ocean coasts, and at the same level; they are illustrated by Teichert (1950). The existence of these makes it certain that the lakes were connected to the sea at a time when sea level was little different from the present. Most of the common species of the shell deposits still live in coastal waters near Fremantle (principally in the shelter of Cockburn Sound). Of the others, many, e.g. *Katelysia* spp., are common along the south coast of W.A. and a few are known only from the north west (Shark Bay). Most live in sand or silt but both *Notoacmea* and *Hermomya* live on rocky shores. The fauna is that of a marine gulf under stable conditions of temperature and salinity (G. Kendrick, in lit.).

E. P. HODGKIN.

18.—Fresh Water and Brackish Water Swamps of Rottnest Island

These swamps lie in the eastern half of the Island and, in comparison with the salt lakes, have a very limited area. Most of the larger swamps (Lighthouse, Salmon, Barkers, Bulldozer, Bickley, Rifle Range and Parrakeet) are situated in interdune depressions. Aerodrome Swamp was however, originally part of Government House Lake; it was isolated during the construction of the aerodrome in 1943 and is now much less saline. Corio Pool and the two small Garden Pools lie adjacent to salt lakes and, like the seepages round the lakes, appear to be fed by a seasonally variable seepage. In addition to these waters, there are some wells which act as breeding sites for mosquitoes.

Two important factors affect the biology of the swamps.

(a) Water is generally present only during the winter; the ponds fill near the time of the first heavy winter rains in May or June and the last free water evaporates with the higher temperatures of late October and November. Pools in Bickley Swamp and Aerodrome Swamp may retain water through summer and even in the shorter lived swamps the soil remains moister than in the surrounding dunes.

(b) The water of some swamps is brackish and shows marked seasonal changes in salinity.

Apart from research on frogs and some preliminary studies on dragonflies, no study has been made of the faunal succession of the Rottnest swamps. The frogs have been studied by members of the Zoology Department as part of investigations of the Western Australian amphibian fauna, and the results will be published elsewhere in the near future.

Collections were made from all the freshwaters in October, 1958. Unfortunately, identification of the material is still incomplete, but Table 1 shows the distribution of animal groups. It is evident that not only is the total fauna a restricted one, but that it differs from one swamp to another. It is clear also that animals maintaining populations in the temporary swamps must show certain adaptive characters in relation to the factors mentioned above. *(a)* They must either aestivate as a drought resistant stage or recolonise the ponds annually from the mainland. All the Crustacea belong to groups known to have aestivating eggs, with the exception of the amphipod, which is the littoral rockpool talitrid, *Hyale rubra* (kindly identified by Dr. K. Sheard). In contrast, larval dragonflies *(Anisoptera)* cannot withstand drying and annual recolonisation occurs; successful breeding depends on rapid growth, but in years when the ponds are short lived, breeding is frequently unsuccessful (Hodgkin and Watson 1958). *(b)* They must be able to withstand some degree of salinity; the capacity for osmoregulation being important in the range of swamps inhabited. Investigations of the fauna of the Rottnest swamps must give valuable information relative to adaptation to seasonal aridity and to salinity and may also throw light on divergence from the mainland swamp fauna.

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Reference

Hodgkin, E. P., and Watson, J. A. L. (1958).—Breeding of dragonflies in temporary waters. *Nature Lond.* 181: 1015-1016.

19.—The Littoral Environment of Rottnest Island

Fauna and flora of the rocky shores of the Island have been studied over many years and are now fairly well known. Sandy bays and beaches, and the abundant life of the sublittoral rocks have, however, received little attention. Zonation of the animal and plant life of the intertidal limestone platforms, in relation to tide levels and exposure to wave action, has been the particular interest of the writers. Surveys have been made over a number of years; the results have been presented as theses (Marsh 1955, and Smith 1952) and are in preparation for publication.

Tidal range is small, maximum daily range is about 3 ft and extreme range about 5 ft, sea level being influenced by air pressure, water temperature, and prevailing winds (Hodgkin and Di Lollo 1958). Sea temperature varies remarkably little; it rarely exceeds 23° C or is less than 18° C. The water is generally very clear and estuarine water from the Swan River rarely reaches the east end of the Island, even during heavy winter rains.

Sandy bays and rocky headlands with intertidal platforms alternate around the 20 miles of coastline and narrow limestone bars, barely

TABLE I

LOCALITY		CORIO POOL	GARDEN POOL	LIGHTHOUSE SWAMP	GARDEN POOL (NORTH)	BUCKLEY SWAMP (Pumphouse)	BUCKLEY SWAMP (West Flat)	SALMON SWAMP	TUART PLANTATION WELL	AERODROME SWAMP	BARKER'S SWAMP	BULLDOZER SWAMP	PARRAKEET SWAMP
APPROXIMATE AREA		25 Sq. yd.	15 Sq. yd.	1·2 Acre	30 Sq. yd.	4·6 Acre		1·4 Acre	1 Sq. yd.	1·5 Acre	2·0 Acre	1·0 Acre	0·4 Acre
CHLORINITY ‰ (SEA-WATER 19‰)	18. X. 1958	0·6	1·2	1·7	1·8	2·4		2·6	3·1	4·4	4·8	7·0	Dry
	26. XI. 1958	0·8	2·4	Dry	5·0	3·8		Dry		8·4	Dry	14·2	Dry
	9. II. 1959	Dry	Dry	Dry	Dry	4·2	—	Dry	—	68·5	Dry	Dry	Dry
AQUATIC VEGETATION	"Chara" sp. 1	*	*	*	*	*		*		*	*	*	
	"Chara" sp. 2									*		*	
	Cycnogeton procerum (R. Br.)							*					
	Elodea canadensis Michx.	*											
	Crassula natans Thunb.			*	*	*		*			*		O
	Ruppia maritima L.			*	*	*		*			*		O
	Lepilaena preissii (Lehm.)									*			
FAUNA — ANNELIDA:	OLIGOCHAETA sp.	*	*			*	*				*		
HYDRACARINA:	*Hydrachna* sp.		*			*							
	Eylais sp.	*			*								
	Diplodontus sp.			*									
	sp. 4			*									
CLADOCERA:	*Simocephalus* sp.	*						*					
	Moina sp.			*				*					
	Pseudomoina sp.			*		*	*	*				*	
OSTRACODA:	*Cypris* sp.					*	*	*			*		
	sp. 2	*	*	*	*	*	*	*	*	*		*	
	sp. 3						*	*				*	
	sp. 4									*			
	sp. 5				*					*		*	
	sp. 6	*					*						
COPEPODA:	sp.		*	*		*	*	*				*	
ISOPODA:	sp. 1				*								
	sp. 2									*			
AMPHIPODA:	*Hyale rubra*		*	*		*	*	*				*	
ODONATA	*Anax papuensis*			*	*	O		*				O	
	Aeshna brevistyla	*											
	Hemicordulia tau	*			*	O		O					
	Orthetrum caledonicum	O											
	Austrolestes annulosus			O		*	*	*				*	
HEMIPTERA:	VELIIDAE.	*											
	GELASTOCORIDAE.	*											
	NOTONECTIDAE. sp. 1	*		*	*	*	*	*					
	sp. 2											*	
	CORIXIDAE. sp. 1	*	*			*		*					
	sp. 2					*							
COLEOPTERA:	DYTISCIDAE. (adults). sp. 1		*				*				*	*	
	Lancetes sp.			*	*		*					*	
	sp. 3						*						
	sp. 4	*			*		*						
	sp. 5	*	*	*	*	*	*			*		*	
	Rhantus sp.				*		*					*	
	DYTISCIDAE. (larvae). sp. 1	*	*		*	*				*	*		
	sp. 2			*		*		*					
	sp. 3		*										
	HYDROPHILIDAE (adult) sp.				*	*		*			*	*	
	HYDROPHILIDAE (larvae) sp. 1		*					*			*		
	sp. 2			*		*		*					
	HALIPLIDAE. (adult) sp.					*		*			*	*	
	HALIPLIDAE. (larva) sp.					*							
DIPTERA:	CHIRONOMIDAE. sp. 1					*					*		
	sp. 2		*				*				*		
	Procladius sp.		*										
	Chironomus oppositus		*		*			*			*		
	CULICIDAE. *Aedes australis*		*										
	Aedes camptorhynchus								*				
	Aedes sp.								*				
	Anopheles annulipes			*	*				O				
	STRATIOMYIDAE sp.	*	*	*	*	*	*	*		*	*	*	
GASTROPODA:	*Coxiella striatula* (S shells only)				S	S	S			S	S	*	
AMPHIBIA:	*Crinia insignifera*			O				O					O
	Heleioporus eyrei	O	O	O	O	O	O	O		O	O	O	O
	Hyla moorei Copeland	O	O		O	O							

* — Collected 18. x. 1958. O — Collected prior to 18. x. 1958.

submerged, join headland to headland partially enclosing many of the bays. The littoral environment is made even more varied by the different aspects of the coast: swell is mainly from the SW., with winter storms from the NW.; Cape Vlaming is almost continuously wave beaten, whereas Thompson Bay is sheltered and the sea often calm.

In the bays the water is generally not more than 20 ft deep and the sandy floor bears extensive stands of sea grasses; principally *Posidonia australis* and *Cymodocea antarctica*. The sea grasses are heavily epiphytised by small algae such as *Polycera zostericola*, *Asperococcus bullosus*, *Bryopsis plumosa* and the corallines *Melobesia* sp., *Jania micrarthrodia*, and *Corallina cuvieri*. No systematic study has been made of the fauna; the foraminiferan *Marginopora* lives on the sea grass and is washed up in great numbers on some beaches, the sand anemone *Radianthus concinata*, tectibranchs, and holothurians may be common. The calcareous sand varies from a fine white sand (e.g. west end of Salmon Bay) to a coarse-grained material in which the nature of the shell particles is readily recognised under a hand lens (e.g. Cape Vlaming). The burrowing ghost crab *Ocypode*, the gastopod *Oliva australis*, and the sipunculids occur sporadically, and terebellids and other burrowing polychaetes are common on beaches relatively rich in organic matter. Again this beach fauna has not been specifically studied.

Intertidal Platforms

The rocky shores have the characteristic conformation of all limestone coasts of south western Australia of the type described by Fairbridge (1950): flat, intertidal platforms which vary in width from a few feet up to a hundred yards and in level from just below mean L.W. to almost M.S.L., above this an undercut hard rock face with an overhanging "visor" 6 to 8 feet above the platform; the platform terminates abruptly to seaward and is generally undercut beneath, often deeply. In places the intertidal undercut is replaced by a sloping "ramp", sometimes kept free of littoral organisms by moving sand.

Zonation of fauna and flora is similar to that of mainland coasts. A littoral zone above H.W. is dominated by *Melaraphe unifasciata* and *Tectarius rugosus;* below this two limpets, *Notoacmaea onychitis* and *Siphonaria luzonica*, are dominant down to about M.S.L.; succeeded by the limpet *Patelloida alticostata* in the lowest part of the undercut and on to the platform. The secondary organisms of the *Patelloida* zone, two species of *Patellanax*, *Melanerita*, three chitons, an anenome *(Actinia)* and a barnacle *(Tetraclita)*, vary in occurrence with shade and exposure to wave action.

The rock immediately above platform level often bears sparse communities of macroscopic algae during the winter; *Enteromorpha* sp., *Ulva lactuca*, *Chaetomorpha aerea*, *Cladophora* spp. and *Porphyra umbilicalis* are the chief components. Within the rock surface a permanent community of filamentous blue-green algae extends from platform level to well above the littorinid zone. The more encrusting blue-green, *Calothrix* sp. is also widespread in this zone. Both algal communities form the principal food of the browsing molluscs and are also browsed by the shore crab *Leptograpsus variegatus*.

Where the intertidal platform is narrow the vertical zonation continues with no break to below L.W., and the *Patelloida* zone is succeeded immediately by the lithothamnion zone, described below, which extends to mean low water level. M.L.W. is often marked by an abrupt line, the upper limit of large algae, *Ecklonia radiata* and *Sargassum* spp. marking the sublittoral fringe.

On wide platforms the vertical zonation is interrupted and there is a horizontal zonation across the width of the reef. Because the platforms lie at various heights in the intertidal range, may or may not retain water, and have different exposures to wave action, there is much variation in the development of the zones on the platforms. The following four principal zones can be recognised:

Patelloida **zone.**—Considerable areas of platform are grazed bare by *P. alticostata;* nothing else lives in such places except tufts of small algae on the limpets themselves. This is found particularly on slightly higher parts of platforms from which water drains at L.W.

Jania **zone.**—The coralline alga, *Jania fastigiata*, forms extensive turf-like masses which retain sand and form a matrix in which large stands of *Caulerpa cylindracea*, *Centroceras clavulatum*, and *Laurencia heteroclada* often occur. Small crustaceans, polychaetes and other worms abound in this turf. There are usually few larger animals though the gastropods of the brown algal zone are sometimes common. This community often covers wide areas of platform (e.g. west of North Point), particularly where shallow water lies on the inner parts at low tide.

Zone of brown algae.—Bushy brown and red algae often cover parts of the platform over which water normally washes, even at low tide. The dominant species are the fucoids, *Sargassum* spp., *Cystophora uvifera* and *Cystoseira abrotanifolia*, and the red algae, *Pterocladia capillacea* and *Hypnea musciformis*. The fucoids are often stunted and sterile for most of the year. This algal community provides a suitable habitat for browsing gastropods of which the commonest are *Euplica bidentata*, *Pyrene* spp. and *Senectus intercostalis*.

Lithothamnion zone.—The term "lithothamnion" is used for the encrusting coralline algae which form a thin or thick cover to the rock. It is particularly well developed where waves break on the outer parts of the platform. With it, and sometimes entirely replacing it are the following browsing molluscs: *Onithochiton occidentalis*, *Clavarizona hirtosa*, *Haliotis roei*, *Patelloida alticostata*, *Patellanax laticostata;* of more variable occurrence are the barnacle *Balanus nigrescens* and the anemone *Isanemonia australis*.

In exposed places this zone may be 10 or more yards wide while in more sheltered places it may be only a narrow fringe a foot wide bordering the edge of the platform.

Interesting differences are shown in the development of this "outer edge" fauna. A high ridge at Cape Vlaming constantly swept by heavy waves has an exceptionally dense population of *Onithochiton*, *P. laticostata* and *Balanus* with small numbers of *Clavarizona* and *Patelloida*. High platforms at the outer edge of the main platform in less wave-exposed places have the same species, but dominated by *Patelloida*. On a low level platform in the much more sheltered waters at the west end of Salmon Bay *Haliotis* is abundant and *Clavarizona* largely replaces *Onithochiton*; *Patelloida*, *Patellanax* and *Isanemonia* are also common.

Zoogeography

The littoral fauna of the mainland coast from the mouth of the Murchison River southwards is predominantly Flindersian in its distribution. The littoral fauna of Rottnest however includes a considerable number of species which are Dampierian or found throughout the tropical Indo-Pacific region. They are particularly abundant on the platforms at the west end. A few of these, especially the gastropods, occur further south between Cape Naturaliste and Cape Leeuwin, but most are rare or absent south of Rottnest. These "tropical" species include: Three species of Echinoidea (*Echinometra mathaei* is particularly abundant), six species of *Zoanthidea*, an actiniarian, one coral, *Pocillopora damicornis*, and seven species of Gastropoda. In addition to these we have found ten species of hermatypic coral in the sublittoral; they are most abundant on the south coast where they occur as scattered colonies. *Pocillopora* alone forms a "reef", near Parker Point, but this grows on the limestone and there is no true reef building. Associated with the *Pocillopora* are crabs and gastropods not found elsewhere; hermit crabs are also abundant.

Sublittoral

The intertidal platforms are deeply undercut below low water These "sublittoral undercuts", pieces detached from the edge of the platforms, and the "bars" across bays are the principal rock surfaces accessible from the shore. The algal flora is a rich one and is reasonably well known systematically, mainly from the collections made by Preiss and Harvey in the vicinity of Rottnest in colonial times. The fauna has as yet received little systematic study. Distribution of fauna and flora in the sublittoral rocks is known only from preliminary surveys with face masks and self-contained diving apparatus. The better illuminated surfaces are generally covered by large algae over a lithothamnion encrustation, though flat surfaces sometimes carry a thick cover of *Jania* and other coralline algae. The brown algae *Ecklonia radiata*, *Scytothalia dorycarpa*, *Scaberia agardhii* and *Sargassum* spp. are abundant, also the red alga *Metamastophora flabellata*. On well illuminated rocky substrata towards the sublittoral fringe there is an abundance of Siphoneae, Dictyotales, and Ceramiales.

In the undercut much of the rock surface is again covered by encrusting coralline algae, but leafy algae are sparse and confined to a few Rhodophyceae in the more shaded parts. Beneath the overhanging rock and further back in the undercut the dominant organisms are a great variety of sedentary animals. These include many sponges (16 species being noticed in a collection sent to Dr. M. Burton at the British Museum); hydroids, zoanthids, alcyonarians, corals, and sometimes a rich growth of the many coloured gorgonian *Mopsella* spp.; Bryozoa; and simple and compound ascidians (Kott 1952 and 1957). Actively moving animals are not abundant: those noted include nudibranch gastropods, ophiuroids and a great variety of worms, under the lithothamnion, sponges and ascidians. *Heliocidaris* is present in the sublittoral of Thompson Bay, but the "tropical" echinoids of the west end have not been seen in the sublittoral.

The Crayfish

Panulirus longipes is the commercial crayfish of W.A.: in the year 1958 13½ million lb. of crayfish were taken. This yielded nearly 5 million lb. weight of crayfish tails worth £A2½ million for export to the U.S.A. Commercial crayfishermen operate from boats in water up to 100 meters in depth, but the species is common also on rocky shores around Rottnest and fronting the mainland from Dirk Hartog to Mandurah. During the night the crayfish emerge on to the intertidal platforms and graze on any plant or animal material that projects above the general level of the rock. They return before daybreak to the sublittoral or to large pools in the platform and hide in crevices in the rocks, particularly in the undercut. Investigations by George (1959) into the breeding and moulting cycles and feeding habits were made partly on Rottnest, and these add greatly to basic biological knowledge of the crayfish.

In Rottnest waters the mature females moult in June-July and mate a few weeks later, eggs are discharged on to the pleopods in November-December and fertilized (the spermatophore is ruptured by scratching), eggs are released in January-February and larvae hatch as naupliosoma, after which the female moults again. Tagging has shown that females breed annually. Small immature "white crayfish" have been tagged; when recaptured in the following season most were still whites, but some had normal red pigmentation proving that the white crayfish is only a developmental phase of *P. longipes*—contrary to the belief of many fishermen (George 1958). Recaptures showed a mean increase in carapace length of 0.3 in. or 12.5 per cent in those size groups.

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20.—Population Studies in the Littoral at Rottnest Island

Preliminary studies have been carried out on a common crustacean and a common mollusc of the rocky shores.

Leptograpsus variegatus.—This species of rock crab is ubiquitous throughout the rocky shores of the temperate southern hemisphere. On Rottnest the females are carrying eggs externally from September through the spring and early summer until the end of February. Moulting, as gauged by the feel of soft carapaces when handling the animals, occurs at all seasons but seems to increase in frequency just before and just after the season when the females are carrying eggs. The animals are omnivorous scavengers. They have been noted eating dead fish and limpets detached from the rocks, but they appear to live mainly on the marine algae which they pick from the rock with their pincers.

The natural habitat of these crabs is on rocky surf-exposed shores and rocks just above the water line. During the day they retire into rock crevices or hide in rock debris. However they are known to move about in the shadow during the day but are extremely wary and retreat to cover in a flash if approached by an observer. At night the behaviour pattern is entirely changed. When approached by an observer with a flashlight the crabs in most instances remain motionless or continue eating. Their capture and examination is extremely easy under these conditions.

As the specific name indicates, *Leptograpsus* is noted for the individual colour variation which ranges from a very dark blue to orange and a light slate colour. By arranging some 200 of these crabs in a colour sequence it was obvious that this great variation in colour was not continuous but discrete. There were in fact only two distinct colour groups the one a blue phase and the other an orange grading into slate. The latter phase contained a preponderance of orange coloured males and, contrariwise, a preponderance of slate coloured females.

The study method used is to walk along the reef platform at night with a flashlight in several selected study areas and by this linear traverse method score some 150-200 crabs for colour phase, sex, place in the undercut (whether in the splash zone, water, or on the dry rock face). The linear sequence of such observations is preserved. The study areas have in most instances been marked with paint division lines—generally the whole traverse is divided into 10 subdivisions.

Analysis to date of these traverse scorings has revealed several interesting facts. Firstly the colour phases seem to have differing affinities for the rock positions where they feed. Blue phase crabs show a propensity to locate themselves higher up on the rock face whilst the orange and slate colours have a tendency to be found lower down on the wet rock face or actually in the water. Secondly, by subdividing the traverse it has been possible to determine whether the one phase tends to inhabit a certain locality. This has proved the case; certain areas have a stable population of one phase rather than the other and this stability is maintained throughout the season. One study traverse—Wilson Bay—has been intensively worked over a period of two years and the above results are mainly from this place. However about 6 other standard study traverses have been worked and the analysis from all these places supported that from Wilson Bay. It appears that the orange/slate phase prefers the wetter part of its habitat. It inhabits the lower part of the reef predominating where the undercut faces open or broken water, i.e., those sections of the traverse having a preponderance of orange phase animals are generally those where the surf breaking on the rock is more intense.

Here then we have a polymorphic species in which the morphs have separate ecological preferences. These preferences are not absolute ones but are only revealed and statistically established after a large number of observations. Perhaps this species is in the process of splitting into two species in an early stage of Darwinian evolution.

Melanerita melanotragus.—The black periwinkle *Melanerita melanotragus* abounds on the limestone surf rocks about mean sea level over the whole of Rottnest. It has attracted interest as an experimental animal for population studies because of several of its attributes. The variation in size of individuals of the various colonies throughout the island is great. In areas where there is a low density the animals tend to grow to a large size and where the concentration is high they are of a relatively small average size. Moreover these average sizes and the population size compositions have not changed over a period of 5 years. Four experimental populations have been divided into 5 size classes over this period by seiving through standard mesh screen; all populations appear to be maintaining their size composition. Further work is devoted to determining whether this stability is environmental or genetic, or whether the fortuitous initial density of animals is the controlling factor.

Some five years of marking of individual animals indicates that the extreme age of the animals can probably exceed 15 years. In addition this work has shown that although in general the animals are restricted in their movements they can move up to 16 feet over the rock face in one night.

The studies are proceeding mainly with the aid of student labour; further work is to be devoted towards establishing life tables for the several study populations.

J. W. SHIELD.

21.—Student Training at the Rottnest Biological Station

At the present time the Station is used only by the Zoology Department for regular student training although staff and students of other University departments use it from time to time. Training is at three levels: postgraduate, during the third year of the degree course, and at the beginning of the second year.

Postgraduate

Participation in research projects discussed in other parts of this report has formed a large part of the training of Honours, M.Sc. and Ph.D. Candidates. The Station has been the base for their field operations with the island fauna their main research material. No separate account of this aspect of student training is required here.

Population Ecology

At the end of their third year course students spend a week at the Station making a practical study of the dynamics of animal populations. This is regarded as an integral part of the Zoology course and a short written examination has been included during the last two years. The fact that staff and students live and work together the whole time effectively counteracts any tendency to take the course light-heartedly after the major examination tension has ended. There are opportunities both for fun and relaxation and for stimulating discussion as a result of common interest in the problems studied. For staff this is often also an opportunity to evaluate the results of the year's teaching, sometimes with outspoken criticism from students, and to plan future teaching and research programmes.

The ordinary laboratory course necessarily presents the student with the animals he is studying as individuals. Whether it be in the study of systematics, comparative anatomy, or physiology, the animal is usually treated as a unit, representative perhaps of a family, class, or phylum, but rarely as one of a population of similar individuals. In this field course emphasis is laid throughout on a study of quantitative attributes of populations of animals: reproductive rates, mortality rates, immigration and emigration rates, age structure, and total numbers in the populations.

The methods used are those which have yielded research results in population studies. The same species of animal, and in many cases the same populations, have been studied in successive years and the results obtained form part of research programmes discussed elsewhere in this report.

The statistical knowledge necessary to the working of the various estimates is acquired through a series of lectures in biological statistical methods given during the third-year course.

The principal animals studied are:

1.—Jewel beetles, *Castiarina hopei*, on flowers of the "Rottnest daisy." Random samples are captured on discrete daisy patches, marked, released, and recaptured over successive days, with the object of determining adult life span, adult recruitment rates, and population total numbers.

2.—The black periwinkle, *Melanerita melanotragus*, on intertidal rocks. This has proved ideal for student exercises in estimation of population size because estimates made by the mark and return method can be immediately checked by a total physical count.

3.—The whelk, *Dicathais aegrota*, on intertidal rock platforms. Samples attracted to baited traps are marked, returned, and recaptured. "Latin square" evaluation of captures makes it possible to study food preferences and distribution on the platforms.

4.—The rock crab, *Leptograpsus variegatus*, is caught by hand at night on intertidal rocks for estimation of total population and habitat preference of the three colour phases. The size of the population is determined by the method of removal of one sex and a subsequent count to reveal a change in sex ratio from which a population size estimate is made.

5.—The quokka: estimation of population size by ear tagging and return, and a measure of relative abundance by visual counts on a regular circuit.

Second-year Camp

This is held over four days immediately before the start of first term and all students entering the second year course in Zoology are required to attend. The camp has two main aims: first to enable staff and students to get to know one another in the friendly atmosphere of a camp, and second to introduce students to living representatives of the various phyla.

The marine environment is the richest source of material and receives most attention, but collections are also made in the salt lakes to show the restricted fauna of a specialised environment, and students assist in aspects of the quokka research programme. Animals collected are brought back to the laboratory and are identified as far as possible with standard texts, by means of simple keys, and sometimes by reference to original literature. In most cases no attempt is made to run them down to species, the emphasis being rather on learning to recognise the broad systematic position of the animals and to know *how* to identify them.

The second year course has an ecological background, but animals handled in the systematics course are of necessity often preserved. The emphasis in this introductory camp is on seeing as many kinds of animal as possible alive in their natural environments. Attention is constantly drawn to the relationship of the animals to their physical environment and to one another.

E. P. HODGKIN and J. W. SHIELD.

22.—Rottnest Island Board

Background

For many years Rottnest had provided a secure place of confinement for native prisoners, but as farming areas developed on the mainland and the country became more settled so the need for such a place grew less urgent. At the same time the Island was used as a desirable place of recreation by the fortunate guests at the Government House shooting parties but no members of the public were allowed to land without permit. A flush of money at the time of the gold rush in the eighteen-nineties enabled the building of several ministerial cottages along the Thompson Bay front.

First mention of the possibility of a wider recreational use seems to have come from the Speaker of the Legislative Assembly after his first taste of island hospitality. In 1905 he urged the development of the Island as a tourist resort. Immediate steps were taken to survey the position, and a most extravagant plan of works emerged. Only strong outside pressure prevented the subdivision and sale of 300 blocks of land on the Island to provide finance for this.

Vice-regal support for a wider use was positive as will be seen from the following extract from a minute dated March 1907, from the office of His Excellency Admiral Sir Frederick Bedford:

(1) The Island should be declared a Public Park and recreation ground for ever. It is very desirable to avoid the idea getting about that the Island is being exploited for the benefit of the few men, who at this time could afford to buy or rent plots to build.

(2) That the natural beauty of the Island shall not be disturbed more than is absolutely necessary.

(3) Better communication with mainland.

(4) That it should be made more attractive by planting trees and making roads.

Further opposition killed any idea of subdivision, and the government began some small building development in the area of the present barracks. A change of government swung the location of settlement in the opposite direction towards Bathurst, but before much could be done the impact of World War I held up all progress while during a long term stay of prisoners-of-war much was destroyed of what little building had been attempted.

On 12/5/17 the Island was gazetted a Class A Reserve under "The Permanent Reserves Act, 1899," and a Board appointed under the Chairmanship of the Colonial Secretary (Mr. H. Colebatch). As it received no subsidy, the Board immediately found itself in financial difficulty. To this day the Board functions under the same condition and under the same anxiety. In order to arrive at some measure of assistance, the experiment was tried of establishing a new prison camp in the valley between Lakes Herschell and Bagdad, for good conduct prisoners. This however proved unsuccessful and after three years, 1922 saw the departure of the last prisoners, white and black. (The Boys' Reformatory in the present Hostel had ceased to function in 1901.)

Present Constitution

The Board today functions under the Parks and Reserves Act, and in status is a statutory body free of any departmental authority. With its freedom of function however, it remains free of subsidy so that its very limited resources come from rents, leases and landing fees. One exception is the recent establishment of water catchment area and storage of approximately one and a half million gallons—a project quite beyond the resources of the Board and met by the government of the day.

The Board is presided over by a Minister of the Crown (in 1958, Mr. Kelly—Minister for Lands and Agriculture) and its personnel consists largely of experts in the field of building and architecture, engineering, roadmaking and law.

The duties of the Board embrace:

(a) The extension of residential facilities.

(b) The maintenance of existing buildings.

(c) The maintenance and extension of services—water, sewerage, lighting and power.

(d) Administrative.

(e) Beautification of island, particularly in the restoration of trees.

(f) Development of recreational services.

(g) Protection of the Island's natural resources.

The Island administration is in the hands of the Managing Secretary, who is resident there.

Biological Aspects

On the one hand the Island presents a wonderful potential for natural life, with its sheltered valleys, its many protected bays, its very large expanse of wide shore reefs and its delightful system of salt lakes. Unhappily on the other hand it is a typical example of the human flair for destruction of natural resources. Decades of bushfire destruction—much of it deliberate to disclose game—have reduced half the Island to bare heath. Present day control in this respect has been offset by protection of the indigenous quokka, which has now increased very greatly in population to the extent that natural regeneration of unprotected vegetation is practically impossible.

The protection of the crayfish from illegal fishing is a major problem with such a long shore line and with settlement so firmly established at one end. At the moment the spear fishermen are suspect of large scale disturbance if not depletion of marine life in the pools and reef areas. The birds appear to be comparatively free from disturbance and the eye of the visitor is delighted with the sight of the many aquatic birds about the lakes. An occasional peacock and the small population of pheasants are descendants of those introduced in the year 1912. There is also a well established population of small land birds.

Re-afforestation

Over the last three decades the Board has been actively engaged in an attempt to restore some of the lost vegetation. The main indigenous trees of the Island include; *Callistris robusta* (Rottnest Pine); *Melaleuca pubescens* (Rottnest Tea Tree); *Acacia rostellifera* (Rottnest Wattle); *Pittosporum phillyracoides* (Native Pittosporum); *Templetonia retusa* (a shrub).

As early as 1886, a grant of £50 for the establishment of a pine plantation allowed the experimental planting of 500 trees of several types in the Bathurst area. Reports in 1889 indicated an almost complete failure due no doubt to the combined influences of soil deficiencies, wind, drought and the attacks of animals.

There was no revival of effort till 1907 when 200 trees were planted at Mt. Herschell and 600 near Bickley Swamp. Before the onset of summer practically all with the exception of a few aloes were lost. Later still more care and watering developed the magnificent avenue of Moreton and Sydney figs and olives through the settlement and the large pines to be found in the older parts of the settlement.

It rested with the late Dr. W. Somerville to bring to bear the conviction and energy necessary to force successful results.

A disappointing start in 1929 stressed the need for a local nursery. From 1932 onwards the story is one of continual progress. After experimenting with native trees from the mainland, the outstanding result was the discovery of the hardihood and quick growing qualities of the Tuart (*Eucalyptus gomphocephala*). Somerville's book "Rottnest Island" from which much of this information was taken, shows photographs of trees planted by Italian prisoners-of-war in 1942. After seven years these trees had reached a height of 55 feet. Between 1934 and 1944 he was responsible for the raising and planting out of 5,000 tuarts in the plantation near the head of Serpentine Lake. At the same time there was developing to the north of the settlement a large plantation for use as a camping area. Altogether during eleven years it was estimated that 41 acres of plantation and 210 chains of line planting had been effected. Planting has continued at the approximate rate of five to six hundred trees per year. The present beautification of the settlement area stands as a memorial to Somerville, who was also largely responsible for the original planning of the beautiful University grounds at Crawley. As an example of the experimentation that went on, the following still exist on the Island, *E. gomphocephala* (Tuart), *Ficus macrophylla* and *F. Australis*, *Araucarea excelsa* (Norfolk Is. Pine), *Agonis flexuosa* (Peppermint), *E. erythrocorys*, *E. meliodora*, *E. camaldulensis*, *E. torquata*, *Casuarina glauca* and *C. stricta* (Sheoaks), *Ceratonia siliqua* (Carob Bean), *Olea europea*, *Melea azedarach* (Cape Lilac), *Pinus halepensis* (Aleppo Pine), *P. pinea*, *P. canariensis* (Canary Island Pine), *Cupressus* sp., *Washingtonia felifera*, *Pheonix canariensis*.

Present Activity

Somerville's phase of activity resulted in the beautification of the settlement. The next stage of development (now under way) consists of the effort to replace valley groves and to line the main tourist roads with quick growing trees. Line planting along the north road across the lakes has reached the sealed road and is expected to reach the central light-house next season. In order to re-establish valley groves it is necessary to enclose areas for protection of young trees against the quokka, and in this project there are to date six large fenced areas and a number of small areas all planted with trees. The first two have reached the stage when next season the fences will be removed to fence two fresh areas. Happily, sales of quokkas to overseas zoos have gone a long way towards financing these ventures. In general the policy is to try and preserve the balance between native and exotic, for which reason emphasis in 1958 was given to Tea Tree and special attention in 1959 will be devoted to Rottnest Pine.

As an example of the scale of planting being attempted, this season's planting (1958) is a record planting of 1250 trees, mostly line and plantation. Experimental planting has included, Native Pittosporum (indigenous), *E. lehmanii*, *E. calaphylla*, and palms, unnamed, from U.S.A. With the help of public donations following disastrous fires a few years ago, the nursery has been enlarged and reorganised. Leading from the nursery an avenue of young trees show examples of the types now being used.

Scientific Use of the Island

It is appropriate and very desirable that the unique features of the Island should be available to scientific study and experiment. In 1930 the then State Apiculturist (Mr. W. Lance) established an apiary for the breeding of pure Carniolan Queens, and this is now a well established project.

In more recent years the Biological Committee, representing Fisheries Department, University Department of Zoology, and K. Sheard have found it possible to establish permanent quarters in the centre of the Island. Apart from what help the Board can offer in the matter of labour, there is little that it can do to help such highly specialised bodies. There are however fairly frequent occasions when good turns can be offered from both directions. At all times in both the apicultural and the biological fields, relationships with the Board and Board Management have been excellent. From the beginning the Board was represented at Biological Section meetings. In the early stages, its Chairman attended to represent the Board and in latter times his place has been taken by the Board member most interested in the biological field (Mr. T. Sten). The same relationships exist with the Departments of Agriculture, Forestry and other bodies to whom the Board must turn from time to time for expert advice. It is not to be expected that the full scientific potential has yet been exploited, and it is to be hoped that the Island will be able to make an even greater contribution in this direction in the future.

T. STEN.

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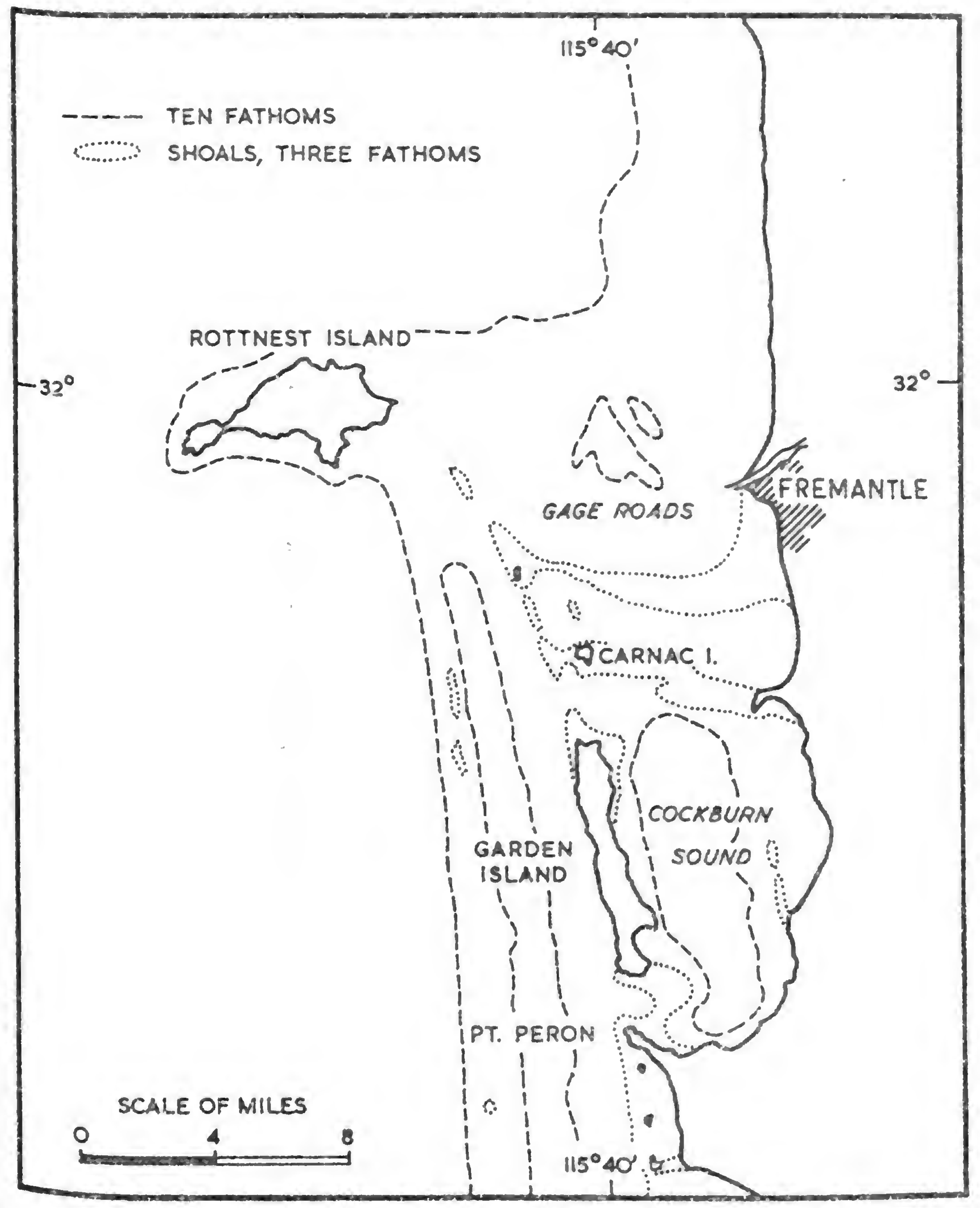
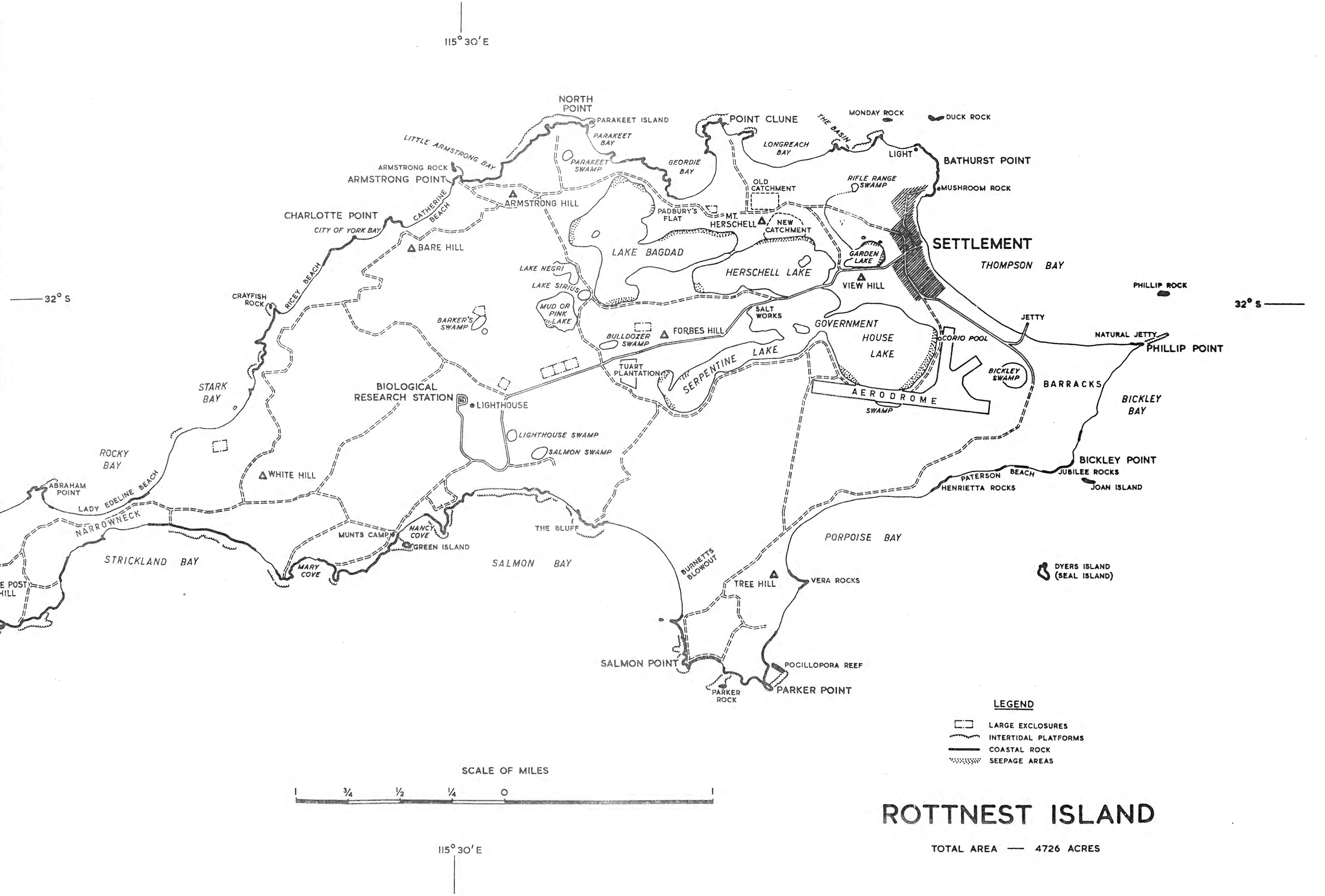
In each the present address is given first where that has changed; that during the course of the contribution second, in brackets.



LOCALITY MAP



ROTTNEST ISLAND

TOTAL AREA — 4726 ACRES

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24.—The Effect of Frequent Burning on the Jarrah (Eucalyptus marginata) Forest Soils of Western Australia

By A. B. Hatch*

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An examination of the surface soils from regularly burnt firebreaks and adjacent protected compartments in the jarrah forest of Western Australia showed no differences in the following analyses; pH, total soluble salts, organic carbon, nitrogen, exchangeable metal ions and exchangeable hydrogen.

It has been shown that the temperatures of these controlled burns are of the order of 320-450°C., and the forest soil is not exposed to any prolonged high temperatures.

If the burning does cause any temporary loss of organic matter and inorganic nutrients from the immediate surface soil these losses are replaced by natural leaching of the following year's leaf fall.

Introduction

In the fire protection of the jarrah (*Eucalyptus marginata*) forest in Western Australia regular controlled burning of strips of forest along railway lines, main roads, etc. is carried out to reduce the fire risk to adjacent areas of forest. This burning is normally carried out during the latter spring months and the first half of December, and the frequency of burning of these firebreaks varies from annually to every third year, depending on the litter fall and the fire risk involved.

The forest country adjacent to the breaks has been protected from fire as completely as possible for periods ranging from 15 to 25 years, and has an Ao horizon ranging from 4½ - 6½ tons per acre (oven dry weight). By contrast the firebreaks have only a sparse accumulation of litter, which is regularly removed by burning.

The aim of this study was to compare the chemical properties of the two groups of surface soils, and to ascertain what changes had taken place in the surface soils as a result of the regular burning.

Location

The samples were collected from several areas in the Dwellingup Forest Division, which forms part of the prime jarrah forest of Western Australia.

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Climate

The jarrah forest region experiences a typical Mediterranean climate, with cool wet winters and hot, dry summers. The average annual rainfall at Dwellingup is 50.88 inches, spread over 134 days. The rainfall distribution shows a marked winter maximum, 81 per cent. of the annual rainfall occurring during the months May to September. The mean monthly temperatures vary from 69.7°F. in February to 49.4°F. in July.

Soils

The soils are typically lateritic gravelly soils with a shallow dark grey gravelly sand overlying deep yellow brown very gravelly sands. Laterite boulders occur frequently throughout the profile.

Experimental

Surface soil samples, (0-3½") were collected during January, 1954, from twelve pairs of adjacent areas, using a constant volume soil sampler. The areas were selected for similarity of topography, soil and forest vegetation. Details of the fire history of these areas are shown in Table I.

TABLE 1

Experimental Areas
Fire History

Location.	Fire History. Compartment.	Fire History. Firebreak.
1. Amphion, Compt. 6	1932	Triennially.
2. Curara, Compt. 5	1930	Annually.
3. Curara, Compt. 8	1937	Triennially.
4. Holmes, Compt. 1	1929	Annually.
5. Holmes, Compt. 3	1934	Annually.
6. Holmes, Compt. 11, Plot 11	1934	Triennially.
7. Holmes, Compt. 11, Plot 13	1934	Triennially.
8. Holmes, Compt. 12	1934	Triennially.
9. Holmes, Compt. 14	1935	Triennially.
10. Marrinup, Compt. 4	1938	Annually.
11. Mt. Wells, Compt. 10	1931	Frequently.
12. Teesdale, Compt. 2	1939	Triennially.

In the soil sampling, twenty-seven individual samples were collected from each of the burnt and unburnt areas, and combined to give three composite samples from each treatment.

In the laboratory the samples were air dried, and then passed through a 2 mm sieve. The fine earth fractions were analysed for pH, total soluble salts, organic carbon, nitrogen, exchangeable metal ions and exchangeable hydrogen.

In the analysis of the soil samples, most of the methods used were those described by Piper (1942), but at a result of recent investigations a newer method was used for the determination of the exchangeable metal ions. These were extracted by leaching with neutral normal ammonium acetate, and the calcium and magnesium determined by titration with E.D.T.A. after destruction of the ammonium acetate. (Bond and Tucker 1954 and Hutton 1954). Potassium and sodium were estimated by the EEL flame photometer (Hutton and Bond unpublished data) after the ammonium acetate had been removed by gentle ignition.

Analytical Data

The means for the two groups of surface soils are tabulated in Table II, and in addition the individual means for pH, nitrogen and exchangeable calcium are shown in Tables III, IV, and V.

TABLE II

Analytical Data

Surface Soils (0-3½") from Protected Compartments and Regularly Burnt Firebreaks

Analysis	Means				Difference		P .05 Difference for Significance	
	Compartment		Firebreak					
pH	6·27		6·38		0·11		0·21	
Total Soluble Salts (%)	0·016		0·015		+0·001		0·005	
Organic Carbon (%)	2·96		3·00		-0·04		0·64	
Nitrogen (%)	0·125		0·128		0·003		0·025	
Exchangeable Cations								
Calcium m.e. %, %	3·92	67	4·23	69	—0·31	—2	1·25	4·9
Magnesium m.e.%, %	1·35	24	1·42	23	—0·07	+1	0·46	3·3
Potassium m.e. %, %	0·11	2	0·10	2	+0·01	0	0·03	0·4
Sodium m.e. %, %	0·35	7	0·34	6	+0·01	+1	0·11	2·6
Exchangeable Metal Cations	5·73	100	6·09	100	—0·36	—	1·67	—
Exchangeable Hydrogen (pH 8·4)	12·00		10·97		+1·03		2·70	
Total Exchange Capacity m.e. %	17·73		17·06		+0·67		4·05	
Per cent. Metal Iron Saturation	32·1		35·5		—3·4		4·4	

It is evident from the data that this regular light burning has had no significant effect on the surface soil properties examined.

Both groups of soils are mildly acid, and low in soluble salts. Organic carbon values are relatively high, but nitrogen values are low, giving wide C/N ratios of 24 and 23 for the compartments and firebreaks respectively. These wide C/N ratios are related to the litter fall in the jarrah forest, which is very high in carbon and has a C/N ratio of approximately 100.

In both groups of soils the cation exchange capacity is almost solely dependent upon the organic matter present in the surface horizon, and is relatively low. Calcium is the dominant exchangeable cation in the surface, averaging two thirds of the total exchangeable metal ions. Magnesium is next in importance and potassium and sodium are only of minor importance in the total exchangeable metal ions.

Exchangeable hydrogen values (to pH 8.4) are relatively high, and the soils are moderately unsaturated, the percentage metal ion saturation being 32.1 and 35.5 per cent. for the compartments and firebreaks respectively.

Discussion

There do not appear to be any Australian data available on the effects of fire on the Eucalypt forest soils, and it is difficult to compare the jarrah forest conditions with those quoted by overseas workers.

From a study of the literature it appears to be generally accepted that a very hot fire, such as a slash burn, where fire temperatures are of the order of 850°C. for a prolonged period, has a significant effect on soil properties. Under these conditions there is usually a decrease in organic matter, loss in nitrogen and increase in pH in the surface soils.

However, opinions differ very widely when considering the effects of light and moderate burns on the soil properties.

One group of workers claim that burning has a detrimental effect on the soil. Amongst these are Worley (1933) who stated:

(i) that burning destroyed humus.

(ii) that resultant ash from the burn, containing small amounts of essential elements such as copper and manganese, is easily lost through leaching and a general impoverishment results.

Freise (1939) claimed that repeated burning had an unfavourable effect on the physical and biological properties of the soil, and Elwell and Fenton (1941) stated that burning caused a loss of soil nitrogen, destroyed organic matter and increased soil and water losses.

A second group of workers believe that burning has no significant effect on the soil. Amongst these are Alway and Rost (1928) who suggested that burning appears to be neither beneficial nor detrimental to the soil, and Blaisdell (1953), who claimed that light and moderate burns do not affect soil properties.

TABLE III

Analytical Data

Surface Soils (0-3½") from Protected Compartments and Regularly Burnt Firebreaks

pH Values

Location	Mean Values		Difference
	Compartment	Firebreak	
Amphion, Compt. 6	6·47	6·54	0·07
Curara, Compt. 5	6·27	6·48	—0·21
Curara, Compt. 8	6·26	6·47	—0·21
Holmes, Compt. 1	6·57	6·50	+0·07
Holmes, Compt. 3	5·85	5·93	—0·08
Holmes, Compt. 11, Plot 11	6·19	6·27	—0·08
Holmes, Compt. 11, Plot 13	6·49	6·17	+0·32
Holmes, Compt. 12	6·16	6·34	—0·18
Holmes, Compt. 14	6·24	6·36	—0·12
Marrinup, Compt. 4	5·72	6·27	—0·55
Mt. Wells, Compt. 10	6·47	6·86	—0·39
Teesdale, Compt 2	6·54	6·41	+0·13
Means	6·27	6·38	—0·11

P ·05 difference for significance = 0·21.
Each value shown is the mean of three composite samples.

The third group believe that light and moderate burning has a favourable effect on the forest soil. One of the most important papers in this group is that of Heywood and Barnette (1934), who showed that soils frequently subjected to fire were consistently less acid, and had higher percentages of exchangeable calcium and total nitrogen. Also Burns (1952) found that moderate burning benefited the mineral soil chemically, and probably had a favourable effect on the forest floor, and in 1955 Vlamis, Schultz and Biswell demonstrated by means of pot experiments that light burning increased the nitrogen power of the soil fourfold, and in addition tended to increase the phosphorus supplying power of the soil.

TABLE IV

Analytical Data

Surface Soils (0-3½") from Protected Compartments and Regularly Burnt Firebreaks

% Nitrogen Values

Location	Mean Values		Difference
	Compartment	Firebreak	
Amphion, Compt. 6	0·120	0·132	0·012
Curara, Compt. 5	0·122	0·144	0·022
Curara, Compt. 8	0·152	0·179	0·022
Holmes, Compt. 1	0·090	0·122	—0·022
Holmes, Compt. 3	0·121	0·115	+0·006
Holmes, Compt. 11, Plot 11 ..	0·079	0·097	−0·018
Holmes, Compt. 11, Plot 13....	0·097	0·157	0·060
Holmes, Compt. 12	0·137	0·095	+0·042
Holmes, Compt. 14	0·100	0·142	0·042
Marrinup, Compt. 4	0·176	0·094	+0·082
Mt. Wells, Compt. 10 ...	0·122	0·126	0·004
Teesdale, Compt. 2	0·184	0·132	0·052
Means	0·125	0·128	− 0·003

P ·05 difference for significance = 0·025.
Each value shown is the mean of three composite samples.

It is evident that the data for the jarrah forest soils strongly supports the second group of workers in that there were no significant differences in the surface soil properties examined.

With regard to the effect of the control burn on the forest crop it has been shown by Harris (1956) that the best of the older jarrah saplings are found alongside the old bush tramways, where fires were set by the locomotives as often as a fire would run. In addition Loneragan, (unpublished data) and Harris (1956) have shown that there is no significant difference in girth increments between saplings on regularly burnt firebreaks and protected compartments.

In considering the effects of the controlled burnings of the jarrah forest soil there are several factors which appear to be related to the lack of differences between the two groups of soils.

Firstly, the temperature of the burn is not high, and in some experiments carried out at Dwellingup, it was found that the temperatures of a controlled burn were of the order of 320°-450°C. for two and three year old litter. Secondly, the litter on the firebreak consists mainly of leaves and fine twigs, and thus burns rapidly. Therefore, the soil is not exposed to prolonged high temperatures in the controlled burn. In connection with this work it has been shown by Heywood (1938), that in the Longleaf Pine region of Southern U.S.A., the heat from the majority of forest fires is insufficient to impoverish the soil, and that the slight heat which enters the soil during the fire may even favour plant nutrition.

TABLE V

Analytical Data

Surface Soils (0-3½") from Protected Compartments and Regularly Burnt Firebreaks

Exchangeable Calcium

Mean Values

(m.e.% & %)

Location	Compartment		Firebreak	
Amphion, Compt. 6	3·08	67	5·08	66
Curara, Compt. 5	4·34	69	3·11	63
Curara, Compt. 8 .. .	5·66	71	8·34	72
Holmes, Compt. 1	2·78	72	3·58	73
Holmes, Compt. 3 ...	3·58	65	3·80	66
Holmes, Compt. 11, Plot 11 .	1·65	58	1·96	62
Holmes, Compt. 13, Plot 13 ...	2·47	63	4·41	69
Holmes, Compt. 12	4·69	66	5·08	76
Holmes, Compt. 14	3·13	63	3·56	68
Marrinup, Compt. 4 . .	5·34	65	3·27	73
Mt. Wells, Compt. 10	4·69	77	3·32	71
Teesdale, Compt. 2	5·58	75	5·24	69
Means	3·92	67·6	4·23	69·0

P ·05 difference for significance = 1·25 m.e. % and 4·9%.
Each value shown is the mean of three composite samples.

In addition the controlled burning is carried out during the latter part of the year, and the maximum leaf fall in the jarrah forest occurs during the months of January, February and March. In jarrah regrowth forests the leaf fall during this period may amount to between 12 and 15 cwt. per acre (o.d.wt.), and this leaf litter contains the following amounts of inorganic nutrients; 0.77% calcium, 0.240% magnesium, 0.252% potassium and 0.473% nitrogen.

The fresh leaf litter on the forest floor of the firebreak is exposed to at least one winter's leaching by the rainfall, and it has been shown by Hatch (1955) that jarrah leaf litter loses one third of its oven dry weight during the first winter. This loss in weight includes the majority of the inorganic actions and a considerable amount of readily soluble organic compounds, and evidently this accession of nutrients and organic compounds from the litter is sufficient to replace any losses in the immediate soil surface which may be caused by the burning.

In field inspections of the firebreaks and compartments, the chief differences observed were the absence of a thick A1 horizon in the firebreak soils and also the undergrowth vegetation appeared to be much sparser in the firebreaks.

Conclusion

It is evident that the practice of regularly burning selected firebreaks in the jarrah forest has had no significant effect on the soil properties examined, and the results support the conclusions of Alway and Rost (1928) and Blaisdell (1953).

Also, from the above data, it would appear that the Departmental policy of prescribed controlled burning, which is primarily based on practical and economic considerations related to the present stage of development of this State, is unlikely to cause any soil deterioration to take place.

Acknowledgments

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25.—Jurassic Stratigraphy of the Geraldton District, Western Australia

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This paper is a detailed account of the stratigraphy, structure, and petrology of the Jurassic sediments of the Geraldton district. These sediments are almost horizontal and were deposited on an irregular, weathered surface of Precambrian gneisses and granulites. The Jurassic sediments are divided into seven formations, of which the lower six form two groups. They are, from the base up, the Greenough Sandstone and Moonyoonooka Sandstone (making up the Chapman Group), the Colalura Sandstone, Bringo Shale, Newmarracarra Limestone, and Kojarena Sandstone (making up the Champion Bay Group), and the Yarragadee Formation. The age of the Chapman Group has not been definitely established owing to lack of fossil evidence. It consists of continental fluviatile sandstones and is tentatively placed in the Lower Jurassic, though all or part of the group may be Upper Permian or Lower Triassic. The Champion Bay Group consists of marine sediments of Middle Jurassic age. One formation, the Newmarracarra Limestone, is very fossiliferous, and has been accurately dated as Middle Bajocian.

The flat-topped hills of the Geraldton district are usually capped by laterite, which is often overlain by sand. These hills are remnants of the well-dissected Victoria Plateau. The laterite in the district formed after uplift and dissection of the plateau. Both the Precambrian granitic rocks and the Jurassic sediments (especially the Newmarracarra Limestone) have undergone extensive alteration beneath the laterite.

The major structural feature of the area is the Geraldton Fault, which is known to have had a throw since the Jurassic of 750 to 800 feet, and a total throw of at least 1,500 feet. Minor faults, cutting both the Jurassic sediments and the Precambrian rocks, have also been noted in the area.

Contents

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Introduction

Location of Area

Geraldton is situated on the coast of Western Australia, about 230 miles north of Perth, the capital city. It is a port on Champion Bay, serving the surrounding agricultural and mining districts.

During this investigation an area of approximately 400 miles around Geraldton was examined in reconnaissance (see Plate 4), and a detailed survey was carried out on approximately 14 square miles in the vicinity of Bringo, a small railway station 19 miles from Geraldton on the line to Mullewa.

Purpose of Investigation

The marine Jurassic sediments of the Geraldton district have been known since the middle of the last century, and were until comparatively recently the only known exposure of marine Jurassic in Australia. Nevertheless no detailed geological investigation of the area has been undertaken previously, due largely to the lack of any economically important deposits associated with the sediments. The objects of the present survey were firstly to map a small area of the Jurassic sediments in detail, establishing the rock units present, collecting fossils, and carrying out a laboratory examination of the sediments; secondly to map a larger area in reconnaissance, measuring stratigraphic sections throughout, and obtaining information on the lateral extent of the rock units. The overlying lateritic deposits and underlying Precambrian metamorphic rocks were also studied.

This paper was originally submitted in March, 1953, as part of the requirements for the degree of Bachelor of Science with Honours at the University of Western Australia. Since then, part of the Geraldton area has been re-examined by Mr. S. P. Willmott and myself during the course of a regional geological survey of the Perth Basin on behalf of West Australian Petroleum Pty. Limited. Some alteration to the original manuscript has been necessary as a result of this additional work.

Methods of Study

The area around Bringo which was examined in detail (see Plate 5), was mapped using vertical aerial photographs, on a scale of four inches to the mile. In this area every outcrop was visited and examined. The reconnaissance survey (Plate 4) was carried out using the army topographical maps on a scale of one inch to the mile. For this survey all outcrops were not visited, but roads and important tracks in the area were covered by motorcycle, with visits to significant exposures. The regional map was completed in Perth using vertical air-photos loaned by the Army Survey Corps.

The Bringo railway cutting (Plate 6) was mapped on a section prepared from measurements supplied by the Engineer's Department, Western Australian Government Railways.

A petrological examination was carried out in the laboratory of samples collected mainly from the area mapped in detail. This analysis consisted of mechanical analysis, sphericity and roundness determinations, and mineralogical study of the disaggregated sediments, supplemented by thin section work. Chemical analyses were carried out on the phosphatic rocks to determine their content of P_2O_5.

Macro-fossils were identified from the literature and the ammonites were sent to the late Dr. W. J. Arkell.

The army one-mile grid system is used on the geological maps of the Geraldton and Bringo areas respectively (Plates 4 and 5). Localities mentioned in the text are referred to this grid. Taking Bringo as an example, the east-west reading is 75.9 and the north-south reading is 36.5, then the grid reference is given as (759365). In the same way the grid reference for "Moonyoonooka" homestead is obtained as (708325).

Historical Review

The Geraldton district was one of the earliest parts of Western Australia to be settled, and in the early 1850's several sheep stations were established in the area covered by this report. Such stations as "Newmarracarra," "Tibradden," "Ellendale," and "Sandspring" were soon flourishing in an area which proved to be among the richest pastoral districts in Australia. It is not surprising that the richly fossiliferous rocks of the area attracted the attention of these early settlers, and as a result several fossil collections were sent to England.

The first to record the Jurassic age of these fossils was Moore (1862), who examined specimens forwarded by a Mr. Clifton, and also those sent by F. T. Gregory to the Geological Society of London. Moore expressed the opinion that the fossils were referable to the Upper and Middle Lias of the English succession. Earlier, A. C. Gregory (1849), J. W. Gregory (1849), F. von Sommer (1849), and F. T. Gregory (1861) had written brief accounts of the geology of the district, but none had recognized the Jurassic age of the sediments.

The Reverend W. B. Clarke (1867) published a paper on fossils he had been sent from the Moresby Range, near Geraldton. His conclusion was that "Taking the general aspect of these fossils, and the occurrence of such forms as *Avicula Munsteri*, *Ostrea Marshi*, and *Ammonites Moorei*, it is almost certain that the nearest representative of the formation is the Inferior Oolite." This conclusion is held to the present day, the Newmarracarra Limestone being considered to be of Bajocian ("Inferior Oolite") age, though it has been further narrowed down to the Middle Bajocian.

Further palaeontological papers on fossils from the Geraldton area were published by Neumayr (1885), Crick (1894), Etheridge (1901, 1910), and Chapman (1904, *a* and *b*).

The first geologist to map the Geraldton district at all thoroughly was W. D. Campbell (1907), who published a geological map of the Greenough River district, with accompanying notes. This map shows the broad distribution of the Jurassic sediments, Precambrian rocks, and laterite, but the notes give little information on the stratigraphy of the area.

Further work on the area by Campbell (1910) was published as part of his outstanding contribution to the geology of Western Australia—"The Irwin River Coalfield and the adjacent districts from Arrino to Northampton." This report embraced an area of about 2,000 square miles, and included the area covered by the present survey. However, Campbell was mainly concerned with the Permian sediments of the Irwin River district, and his report contains no detailed information on the stratigraphy of the Jurassic sediments.

The next palaeontological paper was by F. W. Whitehouse (1924), who examined fossils collected by Professor W. G. Woolnough from a railway well near Bringo. He named several new species, and on evidence supplied by ammonites, suggested a Middle Bajocian age for the fauna. This dating was confirmed by Spath (1939), who described a small collection of ammonites from the Geraldton area. He considered that they were referable to either the Sauzei Zone or the Sowerbyi Zone (Middle Bajocian) of the European succession.

The geological survey of the Irwin River and Eradu coal basins (Permian) by Johnson, de la Hunty, and Gleeson (1954) overlaps the present reconnaissance in the vicinity of Wicherina. However their paper gives little information on the Jurassic sediments.

The field work for the present investigation was undertaken in December 1951, January, February, June, August and November 1952, and March 1953, a total of 17 weeks being spent in the field. The laboratory work was done during the academic year of 1952.

Since the present paper was submitted as an Honours thesis in 1953 two papers have been published dealing with the Jurassic sediments of the Geraldton area. The first (Arkell and Playford 1954), deals primarily with the ammonities of the Newmarracarra Limestone, which are described in that section of the paper written by Arkell. He considers the fauna to be Middle Bajocian in age, and to correlate, at least in part, with the Sowerbyi Zone of the European succession. The Sauzei and Humphriesianum Zones of the Middle Bajocian may also be present. The other section of the paper, by myself, summarizes the stratigraphy of the Jurassic sediments. In "The stratigraphy of Western Australia" by McWhae, Playford, Lindner, Glenister, and Balme (1958), the latest information on the Jurassic sediments of the Geraldton area is given in summary form.

Acknowledgments

During this investigation ready assistance and advice were given by Dr. R. W. Fairbridge and Dr. A. F. Wilson, and I wish to express my sincere thanks to both. I am also indebted to Professor R. T. Prider for his interest and advice. Other members of the Geology Department, University of Western Australia, gave valuable support and encouragement, for which I am grateful.

Since the paper was first written, Dr. R. O. Brunnschweiler, Mr. S. P. Willmott, Dr. J. R. H. McWhae, Mr. D. Johnstone, and Mr. M. H. Johnstone have given valuable assistance in a number of ways, for which I wish to extend my thanks.

Physiography

General

The Geraldton district is situated in the northern part of the Perth Basin. It falls within the Greenough Natural Region of Clarke (1926), the South-West Physiographic Division of Jutson (1934), and the Greenough Block Subregion of the Swan Coastal Belt (Physiographic Region) of Gentilli and Fairbridge (1951).

The country to the east of Geraldton consists of the remnants of a plateau dissected by the Greenough and Chapman Rivers, leaving flat-topped hills of Jurassic sediments, often capped by laterite, and underlain by Precambrian granitic rocks. The western margin of the dissected plateau is marked by the Geraldton Fault Scarp (Jutson 1914). This scarp is deeply dissected and has retreated several miles. It is fronted by a coastal plain, 3 to 10 miles wide, which slopes gently to the sea.

In those areas where the rivers have cut through the sand-covered plateau, there are rich pastoral properties supporting large numbers of sheep. Cereal crops are also grown, being most successful in the drier years, while there are numerous market gardens on the coastal plain.

The climate of the area is characterized by an annual rainfall of 15 to 20 inches, nearly all of this falling in the winter months. Summer temperatures are high, with the maximum often over 100°F.

The natural vegetation has been largely removed in the valleys of the Chapman and Greenough Rivers, but on the granitic and Jurassic areas it apparently originally consisted predominantly of "Jam" (*Acacia acuminata*), "York Gum" (*Eucalyptus foecunda*, var. *loxophleba*), "Needle Bush" (*Hakea recurvata*), and "Sheoak" (*Casuarina*). There is a marked change of vegetation on the sand-plain, which supports a low scrub, including stunted species of *Acacia* and *Banksia*, with occasional "Christmas Trees" (*Nuytsia floribunda*).

River Systems

The Geraldton district is drained by two main rivers, the Greenough and the Chapman. Another so-called river, the Buller, is in reality little more than a creek. Like most Western Australian rivers they are intermittent, only flowing after heavy rain.

The Greenough River rises 130 miles north-east of Geraldton, and only the lower part of its course lies within the area examined. In this part of its course it receives two main tributaries, Wicherina Brook and Colalura Brook, the latter draining the area surveyed in detail.

Upstream from the road crossing near Ellendale (890232) the Greenough River flows through Jurassic sediments in a series of large ingrown meanders, with undercutting along high cliffs and prominent slip-off slopes. These ingrown meanders continue upstream in the Eradu district, and as suggested by Johnson, de la Hunty and Gleeson (1951), they indicate a rejuvenation of a river which had reached the "old age" stage of development. This rejuvenation must have occurred following uplift of the plateau in late Tertiary times. The Murchison River, 80 miles to the north, shows even clearer evidence of rejuvenation. West of the Greenough Block (Precambrian granitic rocks) it flows in a deep, narrow gorge with well-developed incised meanders.

For 10 miles south of its mouth the Greenough River flows over a rich flood-plain known as the Greenough Flats. These flats are divided into two parts by a low sand-covered ridge of Coastal Limestone, which is parallel to the coast. (This ridge is about three miles inland and represents consolidated coastal sand dunes of Pleistocene age.) The river flows between the ridge and the present dunes, following them north for 10½ miles before breaking through to enter the sea. This northerly deflection of the river is due to the strong prevailing south-south-west winds which sweep the coast. The picturesque trees along the Greenough Flats, bent over almost parallel to the ground, testify to the constancy and strength of these winds. Sand carried by the resulting northerly long-shore drift, combined with the slow migration of sand dunes, has caused the mouth of the river to migrate northwards, as its old mouth is progressively filled in.

As first pointed out by Jutson (1914) Rudds Gully probably represents an abandoned course of the Greenough. This gully breaks through the Pleistocene dune limestones and is up to 90 feet deep, but today it carries only a small creek which seldom flows. It seems very likely that during the Pleistocene the river emptied into the sea at Rudds Gully, flowing north behind the Pleistocene dunes just as today it flows behind the present dunes.

The Chapman is much smaller than the Greenough. It divides into two branches near "Narra Tarra", and these are known as the Upper Chapman and East Chapman branches. The Upper Chapman rises 35 miles north of Geraldton, and the East Chapman rises near Northern Gully.

Victoria Plateau

The Victoria Plateau was named by Johnson *et al.* (1951), who defined it as the dissected plateau bounded on the east by the Darling Fault, and on the west by the Geraldton Fault and the high sea cliffs north of Geraldton.

In the Geraldton district the Victoria Plateau has been deeply dissected by the Greenough and Chapman Rivers, leaving large remnants such as the Moresby Range. The surface of the plateau is covered by sand overlying laterite, generally at shallow depth. The laterite itself outcrops along the edges of the plateau, or in those places where the sand has been removed by erosion.

The surface of the plateau shows only minor undulations, and averages about 800 feet above sea-level.

Hills

The most conspicuous hills of the Geraldton district are flat-topped (buttes and mesas), their outline being due to the resistant nature of the laterite cap overlying soft Jurassic sediments. The laterite cap is generally flat, though in some cases it shows a sloping surface.

The Moresby Range is made up of a series of parallel, elongated mesas and buttes, trending north-north-west, and standing about 200 feet above the surrounding plain. Laterite, sometimes overlain by sand, caps most of the range, though in places this has been removed by erosion, and Jurassic sediments outcrop at the top. The western edge of the range is the retreated scarp of the Geraldton Fault, and the eastern margin is due to dissection by the Chapman River, which parallels the range.

Those hills of Jurassic sediments which are not capped by laterite have a rounded outline, and examples of these are found typically in the area mapped in detail.

Springs

Springs are common throughout the area examined. Some issue at the unconformity between the Jurassic sediments and the Precambrian rocks, and these are generally brackish or salt. Others, either fresh or brackish, are found in the sediments at the contact between sandstone and shale, or limestone and shale. The latter type has a widespread development east of Bringo, where limestone overlies black shale.

Much of the rain falling on the sand-plain sinks in, there being very little run-off, and the water often reappears as fresh-water springs beneath the underlying laterite.

General Geology

Precambrian

Precambrian metasediments outcrop over a large proportion of the area, though exposures are generally poor. These rocks have undergone high-grade regional metamorphism, and consist of granitic gneisses and granulites, which are characteristically garnetiferous.

The petrology of the Precambrian metasediments has not been intensively studied, though thin-sections of some of the most typical rock types have been examined.

The gneisses are the most abundant of the Precambrian rocks present in the area. They are usually medium-grained, uniformly banded, and almost invariably carry garnet. Sillimanite is sometimes present, usually as a minor accessory. Some of the gneisses also contain cordierite. Typical examples of the gneisses are specimen No. 34797 (University of W.A. Geology Dept. registered number), which is a quartz-orthoclase-andesine-garnet gneiss, and specimen No. 34798, which is a quartz-microcline-oligoclase-garnet-cordierite gneiss.

Several types of granulite have been noted in the area, but they have not all been examined microscopically. Most have a composition similar to that of the granitic gneisses, and at several localities the granulites and gneisses grade into one another. Other types are interbedded with the gneisses and include charnockitic granulites, hornblende granulites, and garnetiferous quartzites.

The metasediments are cut by pegmatites, and at several localities by quartz veins, which are probably associated with pegmatites.

At a few places in the area the gneisses and granulites are intruded by dolerite dykes. The one crossing the area mapped in detail is at least 2½ miles long, stretching from a quarry at (746361) to (728325), near Spion Kop. The strike of 26° closely parallels that of the dyke swarm of the Northampton district, 30 miles to the north, where the dolerite dykes have introduced lead, copper, and zinc into the gneisses.

Lineation is seldom pronounced in the gneisses, but readings have been taken at three widely separated localities (635426, 774356, 811215). The strike of the lineation is rather constant, averaging 335°, while the angle of plunge varies from 12° south to 70° north. This north-north-west tectonic trend is usual in the West Coast Province of Prider (1952).

Throughout the area the foliation of the gneisses varies little from a northerly strike and easterly dip, and they are probably isoclinally folded.

The contact between the Precambrian rocks and the Jurassic sediments is very irregular, and east of the Geraldton Fault the elevation of the unconformity above sea-level varies from about 250 feet near "Narra Tarra" and "White Peak" to 717 feet at Mt. Davis.

Although the Precambrian basement rises gradually from west to east, this rise is not uniform. There are irregularities in the surface of the unconformity, which existed as hills and valleys at the time when the Jurassic sediments were deposited. The basal formations of the Jurassic are found to pinch out against these buried hills, so that the lower the elevation of the unconformity, the greater is the thickness of the sediments.

The metasediments beneath the unconformity are frequently deeply weathered, the felspars being completely kaolinized to depths of 100 feet or more. This is particularly well seen in various small railway cuttings near Bringo. However most of this remarkable depth of weathering is believed to be associated with lateritization, and was not present in Jurassic times. Similar deep weathering of metasedimentary rocks beneath laterite is known in many other places in Western Australia. Nevertheless a certain amount of weathering of the Precambrian rocks is believed to have occurred in Jurassic times. The basal formation of the Jurassic succession, the Greenough Sandstone, is made up of highly weather granitic material, and is believed to be locally derived.

Lower Silurian (?)

There are a few exposures of the Tumblagooda Sandstone in the area west of Wicherina. These are the southernmost known outcrops of this formation, which is best known along the Murchison River on each side of the Greenough Block. The Tumblagooda Sandstone is probably of Lower Silurian age.

The exposures of Tumblagooda Sandstone near Wicherina consist of fine- to very coarse-grained, grey to yellow, well-sorted sandstone, which is partly silicified. The sandstone is crudely to well-bedded and sometimes shows cross-bedding. Scattered well-rounded pebbles and cobbles of quartz and quartzite are a feature of these exposures of the formation. At the large water tank 2½ miles west-south-west of Wicherina Dam, many pebbles and cobbles have weathered out of the formation and are scattered over the surface.

The relationships between the Tumblagooda Sandstone and the over-lying Jurassic sediments cannot be seen in the exposures near Wicherina. However 5½ miles north of Northern Gully (off the map) the Lower Jurassic Chapman Group can be seen resting unconformably on the Tumblagooda Sandstone. The Tumblagooda Sandstone overlies the Precambrian granitic rocks unconformably. Only one satisfactory dip could be measured in the exposures of the formation near Wicherina, at (879400). There the unit is crudely bedded and cross-bedded, but it appears to strike 140°, and dip 15° west.

The only fossils known from the Tumblagooda Sandstone are invertebrate tracks, which indicate an early Palaeozoic age. However there is evidence to suggest that the formation is at least in part of Lower Silurian age, though it may extend down into the Ordovician. This dating is indicated by the fact that the formation appears to underlie conformably the Middle Silurian Dirk Hartog Limestone in the Dirk Hartog 17B bore (McWhae *et al.* 1958).

The exposures of the Tumblagooda Sandstone near Wicherina are only a few feet thick. However on the Murchison River it appears that the unit is at least 6,000 feet, and probably exceeds 10,000 feet in thickness. It is probably present at depth throughout most of the Perth Basin and is believed to be a continental fluviatile deposit laid down following the first major period of movement along the Darling Fault, in Lower Silurian or late Ordovician times.

Johnson *et al.* (1954) correlated the exposures of Tumblagooda Sandstone near Wicherina with the Enokurra Sandstone of the Yandanooka Group, which is exposed 60 miles to the south-south-east. However the exposures near Wicherina have now been shown to be essentially continuous with those of Tumblagooda Sandstone extending down from the Murchison River, and the correlation with this formation cannot be seriously doubted. The lithological similarity with the Enokurra Sandstone is quite strong, but this is not sufficient to establish correlation. Indeed it is now believed that the Yandanooka Group is distinctly older than the Tumblagooda Sandstone.

Upper Permian or Lower Triassic

Sediments of Upper Permian or Lower Triassic age were first discovered in 1956 in cores from the Geraldton Racecourse Bore (569307). This bore was drilled with Calyx equipment in 1896-98 and some of the cores were preserved by the Geological Survey of Western Australia. A core from 1,470 feet in this bore was found to contain the uppermost Permian or lowermost Triassic ammonoid *Xenaspis.*

The formation was named the Kockatea Shale by Playford and Willmott in McWhae *et al.* (1958). It consists of partly calcareous, light grey shale, grading into siltstone, with subordinate interbedded medium- to coarse-grained sandstone.

In the Geraldton area the Kockatea Shale is known with certainty only from the Geraldton Racecourse, Municipal, and Station Yard bores. In the Municipal Bore the unit is 1,091 feet thick and overlies Precambrian gneiss, while in the Racecourse Bore it is 1,131 feet thick, without having reached the base of the formation. In both bores the Kockatea Shale is overlain by Jurassic sediments.

Dr. Glenister, who has examined the ammoniod *Xenaspis* from the Racecourse bore, favours a Tatarian (uppermost Permian) dating for the formation (McWhae *et al.* 1958). On the other hand Mr. B. E. Balme, from a study of the spore, pollen and microplankton assemblages, believes that it is more likely to be lowermost Triassic, though he does not rule out the Tatarian dating.

Although the Kockatea Shale is not definitely known to outcrop in the Geraldton area, it could conceivably be present. The Greenough Sandstone, which is tentatively dated as Lower Jurassic, shows lithological similarity to parts of the Kockatea Shale, and they may be partly equivalent. The only certain exposures of the Kockatea Shale in the Perth Basin are found near the junction of Kockatea Gully with the Greenough River.

Jurassic

In the Geraldton District Jurassic sediments are known to extend from the northern end of the Moresby Range as far south as Mt. Hill, and both marine and continental deposits are found in this area. The marine transgression is known to have extended inland at least as far as Eradu, on the Greenough River.

Although a Jurassic age is proved for the marine sediments, one formation being accurately dated as Middle Bajocian, there is no direct proof as to the age of the continental deposits, though they are tentatively placed in the Lower Jurassic.

In summary the sequence, from top to bottom, is as follows:

Yarragadee Formation.—Alternating sandstone and micaceous siltstone, with beds of claystone, shale, and conglomerate.

Thickness: 51½ feet (plus).

Champion Bay Group:

Marine sandstone, shale, and limestone making up the following formations:

Kojarena Sandstone.—Brown ferruginous sandstone, partly fossiliferous, with some claystone and shale near the top.

Thickness: 33 feet.

Newmarracarra Limestone.—Yellow to grey, massive, richly fossiliferous limestone. The limestone is subject to irregular alteration, and may be replaced by hematite, or leached of calcium carbonate, leaving a residue of its clastic impurities.

Thickness: 16 to 38 feet.

Bringo Shale.—Black shale, with thin yellow phosphatic beds. Phosphatic nodules often found at the top. Dwarf pelecypods occur at several horizons.

Thickness: 0 to 8 feet.

Colalura Sandstone.—Predominantly brown to black ferruginous sandstone, rarely grading into yellow sandy claystone. Abundant fossil wood is characteristic, and small oval nodules are frequently found. Both nodules and fossil wood are sometimes phosphatic, but are usually replaced by limonite. Marine fossils rarely present.

Thickness: 0 to 28 feet.

Chapman Group:

Continental sandstone and arkose, with subordinate shale, siltstone, and claystone, making up the following formations:

Moonyoonocka Sandstone.— Predominantly yellow fine-grained felspathic sandstone and arkose, with subordinate shale, siltstone, and conglomerate. Well-bedded, with cross-bedding and current ripple-mark common. Ferruginous concretions are characteristic, fossil wood is quite abundant, and fossil leaves are very rare.

Thickness: 0 to 120 feet.

Greenough Sandstone.—Mottled red, white, yellow, and purple argillaceous sandstone, poorly sorted, with subordinate shale, siltstone, claystone, and conglomerate. Poorly bedded, and containing rare fossil wood.

Thickness: 0 to 280 feet.

In the area examined, the total exposed thickness of the Jurassic and questionable Jurassic sediments probably does not exceed 550 feet. No single section exposes as much as this. The thickest section measured is at Wokatherra Hill at the northern end of the Moresby Range, where about 430 feet of sediments are exposed, the upper portion of the Champion Bay Group and the Yarragadee Formation being missing. The upper section is exposed in the Bringo railway cutting, but there the Precambrian basement is so high that nearly all the Chapman Group is excluded, and the total section is only 115 feet thick.

Jurassic and associated lowermost Cretaceous sediments are widespread in the Perth Basin, and may exceed 8,000 feet in thickness. They are predominantly continental sediments, the only marine Jurassic outside the Geraldton area being found in the drainage area of the Hill River, 100 miles south of Geraldton.

Laterite and Sand Plain

A considerable part of the area is covered by laterite, which is often overlain by sand. These deposits, which have a widespread development throughout Western Australia, are generally considered to be fossil soil horizons, formed during a more pluvial period, probably in late Tertiary times. Laterite may have been deposited under a humid climate of seasonal rainfall as an illuvial soil horizon zone of fluctuation of the water table. The sand-plain which is frequently found overlying laterite is believed to be the fossil eluvial horizon.

The laterite is up to 20 feet thick, and outcrops as large massive slabs around the sides of hills, giving rise to "breakaways." The laterite shows an irregular cellular structure, in some places partly concretionary. The weathered surface is yellowish brown in colour, while freshly broken surfaces are mottled in various shades of brown, yellow, and red.

The laterite consists of hydrous and anhydrous oxides of iron and aluminium, together with quartz and minor amounts of other insoluble minerals. The quartz present is usually of sand grade, though some large, rounded pebbles are occasionally found.

Overlying the laterite, wherever erosion is not too severe, deposits of quartz sand are found, which are light grey to white on the surface, and yellow at depth. This sand, which is probably no more than 20 feet thick anywhere in the area, is believed to be essentially *in situ*, though it may have undergone some redistribution, filling small depressions in the surface of the laterite.

Many of the hills in the Geraldton district which are capped by laterite are flat-topped, though the surface of the laterite is by no means invariably horizontal. It may show dips of anything up to 10°, as at Mt. Hill. Sloping laterite is also well seen on the three adjacent hills Sheehans Hill, Wizard Peak, and Browns Table. It is also found that, in general, the laterite slopes towards the present river valleys, indicating that the general features of the present drainage system were already established at the time when the laterite was forming.

The surface of the laterite in the Geraldton district shows considerable variations in elevation. To the east, where there are large remnants of the old plateau, the laterite (or the overlying sand) is usually more than 800 feet above sea-level, reaching 863 feet near Kojarena, and 821 feet at Mt. Julia. However, laterite (*in situ*) at "Amuri Park" is 350 feet above sea-level, while in the gravel pit at (644317) it is only 210 feet above sea-level. It is clear that laterite in the Geraldton area did not form on a low-lying peneplain of the type postulated by Woolnough (1918). It formed on a land surface already uplifted and eroded, the drainage system found today having been already established during the period of laterization. This is discussed in more detail by Playford (1954).

The effects of laterization in the Geraldton area are found to extend to considerable depths below the laterite itself. These effects are most apparent with the Precambrian granitic rocks and the Newmarracarra Limestone. The granitic rocks are found to be completely kaolinized to depths of more than 100 feet below the laterite. The upper part of this weathered zone is typically mottled white and various shades of red and brown, and is commonly known as the mottled zone. The lower part is simply white due to kaolin, and is known as the pallid zone.

Many of the structures and textures of the original rock are preserved in its kaolinized equivalent, particularly in the pallid zone. Thus gneissic structure is frequently clearly visible, and in the Bringo cutting, the original ophitic texture can still be detected in a thin dolerite dyke, despite the fact that the felspars are completely kaolinized.

The Newmarracarra Limestone is completely altered to depths of 80 to 100 feet beneath laterite. It is either replaced by hematite or simply leached of its calcium carbonate, leaving a residue of the clastic impurities. In those places where the rock is clearly altered limestone it has been mapped as Newmarracarra Limestone, but wherever there is uncertainty, or it approaches normal laterite in appearance, it has been mapped as laterite.

Alteration of the Newmarracarra Limestone by lateritization has been discussed fully in papers by Playford (1954) and Arkell and Playford (1954), and will only be summarized here.

Newmarracarra Limestone replaced by hematite is free of calcium carbonate, and varies in colour from deep red to almost black. Moore (1870) gave analyses of two blocks of the hematite and they contained 49% and 56% of metallic iron. The hematite was probably derived by leaching of the overlying ferruginous Kojarena Sandstone.

Fossils are often very well-preserved in the hematite rock, either as moulds or as replacements. However, in some areas, e.g. in parts of the Bringo cutting, the hematite rock shows a concretionary structure, and fossils are wholly or partly destroyed.

A leached zone is usually present between the hematite rock and the solid limestone. It has formed by removal of calcium carbonate, followed by compaction of the remaining insoluble clastic impurities. Its composition is usually that of sandy, silty claystone, and it is generally yellow in colour. This zone contains few fossils, those which are present being internal moulds of ammonites and pelecypods. The material of these moulds was apparently low in calcium carbonate, so that they were not destroyed during leaching.

The best exposure of the leached zone and associated hematite rock is in the Bringo cutting. There it can be seen that they are not sharply separated, one grading irregularly into the other.

In the field the relationship between limestone outcrop and elevation of laterite is quite apparent. Wherever the undulating surface of the laterite is closer than about 90 feet to the base of the Newmarracarra Limestone, the limestone is completely leached. Exposures of unaltered limestone are only found where the laterite is more than about 90 feet above the base of the formation.

The other sediments also show the effects of lateritization, though not so clearly as the Newmarracarra Limestone. The mottled zone is frequently visible close to laterite in all formations, and beneath this there may be a bleached zone, though this is seldom exposed, as removal of the iron oxide cement of many of the sand stones makes them friable.

A feature which is believed to be associated with laterization is the occasional silicification of sediments. Near Mt. Hill, about ¾-mile west of the summit, the sandstones of the Chapman Group are silicified to a depth of 50 feet or more. These sandstones are at an unknown depth below the original laterite surface, which is known to have been very irregular here, for laterite occurs on the north flank of Mt. Hill, more than 100 feet below the summit, yet it does not occur on the summit itself.

Quaternary Superficial Deposits

In addition to laterite and sand-plain, other superficial deposits have a widespread distribution in the area, but have not been studied in any detail. These deposits include surface travertine, Coastal Limestone, Recent sand dunes, and alluvium. All are of Quaternary age.

The deposits of travertine are found in small patches throughout the area, where they are exposed to erosion, giving rise to surfaces covered by fragments of the white, lime-rich rock.

Alluvial deposits have been spread over most of the coastal plain, and inland around the margins of the Victoria Plateau. Alluvial sand deposits are commonly found around remnants of the plateau, the sand having been washed from the tops of the hills where it previously covered laterite.

Alluvial deposits are exposed in several parts of the Bringo cutting in old valleys cutting through the Kojarena Sandstone and Yarragadee Formation.

Jurassic Stratigraphy

Chapman Group

The name Chapman Group was introduced by Playford, in Arkell and Playford (1954), for the continental sediments lying between the unconformity with the Precambrian rocks and the disconformity with the overlying Champion Bay Group. It was named after the Chapman River. The group was originally considered to be made up of two formations, the Greenough Sandstone and the Moonyoonooka Sandstone, but was expanded by Johnstone and Playford (in McWhae *et al.* 1958) to include the Minchin Siltstone, which lies at the base of the group in the Northampton-Hutt River area. As this formation is not exposed in the Geraldton area, it will not be discussed further in this paper.

The age of the Chapman Group is uncertain owing to the lack of satisfactory fossils for dating. It is not even certain that the formations of the group form a continuous sequence.

However the three formations are tentatively regarded as being of Lower Jurassic age, keeping in mind that one or more could be Lower Triassic or Upper Permian.

(i) *Greenough Sandstone*

Definition.—The name Greenough Sandstone was proposed by Playford, in Arkell and Playford (1954), for the unit of sandstone with minor shale, claystone, and siltstone, lying between the granitic rocks and the Moonyoonooka Sandstone in the area east of Geraldton. The name was taken from the Greenough River, the largest river flowing through the area.

The type section of the Greenough Sandstone is on "Moonyoonooka" property, at 28° 47' 4" S., 114° 48' 3" E. (722319). The following is a description of this section.

Moonyoonooka Sandstone. Comformably overlying—

Greenough Sandstone (90')

	Thickness feet
(6) Sandstone, clayey, mottled grey, white, yellow, red, and purple; in places grades into sandy claystone; top marked by a 3" bed of hard, ferruginous claystone with purplish bands	45
(5) Conglomerate, intraformational, mottled grey, yellow, and red; contains angular and rounded fragments of clay in a matrix of course sand	5
(4) Claystone, mottled red and white, massive	1½
(3) Sandstone, clayey, yellow, mottled red and white; contains scattered fragments of angular and rounded claystone; fills scour channel in underlying shale, conglomeratic at base; bleached and hardened along joints	11
(2) Shale, white to yellowish, mottled red, yellow, and purple; massive claystone at base, but otherwise shaly; lenses of sandstone found in the uppermost two feet; hard ferruginous beds up to ½" thick common throughout	23
(1) Sandstone, conglomeratic, felspathic, brown to reddish brown, ferruginous, contains poorly rounded quartz pebbles up to 6" in diameter; a few felspar pebbles, and occasional boulders of weathered gneiss at the base	5

unconformably overlying Archaean gneiss (weathered).

Lithology.—The Greenough Sandstone is typically a mottled red and white argillaceous sandstone, which is medium to coarse-grained, and is very poorly sorted and poorly bedded. Lenses of siltstone, claystone, and shale are present in the formation, with occasional quartz pebble conglomerates. Lenses of intraformational conglomerate occur rather commonly throughout the section, and cut-and-fill structure, giving rise to local unconformities, has been noted at several localities. Cross-bedding is rarely developed in the sandstones, which are usually massive, with no bedding visible. Sand grains show little or no rounding, but quartz pebbles are sometimes well-rounded.

It is often difficult to recognize the exact position of the unconformity, as the weathered Precambrian rocks frequently appear to grade up into the Greenough Sandstone. This is because the sandstone seems to be merely reworked, highly weathered granitic material, and it is frequently only the relic gneissic structure in the weathered Precambrian, or the presence of a few quartz pebbles in the sediment, which serves to distinguish them.

One of the most distinctive features of the formation is its mottled colouring, red and white being most common, but shades of grey, yellow, blue, purple, and brown are also found. Black or dark grey sediments have not been found in this formation. The origin of this mottling is not definitely known, but most of it is certainly secondary, as it transgresses the bedding. Along joints it is often found that the sandstone is both irregularly bleached and hardened. However much of the mottling does not seem to be connected with joint planes, though it is almost certainly secondary, and due to circulating ground waters. Since the sandstones are mottled even when hundreds of feet below laterite, there appears to be no connection with the mottled zone which is found immediately beneath laterite.

The mineralogy of the formation is very monotonous. Quartz and clay minerals, probably mainly kaolinite, together with a little muscovite, are usually the only "light" minerals. Felspar is rare, only being found near the base of the formation. The heavy mineral suite is also very restricted. Zircon is by far the most abundant of the non-opaque minerals, with minor amounts of anatase, monazite, tourmaline, and rutile. The extreme rarity of metamorphic minerals (kyanite, staurolite, and garnet) is very noticeable, as they are much more abundant in the other formations.

Stratigraphic relationships.—In the Geraldton district the Greenough Sandstone rests unconformably on the weathered, irregular surface of the Precambrian rocks, and is overlain conformably by the Moonyoonooka Sandstone. In the Hutt River-Bowes River area, near Northampton, the Greenough Sandstone rests with a slight disconformity on the Minchin Siltstone.

The contact between the Greenough Sandstone and the Moonyoonooka Sandstone is exposed at the type section, where it is clearly defined, but this contact has seldom been observed elsewhere owing to the poorness of outcrop. In this section the mottled argillaceous sandstone and sandy claystone of the Greenough Sandstone are overlain conformably by a black shale containing numerous lenses of grey sandstone and conglomeratic sandstone. As black and dark grey sediments are not known in the Greenough Sandstone, this shale is assigned to the next formation, the Moonyoonooka Sandstone, which in some areas contains significant amounts of dark shale.

Distribution and thickness.—The distribution of the Greenough Sandstone is limited by the elevation of the Precambrian basement, and if this rises higher than about 530 feet above sea-level, the formation pinches out. Since the basement rises gradually, though irregularly, from west to east, the formation thickens to the west.

At Wokatherra Hill, the most northerly and most westerly section studied, the greatest thickness of the Greenough Sandstone, 280 feet, has been measured. The formation has thinned to 60 feet at Appa Hill, and pinches out near Grant Siding. Outside the area examined the formation is known to reach a maximum thickness of 310 feet, at Kings Table Hill.

The formation is absent over a large part of the area examined, for around Bringo, "Tibradden," "Sandspring," and "Minnenooka," the Precambrian is sufficiently high to exclude it.

Exposures of the Greenough Sandstone are in general poor, for the sediments are usually weakly lithified. In the area mapped in detail the most typical outcrops of the Greenough Sandstone occur on two small hills at (69834), though the type section is the only continuous section exposed. Other good outcrops of the formation are found on "White Peak" property, along the western flank of the Moresby Range, and in a few railway cuttings near Grant Siding.

Fossils and age.—The only fossils which have been found in the Greenough Sandstone are rare, poorly preserved fragments of wood.

The age of the formation has not been definitely established owing to the lack of fossil evidence, but it is tentatively placed in the Jurassic. However it may be Lower Triassic or Upper Permian in age.

Environment of Deposition.—The Greenough Sandstone is considered to be a fluviatile sediment deposited around elevated areas in the Precambrian rocks. Most of the sediment is probably locally derived, having undergone little transportation.

A continental, fluviatile origin of the sediments is indicated by the following features:—

(a) Marine fossils are absent, the only fossils which have been found being fragments of wood.

(b) Individual strata are laterally impersistent, a characteristic feature of fluviatile deposits.

(c) Typical colours found in the formation are red, yellow and brown. The colouring matter is ferric oxide, which is normally reduced under marine, paludal, or lacustrine environments, and is best preserved under non-reducing fluviatile environment.

(d) Subaerial exposure of the sediments is indicated by the prevalence of intraformational conglomerates and breccias. They indicated hardening and cracking of clays due to exposure to the air, followed by scouring of flood-waters, incorporating the hardened blocks in the succeeding sediment. Local unconformities are often associated with the intraformational conglomerates, and these are known to be quite typical of fluviatile deposits.

The sediment making up the Greenough Sandstone is believed to be largely locally derived from the nearby granitic hills. It fills valleys in the irregular surface of the Precambrian rocks. The sediment is almost unsorted, having a kaolinitic cement, and closely resembles the weathered granitic rocks both in composition and appearance. Rounding of sand grains and the bedding are always poor, confirming that the sediment has undergone little transportation.

Economic Aspects.—The Greenough Sandstone has been used to a limited extent as a building stone, and as such it is rather well-suited. The mottled colouring is attractive, and as it is never strongly consolidated, it is easy to work.

Small quarries have been opened at "White Peak" and "Moonyoonooka" Stations for the purpose of extracting this stone.

(ii) *Moonyoonooka Sandstone*

Definition.—The name Moonyoonooka Sandstone was introduced by Playford, in Arkell and Playford (1954), for the continental sediments, predominantly felspathic sandstones and arkoses, between the Greenough Sandstone, or the Precambrian rocks, and the overlying marine Colalura Sandstone. The name is taken from "Moonyoonooka" Station, which embraces a large part of the area mapped in detail (Plate 5). Moonyoonooka is also the name of a small railway station on the Geraldton-Mullewa line.

The type section of the formation is on "Moonyoonooka" Station and overlies the type section of the Greenough Sandstone. It commences in a creek bed at 28° 47′ 18″ S., 114° 47′ 36″ E. (714315), and continues up a hill to (714313). The following is a description of this section:—

Colalura Sandstone. Disconformably overlying—

Moonyoonooka Sandstone (103′)

		Thickness Feet.
(6)	Arkose and felspathic sandstone, very fine- to medium-grained, partly silty, chiefly yellow, occasionally white and grey; contains some thin interbedded shales and siltstones; well-sorted, and usually well-bedded; shows cross-bedding, current ripple-mark, and occasional mud-cracks; some thin intraformational conglomerates are present; ferruginous concretions are common, barite concretions rare; fossil wood common in the centre of ferruginous concretions; one fossil leaf found	66
(5)	Sandstone, medium-grained, brown ferruginous, massive; outcropping prominently	½
(4)	Interbedded shales and fine-grained, cross-bedded felspathic sandstone; variegated yellow, grey, and white; some beds have incrustations of water-soluble salts	11
(3)	Shale, black, carbonaceous, containing indeterminable plant fragments	5
(2)	Sandstone, conglomeratic, brown, ferruginous, massive, lenticular, outcropping prominently, with well-rounded quartz pebbles; contains rare fossil wood	1
(1)	Shale, black, carbonaceous, with lenses of brown sandstone, sometimes felspathic, conglomeratic, and containing rare fossil wood; sandstone lenses most abundant near the base, where they are several feet long, and on the average 3 in. thick	19

conformably overlying Greenough Sandstone.

Lithology.—The Moonyoonooka Sandstone consists for the most part of poorly consolidated felspathic sandstones and arkoses, which are predominantly yellow, but also white, grey, red, and brown. These sandstones are well-bedded, often very thin-bedded, and both cross-bedding and current ripple-mark are commonly found. In the area mapped in detail these indicate a current direction, which though variable, is predominantly from the south-east.

The sandstones are usually fine- to very fine-grained, and contain lenses of shale, siltstone, coarse sandstone, and conglomerate, which are dove-tailed together, conglomerate sometimes cutting through shale. The lenticular nature of these beds is very noticeable. The shales are usually white, grey, or black in colour, while the coarse sandstones and conglomerates are usually brown. Intraformational conglomerates are sometimes found, together with rare mud-cracks.

The sand grains for the most part show little rounding, though an occasional rounded grain is found, and in conglomerates the quartz pebbles and granules may be well-rounded.

Small ferruginous concretions are rather characteristic of the formation. These vary considerably in shape, but the most typical are subspherical, and from one to six inches in diameter. The outer surface is usually yellow in colour, but may also be brown or dark red. The centres of the concretions usually consist of yellow, grey, or green unconsolidated powder, surrounded by a hard limonitic shell. They have apparently formed by the decomposition of pyrite or marcasite. Some contain a piece of limonitized fossil wood, which was once probably pyritic or marcasitic.

A few barite concretions have been found weathered out of the formation, both in the type section, and at (723300). It was not possible to fix accurately the horizon from which they were derived.

The Moonyoonooka Sandstone shows a variable assemblage of minerals, which is in marked contrast to the Greenough Sandstone with its monotonous suite. The "light" minerals consist of quartz, felspar, and muscovite. Felspar is usually present in sufficient quantities to designate the sandstones as felspathic, and frequently there is sufficient to call them arkoses. The felspar, which is usually rather fresh, consists almost entirely of microcline and orthoclase, though odd grains of albite and oligoclase have been noted. Altogether 27 samples, collected over a wide area from this formation, have been examined microscopically to determine their felspar content. Of these, 13 were felspathic sandstones (10 to 24% felspar), 11 were arkoses (25% or more felspar), and three were quartzose sandstones (less than 10% felspar). A noticeable feature of this examination was that of six samples from the type section, five were arkoses, and the other was a felspathic sandstone.

Muscovite flakes are frequently present in the sandstones, in quantities up to 5%. The flakes occur along the bedding planes, so that the sandstones split readily along these planes.

Among the non-opaque heavy minerals, kyanite and tourmaline are the most abundant, while staurolite, rutile, and zircon are well represented. There are minor amounts of other non-opaque minerals present. The most noticeable feature of the assemblage is the abundance of the metamorphic minerals kyanite and staurolite, and the relatively low percentage of zircon. This is in marked contrast to the Greenough Sandstone, where zircon is comparatively abundant, while kyanite and staurolite are very rare.

Stratigraphic Relationships.—Over most of the area studied the Moonyoonooka Sandstone rests conformably on the Greenough Sandstone. However in those places where the Greenough Sandstone pinches out against hills in the Precambrian rocks, the Moonyoonooka Sandstone rests unconformably on these rocks.

The Moonyoonooka Sandstone is overlain disconformably by the Colalura Sandstone, the basal formation of the marine succession. This disconformity has little relief and is best seen in the Bringo cutting, where the phosphatic sandstone of the Colalura Sandstone rests on typical Moonyoonooka Sandstone, whose bedding planes are truncated at the surface of contact (see Plate 1, 1).

Distribution and Thickness.—The Moonyoonooka Sandstone has been recognised from near Kings Table Hill in the Northampton area to Mt. Hill. It extends inland as far as the Bringo cutting.

Throughout the area examined, wherever the Moonyoonooka Sandstone rests on Greenough Sandstone and not the Precambrian rocks, its thickness varies little from 110 feet, the thickest section measured being 118 feet at (713296), and the thinnest is 80 feet near Spion Kop (828326). The formation pinches out in those areas where the elevation of the Precambrian rises higher than 640 feet above sea-level.

The type section is the best known exposure of the formation. Another good outcrop is at (723310), where it has been exposed by gullying combined with landsliding. Other typical exposures occur at The Twins (608410), at Spion Kop (728327), and near "Woolanooka" (782337).

Fossils and Age.—Fragments of wood are the only fossils commonly found in the Moonyoonooka Sandstone. These are sometimes present in the centres of ferruginous concretions.

One fossil leaf has been found near the top of the type section, but this is poorly preserved and is of doubtful value for dating. Dr. A. B. Walkom is of the opinion (in a written communication) that it could be a leaf of the *Linguifolium* type, which would indicate a Mesozoic age, perhaps Jurassic or Rhaetic.

Owing to the lack of satisfactory fossil evidence it has not been possible to date the Moonyoonooka Sandstone, but it seems best considered as Lower Jurassic. It is probably equivalent to part of the Cockleshell Gully Sandstone of the Hill River area, and this formation has been dated as Lower Jurassic.

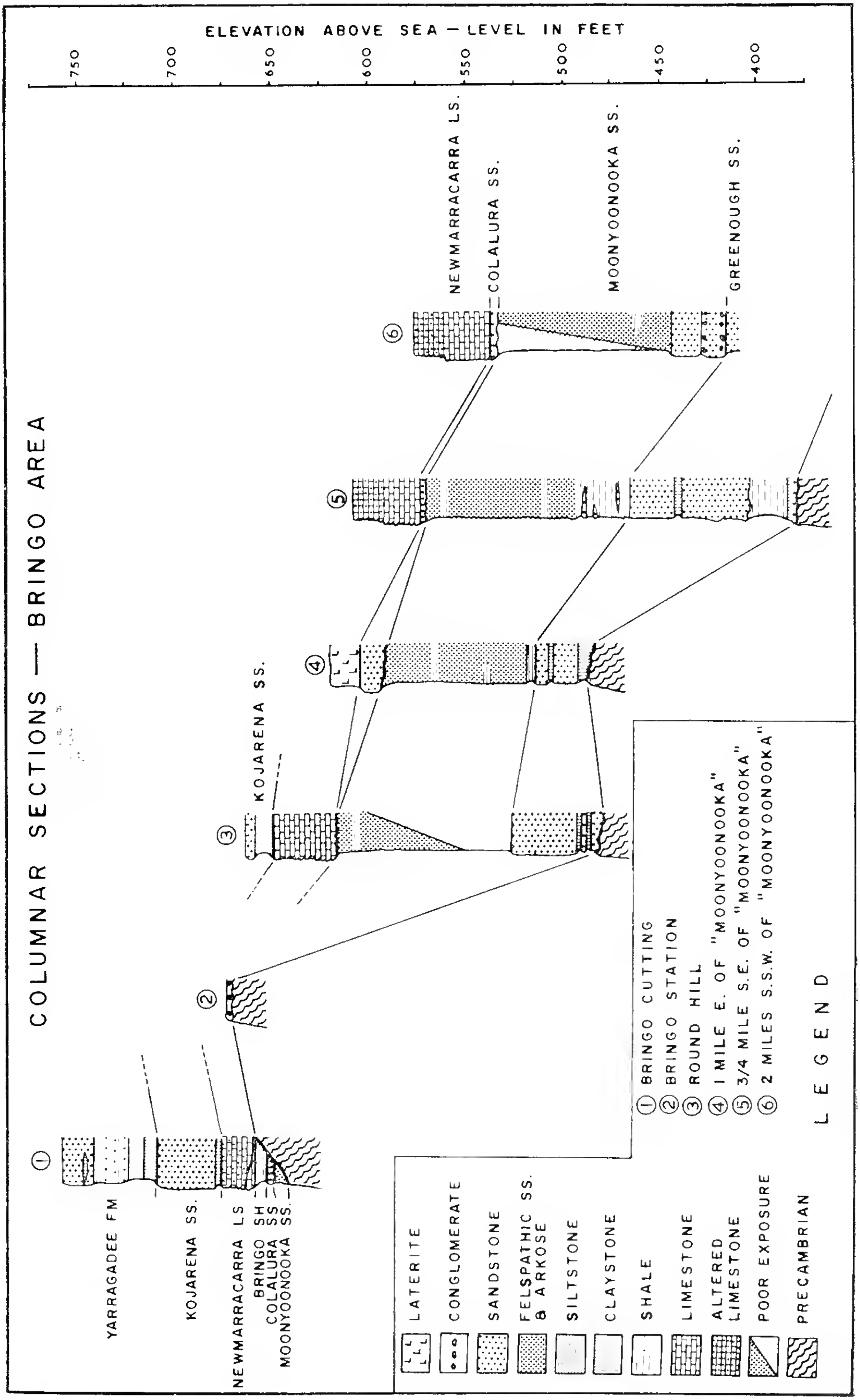
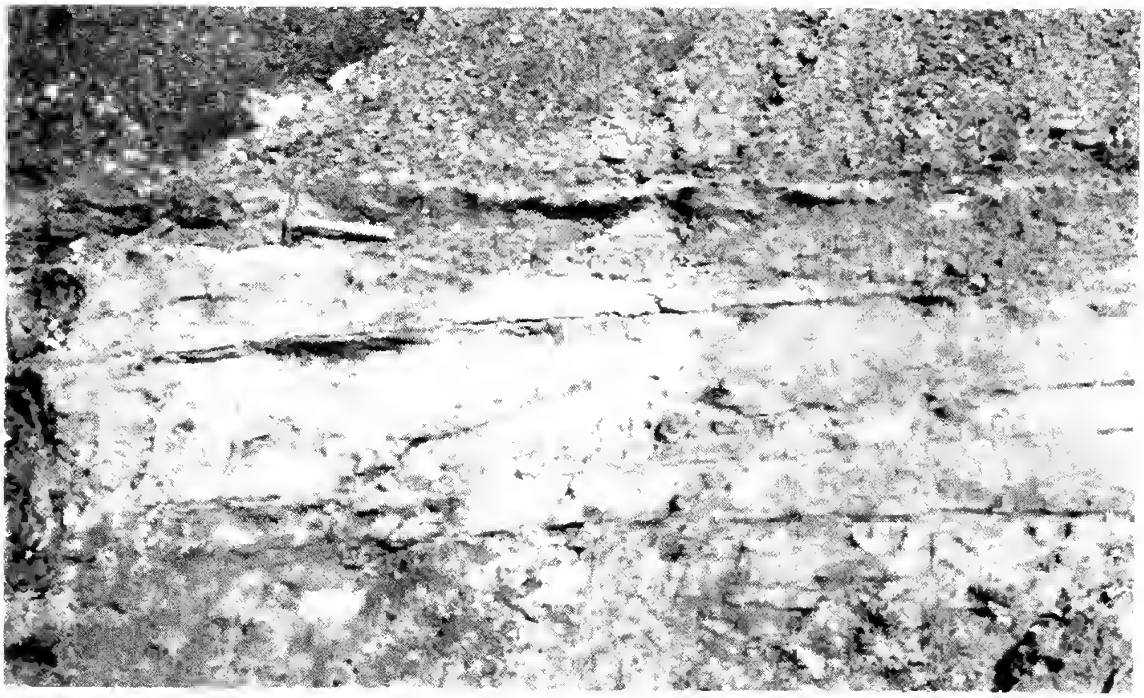

COLUMNAR SECTIONS — BRINGO AREA
ELEVATION ABOVE SEA — LEVEL IN FEET
750
700
650
600
550
500
450
400
YARRAGADEE FM
KOJARENA SS.
NEWMARRACARRA LS
BRINGO SH
COLALURA SS
MOONYOONOOKA SS.
KOJARENA SS.
NEWMARRACARRA LS.
COLALURA SS.
MOONYOONOOKA SS.
GREENOUGH SS.
LEGEND
① BRINGO CUTTING
② BRINGO STATION
③ ROUND HILL
④ 1 MILE E. OF "MOONYOONOOKA"
⑤ 3/4 MILE S.E. OF "MOONYOONOOKA"
⑥ 2 MILES S.S.W. OF "MOONYOONOOKA"
LATERITE
CONGLOMERATE
SANDSTONE
FELSPATHIC SS. & ARKOSE
SILTSTONE
CLAYSTONE
SHALE
LIMESTONE
ALTERED LIMESTONE
POOR EXPOSURE
PRECAMBRIAN

Fig. 1.

1



2

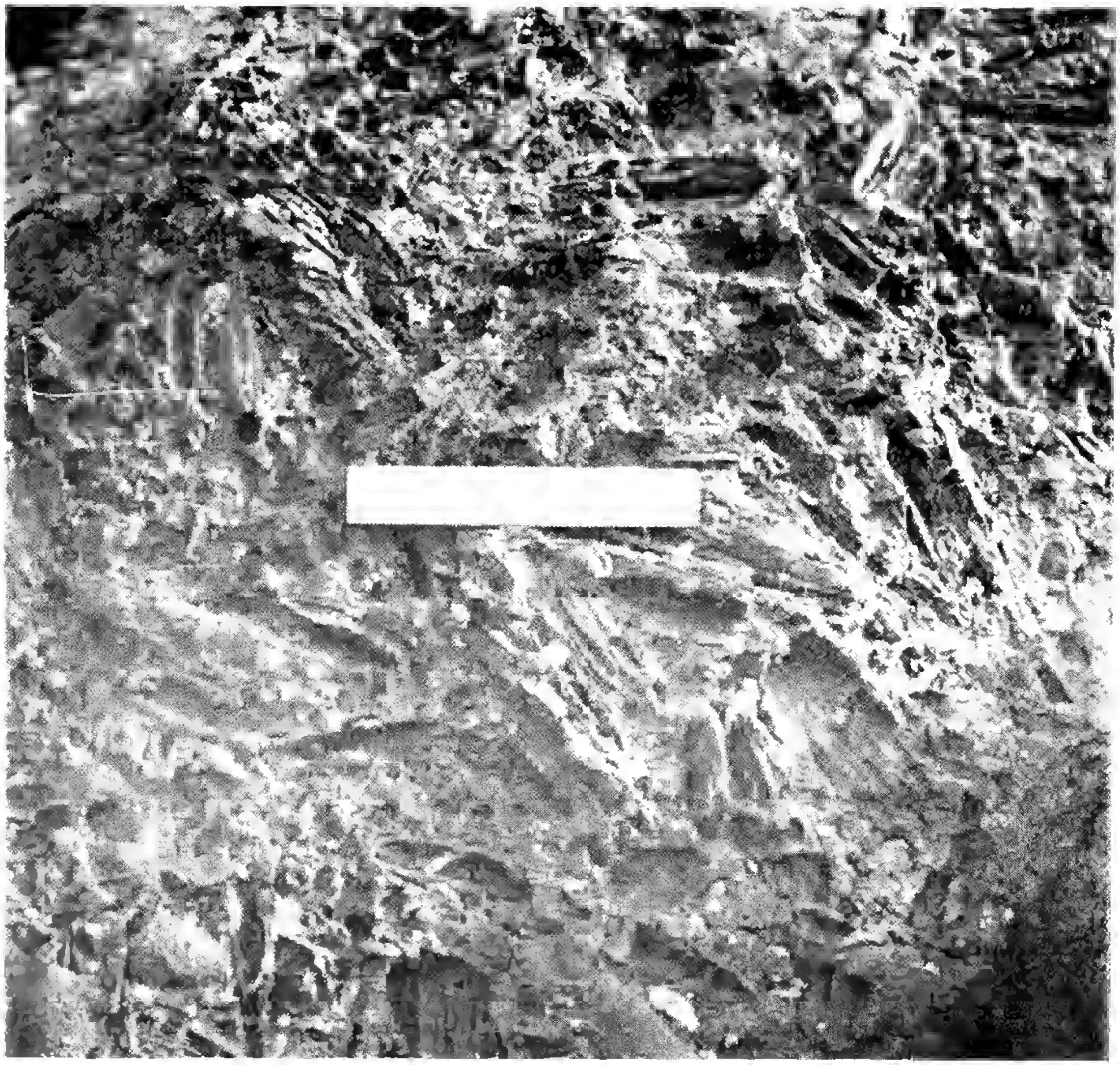


PLATE 1.

1.—Disconformity between Moonyoonooka Sandstone (beneath hammer) and Colalura Sandstone (about 18 inches thick) exposed in the Bringo cutting. The Colalura Sandstone is overlain conformably by Bringo Shale. Note truncation of bedding at the disconformity

2.—Exposure of Colalura Sandstone, showing abundant fossil wood enclosed in a matrix of ferruginous, conglomeratic sandstone. The scale is 6 inches long.

1

2

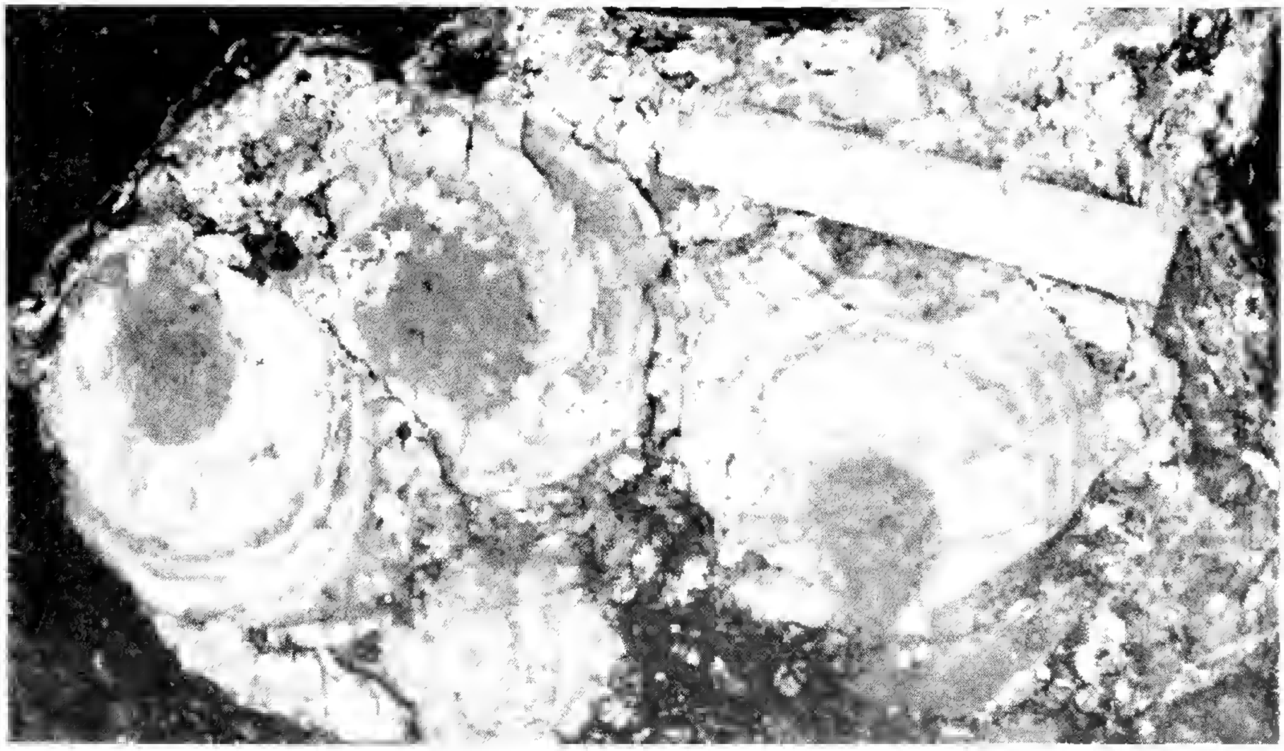


PLATE 2.

1.—Newmarracarra Limestone with numerous *Trigonia moorei*.

2.—Newmarracarra Limestone with several specimens of *Pecten cinctus*.

1

2

PLATE 3.

1.—The western end of the Bringo cutting, showing Jurassic sediments and kaolinized granitic gneiss (right centre). Note the two small west-dipping faults cutting the Jurassic sediments.

2.—Small anticline exposed in the Yarragadee Formation near the eastern end of the Bringo cutting.

Environment of Deposition.—The Moonyoonooka Sandstone is believed to be a continental fluviatile deposit. It shows the following features indicative of fluviatile deposition, many of which are also shown by the Greenough Sandstone:

(a) Fossil wood is present and one fossil leaf has been found, while marine fossils are absent.

(b) A prominent feature of the formation is the lenticular nature of individual beds, with sandstones, conglomerates, and shales dovetailing together in intricate fashion. This points strongly towards fluviatile deposition. The coarse sediments represent the channel deposits, and the finer-grained sediments the flood-plain deposits, while the dark shales represent deposits of small lakes and swamps on the flood-plain.

(c) The characteristic colour of the formation is yellow, a typical colour of fluviatile deposits which accumulate under non-reducing conditions, permitting preservation of such colours as red and yellow, which are due to ferric oxide.

(d) Intraformational conglomerates and breccias testify to the subaerial exposure of the beds.

(e) Cut-and-fill structure is present where coarse sandstones cut through shale or fine-grained sandstone.

(f) The abundance of cross-bedding and current ripple-mark throughout the formation is evidence of the shallow-water nature of the deposit.

(g) Arkose, though not invariably a fluviatile sediment, is most typically deposited under the fluvial environment, so that the prevalence of this sediment, together with felspathic sandstones, supports the suggested mode of origin of the formation.

It is considered that following deposition of the Greenough Sandstone, which rapidly filled major depressions in the surface of the Precambrian rocks, the Moonyoonooka Sandstone was spread over a broad flood-plain, above which some basement hills still projected, though the relief was much less than when the Greenough Sandstone was being deposited. The Moonyoonooka Sandstone is very well-bedded and well-sorted, in marked contrast to the Greenough Sandstone. This is because the Moonyoonooka Sandstone has been transported further than the Greenough Sandstone, and has been spread layer-on-layer by successive floods, whereas the Greenough Sandstone is locally derived.

The prevalence of fresh potash felspar in the Moonyoonooka Sandstone indicates that erosion of the source area was sufficiently rapid to prevent decomposition of this mineral. Rather rapid erosion is also indicated by the rich heavy mineral suite, which includes such relatively unstable minerals as sphene. The extreme rarity of garnet in the non-opaque suite is evidence that the sediment must have been transported a fairly considerable distance, for the local granitic rocks are rich in garnet. As the abundance of felspar and other metastable minerals is very marked in the Moonyoonooka Sandstone, garnet would also have been common had the sediment been locally derived.

It is likely that deposition of the Greenough and Moonyoonooka Sandstones, and indeed of all the continental Jurassic and Lower Cretaceous continental sediments in the Perth Basin, was controlled by movement along the Urella and Darling Faults. These sediments are believed to have been laid down in front of the active faults, and to have been derived by erosion of the area of steep, youthful topography near the fault scarps. The Urella Fault is believed to have been the dominant fault in Jurassic times in the area north of Coorow, while from about Coorow to the south coast the Darling Fault is the main fault. It is important to note that no Jurassic sediments are known in the area east of the Urella Fault.

Champion Bay Group

The name Champion Bay Group was introduced by Playford, in Arkell and Playford (1954), for the Jurassic sediments overlying the Chapman Group. The group is made up of four formations, the Colalura Sandstone, Bringo Shale, Newmarracarra Limestone, and Kojarena Sandstone. Playford and Willmott (in McWhae *et al.* 1958) redefined the Kojarena Sandstone, placing the upper part of the formation as previously understood by Playford in the Yarragadee Formation. The latter formation is not included in the Champion Bay Group.

The Champion Bay Group is of Middle Jurassic age. One formation, the Newmarracarra Limestone, is accurately dated as Middle Bajocian, and the other formations are probably also of Bajocian age.

(i) *Colalura Sandstone*

Definition.—The name Colalura Sandstone was introduced by Playford, in Arkell and Playford (1954), for the sandstone unit resting on the disconformity with the Moonyoonooka Sandstone or the nonconformity with the Precambrian rocks, and overlain conformably by the Bringo Shale or the Newmarracarra Limestone. The formation is named after the Colalura Brook (770330), which drains the southern part of the area surveyed in detail, and flows into the Greenough River.

The type section of the Colalura Sandstone is at Spion Kop (28° 46′ 44″ S., 114° 48′ 24″ E.). The following is a description of this section:

Laterite (lateritized Newmarracarra Limestone) overlying—

Colalura Sandstone (8 to 12′)

	Thickness feet
(1) Sandstone, very coarse- to medium-grained, conglomeratic, yellowish brown, ferruginous, coarsely cross-bedded, containing a few thin claystone beds; several horizons rich in fossil wood and limonitic nodules ..	8 - 12

disconformably overlying Moonyoonooka Sandstone.

Lithology.—The Colalura Sandstone consists almost entirely of sandstone, with minor amounts of claystone, siltstone, and shale. The sandstone is frequently conglomeratic, and varies in colour from black and brown to yellowish-white, a dark brown being most common. Sand grains may be appreciably rounded or unrounded, and their cement is usually ferruginous, but is sometimes calcareous.

A striking and characteristic feature of most exposures of the unit is the presence of abundant ferruginous fossil wood (see Plate 1, 2), and to a lesser extent of oval-shaped ferruginous nodules, generally about ¾-inch long. The wood varies in size from logs 3 feet long, to minute fragments. The nodules and some of the fossil wood are believed to have been originally phosphatic, and to have been ferruginized during weathering. They are still phosphatic in the exposures of Colalura Sandstone in the Bringo cutting and near "Woolanooka" (780238).

The phosphatic nodules, which are dark brown in colour, have a pronounced concentric structure, and frequently contain a nucleus of greyish clay. It is possible that this structureless clayey interior is of coprolitic origin, and the nodule has grown by concentric addition to this nucleus. In the nodules which have been replaced by limonite, this concentric structure is lost, though the clay centres remain.

The nodules are apparently syngenetic (formed before burial in sediments), for the insoluble residue left after treatment of the nodules with acid is fine clay or sand, despite the fact that the nodules are themselves enclosed in a coarse sand.

The abundant limonite in the Colalura Sandstone is probably not entirely secondary, for even in the Bringo cutting where the nodules are still phosphatic, the cementing agent in the sandstone is limonite, with perhaps some hematite, and the nodules themselves contain some ferric oxide. The reason for the complete replacement of the nodules by ferric oxide is not certain, but it may well be connected with laterization.

Stratification is usually absent in the sandstones, though they are sometimes coarsely cross-bedded. The sorting of the sandstones usually appears to be poor owing to the large amounts of fossil wood and nodules present—these may make up as much as 50% or more of the rock by volume. However, the sand remaining after treatment of the rock with acid is often found to be quite well-sorted.

In the Bringo cutting the Colalura Sandstone shows a well-marked facies change from the typical brown sandstone with no marine fossils but abundant dark brown fossil wood and phosphatic nodules, to a yellowish sandy claystone with abundant marine fossils, and occasional fossil wood and phosphatic nodules. The nodules and fossil wood in this claystone are different in appearance from those in the sandstone, and they also contain a higher percentage of P_2O_5. The phosphatic wood is yellow, and the cell structure is clearly visible, even to the naked eye. This fossil wood contains as much as 32.9% of P_2O_5, whereas the fossil wood in the sandstone from the cutting contains only as much as 1.47% of P_2O_5. The nodules in the claystone are yellowish and many have a black coating giving them a high surface lustre. In shape they are similar to the typical brown nodules, and they usually contain a clayey nucleus, though the outer layer shows no pronounced concentric structure. These nodules have as much as 23.8% of P_2O_5, while the dark brown nodules from the sandstone contain up to 6.1%.

The cementing material of the Colalura Sandstone is occasionally calcareous, as at the locality near "Woolanooka" (780238), and at (873307), near "Sandspring."

In some localities the sandstone is stained black by manganese oxide. This is seen well in the Bringo cutting, where the sandstone and claystone of the formation show some black patches due to a thin coating of manganese oxide.

The "light" minerals in the sandstone remaining after treatment with acid consist of rounded and angular grains of quartz, and smaller amounts of felspar and muscovite. The percentage of felspar was not sufficient to designate any of the samples examined as being felspathic, but it is higher than in any formation other than the Moonyoonooka Sandstone. Only potash felspar has been recognized, and the percentage is highest in the finer-grained sandstones, one sample containing 8%.

The heavy mineral suite is rather variable, the most distinctive feature being the abundance of the metamorphic minerals kyanite, staurolite, and garnet. The nature of the heavy mineral suite seems to vary according to the underlying rock. In the Bringo cutting the Colalura Sandstone rests on both the Moonyoonooka Sandstone and the Precambrian gneisses. The heavy mineral residue from the formation at this locality is remarkable for its unusually large content of garnet, which forms more than 50% of the non-opaque minerals. The Precambrian gneisses of this area are very rich in garnet, and the Colalura Sandstone in the Bringo cutting no doubt derived its garnet from this source. On the other hand, specimens examined from localities distant from granitic areas, where the formation overlies thick deposits of Moonyoonooka Sandstone, contain little or no garnet. These specimens are found to contain considerable quantities of kyanite and staurolite, which were probably derived by the reworking of the underlying Moonyoonooka Sandstone, which is rich in these minerals, but contains little garnet.

Stratigraphic relationships.—The Colalura Sandstone usually overlies the Moonyoonooka Sandstone, being separated by a disconformity which shows little relief. In places however, it overlies the Precambrian rocks, as the Moonyoonooka Sandstone lenses out against buried hills. Conformably overlying the Colalura Sandstone is either the Bringo Shale or the Newmarracarra Limestone.

Distribution and thickness.—The Colalura Sandstone is a thin, discontinuous, but persistent formation at the base of the marine section throughout a large part of the Geraldton district.

It is known to extend from near Howatharra Siding (north of the map) to Mt. Hill, and has been recognized as far east as "Sandspring" (873307).

The Colalura Sandstone is absent over part of the area, but where present it ranges up to 28 feet in thickness at (725340). Most exposures are only about 2 feet thick.

As the Colalura Sandstone is often well-consolidated, exposures of the formation are quite frequent, in the form of large slabs, which may migrate some distance down the hill-slopes.

Fossils and age.—As already described, the Colalura Sandstone is rich in fossil wood. Marine fossils have also been found in the formation at several localities. The most important of these is the Bringo cutting, where a claystone unit in the formation contains numerous marine fossils, preserved as moulds. Another locality where fossils are abundant is at (715325), where they are preserved as moulds in a coarse-grained ferruginous sandstone.

The following is a list of fossils which have been identified from the Colalura Sandstone: The pelecypods *Astarte cliftoni*, *Astarte* sp., *Ctenostreon pectiniformis*, *Lopha* cf. *marshi*, *Trigonia moorei*, *Ostrea* sp., *Oxytoma* cf. *decemcosta*, and *Isognomon* sp., and the belemnite *Belemnopsis* sp.

There are also several unidentified species of pelecypods and gastropods, and one echinoid spine, a shark tooth, a reptilian tooth, and a reptilian vertebra were found in the Bringo cutting.

All the species which have been identified are also present in the Newmarracarra Limestone, which is known to be of Middle Bajocian age, and it seems probable that the Colalura Sandstone is also Bajocian in age.

Environment of deposition.—The Colalura Sandstone represents the basal shallow-water deposits of an advancing sea. The clastic constituents were largely derived by reworking from the underlying Moonyoonooka Sandstone and the Precambrian rocks. A shallow-water environment of deposition is indicated by the coarseness of the sandstone and the large-scale cross-bedding. Moreover, it is difficult to visualize such large quantities of wood being incorporated in the sediment except under very shallow water conditions.

The source of all the fossil wood in the formation is not easy to explain. If it has been carried in by rivers, then the sediments carried by those rivers would tend to mask the wood. It is possible that the wood represents the vegetation which was growing on the low-lying flood-plain of the Moonyoonooka Sandstone, which was engulfed as the sea advanced. Against this hypothesis is the fact that no fossil stumps have been found embedded *in situ* in the Moonyoonooka Sandstone.

The origin of the phosphatic nodules in the formation is not known. However the occurrence of these nodules immediately above the disconformity with the Moonyoonooka Sandstone is not unexpected, as phosphatic zones are commonly found elsewhere in the world in association with unconformities.

(ii) *Bringo Shale*

Definition.—The name Bringo Shale was first used by Playford, in Arkell and Playford (1954), for the black shale which overlies the Colalura Sandstone or the Precambrian rocks, and underlies the Newmarracarra Limestone.

The type section is exposed in the Bringo cutting (766364, 28° 44′ 54″ S., 114° 50′ 54″ E.) The following is a description of this section:

Newmarracarra Limestone, Comformably overlying—

Bringo Shale (7 feet)

	Thickness Ft.	In.
(5) Shale, black, becoming yellow in the uppermost foot; phosphatic nodules resting on top; several layers containing small pelecypods	2	6
(4) Claystone, yellowish brown, phosphatic, concretionary		2
(3) Shale, black; rich in small pelecypods		6
(2) Claystone, yellowish brown, phosphatic, concretionary		4
(1) Shale, black; abundant small pelecypods at the base	3	6

conformably overlying Colalura Sandstone.

Lithology.—The Bringo Shale consists of black shale with thin yellow phosphatic beds. A layer of phosphatic nodules is present at the top of the unit, at the contact with the Newmarracarra Limestone. The shale contains some small carbonaceous fragments of wood and a few beds of marine fossils.

The yellow phosphatic clay beds are only a few inches thick, and show pronounced concretionary structures. The phosphate content averages 3.3% of P_2O_5. The phosphatic nodules, which are not common, are flattened, smooth, bulging, asymmetrical bodies, which are up to 6 inches long, and 2 inches thick. They show only a poorly defined concentric structure. The upper surface of the nodules often shows a series of small pits. Sections show that these pits cut through the concentric structure of the nodules, indicating that they are secondary, and it seems possible that they were formed by boring organisms. Another feature of the outer surface is a series of cracks which penetrate about ¼-inch into the nodules. These are subparallel, and are apparently shrinkage cracks produced when the nodules solidified. The phosphate (P_2O_5) content of the nodules varies from 7.6% in the Bringo cutting to 26.8% near "Sandspring".

Stratigraphic relationships.—The Bringo Shale rests conformably on the Colalura Sandstone, or unconformably on the Precambrian rocks. Both relationships are visible in the section exposed at the Bringo cutting.

Overlying the Bringo Shale is the Newmarracarra Limestone. A layer of phosphatic nodules at the contact between the formations suggests an interval of non-deposition, so that they are probably separated by a diastem, though they are essentially conformable.

Distribution and thickness.—The Bringo Shale has a rather limited distribution. It has been traced at the surface from the Bringo cutting to near "Sandspring" (872307), and as far south as (848249). It is probably present in bores in the Eradu area, underlying the Kojarena Sandstone, and resting on the Lower Permian Irwin River Coal Measures.

The Bringo Shale appears to have been deposited only in the restricted environment lying to the east of Precambrian ridges. Thus the unit is present in the Bringo cutting section, to the east of a Precambrian ridge which reaches its highest point near Bringo Station, but it is absent on the western side of this ridge, in the Grant Siding—"Moonyoonooka" area (see section A-B, Plate 5, and Fig. 1.)

No section of the formation has been seen which is more than 8 feet thick, and where it rests on the Colalura Sandstone it is usually about 7 feet thick. At the type section the thickness is 7 feet, near "Sandspring" (872307) it is 8 feet, and at (848249) it is 5 feet.

The Bringo Shale is poorly exposed throughout the area examined. The best section is the Bringo cutting, but elsewhere there is no continuous section exposed.

Springs commonly issue at the contact between the Newmarracarra Limestone and the Bringo Shale, and the running water often exposes the shale to some extent. A typical example is found one mile east of Bringo (775358), where there is a good spring of fresh water issuing at the contact between the two formations.

Fossils and age.—The only fossils which have been found in the Bringo Shale are those from the type section. At this locality there are several layers in the shale which are rich in dwarfed pelecypods, predominantly a species of *Meleagrinella*, together with some oysters. Rare gastropods, and guards of *Belemnopsis* are also found. Balme (1957) has described a small assemblage of fossil spores and pollen grains in a sample of the formation from the Bringo cutting.

The Bringo Shale is believed to be of Bajocian age. The layer of phosphatic nodules at the top of the formation indicates a probable gap in sedimentation prior to deposition of the Middle Bajocian Newmarracarra Limestone, but this gap was probably only of very short duration.

Environment of Deposition.—The Bringo Shale was deposited in an environment having restricted circulation, resulting in anaerobic conditions on the bottom. Under such conditions the benthonic fauna is absent or restricted, and the action of scavengers in eliminating organic material derived from the surface waters is prevented. Nearly all black shales in the geological record are believed to have formed in this way (Twenhofel 1950).

As the Bringo Shale contains several layers with dwarf benthonic pelecypods, and as no iron sulphide has been found in the shale, restriction of circulation was apparently not complete, and there were periods when the bottom was quite well-oxygenated. However, as the benthonic fossils are only found in relatively thin bands, with black unfossiliferous shale in between, the conditions were apparently anaerobic during most of the time when the shale was accumulating.

The cause of the stagnation is to be found in the irregularity of the surface of the Precambrian rocks. It is clear in the Bringo cutting that the shale has accumulated in a barred basin on the eastern side of a hill or ridge of Precambrian rocks. On the western side of this ridge the Bringo Shale is absent, as this area was apparently part of the open ocean, with free circulation, at the time when the shale was accumulating in the restricted environment to the east of the ridge. It is not known whether the ridge was below sea-level when the shale was deposited. If it was submerged, the depth of water must have been small, so that free connection with the open ocean was prevented.

Some change must have occurred in the conditions of circulation following deposition of the Colalura Sandstone. In the Bringo cutting section this formation contains a rich benthonic fauna which clearly grew under normal conditions of free circulation. It is possible that during Colalura times there was free connection with the open ocean through some opening which was barred before deposition of the Bringo Shale commenced. Alternatively the restriction may have followed a slight relative fall in sea-level, making the bar more effective.

The phosphatic nodules at the top of the formation may have been deposited in the form of a gel. This is suggested by their flattened, irregularly rounded shape, which is typically like that of a gel mass, and also by the presence of skrinkage cracks on the outer surface of the nodules. These may have formed as the gel contracted on solidification.

(iii) *Newmarracarra Limestone*

Definition.—The Newmarracarra Limestone was defined by Playford, in Arkell and Playford (1954). The formation overlies either the Bringo Shale, the Colalura Sandstone, the Moonyoonooka Sandstone, or the Precambrian rocks, and underlies the Kojarena Sandstone. The name is taken from "Newmarracarra," a well-known pastoral property in the Geraldton district.

The name "Newmarracarra" had previously been used in a stratigraphic sense by Glauert (1926), who defined the "Newmarracarra Beds" as the fossiliferous beds exposed in the "Nineteen Mile" (later Bringo) railway cutting, from which the fossils described by Whitehouse (1924) were obtained. Actually Whitehouse's fossils were probably obtained from a railway well near Bringo, but in either case they certainly came from the limestone, and Glauert's name must be used in reclassification.

Teichert (1947), apparently independently, proposed the name "Newmarracarra Series" for all the marine sediments of the Geraldton district, but Glauert's earlier usage clearly has priority.

The type section of the formation is on Round Hill, near Grant Siding (729351, 28° 45′ 31″ S., 114° 48′ 23″ E.) The following is a description of this section:—

Kojarena Sandstone. Conformably overlying—

Newmarracarra Limestone

	Thickness Feet.
(4) Limestone, light yellow-grey, sandy, hard, massive, outcropping in large slabs; few fossils	2
(3) Limestone, light yellow-grey, weathering greyish white, hard, massive, outcropping in large slabs; richly fossiliferous	8
(2) Limestone, light yellow-grey, clayey, soft, massive; richly fossiliferous ...	21
(1) Limestone, light yellow-grey, sandy, clayey, hard, massive, outcropping as large slabs, richly fossiliferous	2

disconformably overlying Moonyoonooka Sandstone.

Lithology.—The Newmarracarra Limestone, where it has not undergone secondary alteration, usually consists of limestone composed of entire or little-broken shells. It has a variable content of clastic impurities, and rarely grades into a calcareous sandstone.

The limestone is generally massive, hard, and smooth-weathering, outcropping as large slabs which frequently break off, and tend to migrate down the sides of hills making it difficult to say when the slabs are *in situ*.

The colour of the limestone varies from yellow and grey to red, the most usual being yellow, frequently weathering grey. The red coloration is secondary, and is due to the presence of finely divided hematite in the rock.

The limestone has been subjected to a great deal of secondary alteration throughout the area examined. Over the most of this area a large part of the limestone has been either replaced by iron oxide (mainly hematite), or leached of calcium carbonate, leaving a residue of its clastic impurities. Only in the small area around the type section near Grant is the limestone thought to be unaltered throughout, and even there it is possible that the sandy claystone overlying the limestone outcrop is really leached limestone. The leached zone is found between the hematite and the unaltered limestone, and the thickness of alteration is very variable. This alteration of the limestone is connected with lateritization, and has been discussed already.

The limestone is often stained red by hematite without complete removal of calcium carbonate. This is not connected with lateritization and is often found where the limestone overlies Bringo Shale, with springs issuing at the contact.

The insoluble residue from the limestone consists of clay, rounded grains of quartz, a little felspar, an occasional flake of muscovite, and a small quantity of heavy minerals. The percentage of these clastic impurities is usually rather high, most samples being sandy, argillaceous limestones. The quartz sand present is rounded, having an average roundness of about .29. This value is considerably higher than that for sand in the other formations, and indicates relatively prolonged abrasion of the sand.

It is noticeable that the percentage of clastic impurities in the formation rises to the east, as those elevated areas in the Precambrian rocks still projecting above the earlier sediments are approached. For example, on the road from Northern Gully to "Tibradden" (836367), there is an outcrop of cross-bedded calcareous sandstone at the base of the limestone, and all the limestone is very sandy. The formation abuts a buried hill of Precambrian rocks near this locality, and almost certainly pinches out against this hill. On the other hand the base of the limestone to the west (as at (690297), which is several miles from such elevated Precambrian areas) is comparatively free of clastic impurities.

The high sand content around the granitic hills is probably not due to erosion of these hills when the Newmarracarra Limestone was accumulating. This is indicated by the fact that the quartz grains are comparatively well-rounded, and must have undergone rather prolonged abrasion before deposition. They could not have been abraded to any great extent while the shells were accumulating, for these show little evidence of wear. It is probable that the sand was rounded while the Colalura Sandstone and Bringo Shale were being deposited. During this time the sea probably did not cover the granitic hills, and rounded beach sands may have accumulated around these islands or promontories. The rounded sand now found in the limestone may represent this sand which was redistributed during deposition of the Newmarracarra Limestone.

The most striking feature of the heavy mineral suite is the unusually large quantity of epidote present, as this mineral is only found in small quantities in the other formations. Otherwise the heavy mineral assemblage is rather like that of the Colalura Sandstone, with a fairly high percentage of metamorphic minerals, including garnet.

Stratigraphic relationships.—The Newmarracarra Limestone was deposited in different parts of the area on either the Bringo Shale, the Colalura Sandstone, the Moonyoonooka Sandstone, or the Precambrian rocks. The contact with the Precambrian rocks is a nonconformity, and that with the Moonyoonooka Sandstone is a disconformity. The contact with the Bringo Shale and the Colalura Sandstone is believed to be essentially conformable, though the units may be separated by a diastem.

The Newmarracarra Limestone is overlain conformably by the Kojarena Sandstone.

Distribution and thickness.—Unaltered Newmarracarra Limestone has a very limited distribution in the Geraldton district, the most extensive outcrops being found in the area mapped in detail. Elsewhere outcrops are very sporadic, as the limestone has been largely altered by lateritization. The hematite rock and underlying leached zone can be readily recognized as altered Newmarracarra Limestone in the field, and have been mapped as such. On the other hand, the intensely altered limestone close to true laterite is not readily recognized, and for mapping purposes has been included in the laterite.

Owing to the irregular alteration, the thickness of limestone is very variable, the thickest exposures being near Round Hill, where up to 33 feet of unaltered limestone are exposed. Elsewhere the formation is invariably altered to some extent, so that at least the upper part is replaced by hematite or simply leached of calcium carbonate. Because of the irregular leached zone, which causes compaction of the formation, it is not possible to give accurate primary thickness of the limestone at those localities where it has been altered. The thickest section which has been measured is at (690297), where the formation is about 38 feet thick. At this locality there are about 28 feet of limestone and 10 feet of altered limestone. Nearly all of this alteration is in the form of hematite, and the leached zone is very thin. In the Geraldton Racecourse bore the formation may be 47 feet thick (from 186 feet to 233 feet).

At the Bringo cutting the unaltered limestone is up to 5 feet thick, but passes both laterally and vertically into leached limestone (see Plate 6). The leached zone is up to 8 feet thick, and is overlain by as much as 9 feet of hematite rock. The contact between the leached and hematite-replaced limestone is not well-marked, each grading gradually but irregularly into the other. At this locality the formation is only 17 feet thick, and has compacted considerably owing to the thick leached zone.

Exposures of the Newmarracarra Limestone extend from near Howatharra Siding on the Geraldton-Northampton line (off the map) to Mt. Hill. It is known to lense out to the east, and has been recorded during the recent Wapet survey as far inland as 1¼ miles south-east of Eradu Pool on the Greenough River. It is absent from bores around Eradu itself, though both the Kojarena Sandstone and the Bringo Shale are apparently represented there.

The Cadda Formation of the Hill River area, 100 miles south of Geraldton, is a facies equivalent of the Newmarracarra Limestone. The Cadda Formation contains a high percentage of sandstone and siltstone in addition to limestone, and is also not as richly fossiliferous as the Newmarracarra Limestone.

Fossils and age.—The Newmarracarra Limestone is richly fossiliferous, and fossils are usually well-preserved, though they are frequently difficult to extract owing to the toughness of the matrix. In addition to the abundant marine fossils, fragments of wood up to about 2 feet long are not uncommon in the limestone.

The most abundant fossils are the pelecypods, and of these *Trigonia moorei* is by far the most common. This species is found, perfectly preserved, in great abundance thoroughout the formation, indeed some parts are composed almost entirely of masses of this shell (see Plate 2, 1).

The ammonites, which are of prime importance in dating the formation, are seldom found in any abundance, though there are at least 23 species known. The species most commonly found is *Fontannesia clarkei* and large numbers of this species were collected in the debris from rabbit-burrows in the area about one mile south-east of Bringo. The ammonites have recently been the subject of a detailed study by Arkell (in Arkell and Playford 1954), and he has concluded that the Newmarracarra Limestone can be referred to the Sowerbyi and perhaps Sauzei and Humphriesianum Zones of the European Middle Bajocian.

The following is a list of fossils which have been recorded from the Newmarracarra Limestone. It must be understood that most of these fossils were described many years ago, and many of the names, particularly of the genera, need revision. These forms marked with an asterisk, e.g. **Cristellaria cultrata*, have not been figured or properly described from the Newmarracarra Limestone. Their occurrence has merely been recorded, and there is some doubt as to whether some of them are really present. The Ostracoda, originally described by Chapman (1904*a*), were recently discussed by Kellett and Gill (1956), and they point out that the fauna needs complete re-study. It is certain that all the fossils which have previously been described as coming from the Geraldton district are from the Newmarracarra Limestone.

Foraminifera (Chapman 1904*a*, Moore 1870). *Bulimina gregorii*, *Cristellaria costata* var. *compressa*, *C. costata* var. *seminuda*, **C. cultrata*, *C. daintreei*, *C. decipiens*, *C.* cf. *limata*, *C. prominula*, *C. rotulata*, *C. subalata*, *Discorbina rosacea*, *Flabellina dilatata*, *Haplophragmium neocomianum*, *Marginulina compressa*, *M. solida*, *Polymorphina burdigalensis*, *P. compressa*, *P. gutta*, *Textularia crater*, *Truncatulina wuellerstorfi*, *Vaginulina intumescens*, *V. lata*, *V. schloenbachi* var. *interrupta*, *V. strigillata*.

Echinoidea (Whitehouse 1924). *Cidaris* sp.

Vermes (Clarke 1867, Moore 1870, Etheridge 1910). *Serpula conformis*, **Serpula* spp.

Bryozoa (Whitehouse 1924). **Berenicea* cf. *archiaci*.

Brachiopoda (Clarke 1867, Moore 1870, Etheridge 1910). *Rhynchonella variabilis*, **Rhynchonella* spp.

Pelecypoda (Clarke 1867, Moore 1870, Etheridge 1901, Maitland 1907, Etheridge 1910, Glauert 1910, Whitehouse 1924, Teichert 1940). **Arca* sp., *Lopha marshi*, **Avicula inaequivalvis*, *Ctenostreon pectiniformis*, *Cucullaea inflata*, **C. oblonga*, *C. semistriata*, *C. tibraddonensis*, *Meleagrinella sinuata*, **Gryphaea* spp., **Hinnites* sp., **Lima proboscidea* Sowerby, **L. punctata*, *Modiola maitlandi*, **Mytilus* cf. *gygerensis*, **M. sp.*, **Nucula* sp., *Ostrea tholiformis*, *Ostrea* spp. *Oxytoma decemcosta*, **Pecten calvus*, *P. cinctus*, **P.* cf. *frontalis*, *P. greenoughensis*, **P. valoniensis*, **P.* spp., **Perna sp.*, *Plicatula* sp., *Radula duplicata*, **Radula* sp., *Trigonia moorei*, **Gresslya donaciformis*, **Myacites liassianus*, *M. sanfordii*, **Pholadomya ovulum*, *Astarte apicalis*, *A clittoni*, **Cardium* sp., **Cypricardia* sp., **Isocardia* sp., **Lucina* sp., **Opis* sp., **Panopaea rugosa*, **P.* sp., **Tancredia* sp., *Teredo australis*, **Unicardium* sp.

Scaphopoda (Clarke 1867). **Dentalium* sp.

Gastropoda (Clarke 1867, Moore 1870, Etheridge 1910). **Amberleya* sp., **Phasianella* sp., *Pleurotomaria greenoughensis*, **Pleurotomaria*, sp.,**Trochus* sp., *Turbo laevigatus*, **Turbo* sp., *Cerithium greenoughensis*, **C*. sp., **Chemnitzia* sp., **Nerinaea* sp., *Rissoina australis*.

Nautiloidea (Crick 1894). *Nautilus perornatus*.

Belemnoidea (Clarke 1867, Moore 1870, Crick 1894, Whitehouse 1924). *Belemnites canaliculatus*, **Belemnites canhami*, **B*. sp., *Belemnopsis* sp.

Ammonoidea (Arkell and Playford 1954). *Sonninia playfordi*, *Witchellia australica*, *Fontannesia fairbridgei*, *F. clarkei*, *F. whitehousei*, *F.* spp., *Otoites woodwardi*, *O. antipodus*, *O. (?Trilobiticeras) depressus*, *?O. australis*, *Pseudotoites leicharti*, *P. fasciculatus*, *P. championensis*, *P. robiginosus*, *P. emilioides*, *P. brunnschweileri*, *P. spitiformis*, *P. semiornatus*, *P. spp.*, *Zemistephanus corona*, *Z. armatus*. *?Z* spp., *Stephanoceras (Stemmatoceras)* cf. *subcoronatum*, *S. (S.)* aff. *triptolemus*.

Ostracoda (Chapman 1904*a*, Kellett and Gill 1956). *"Cythere" lobulata*, *"Cytheropteron" australiense*, *"Loxoconcha" elongata*, *"L." jurassica*, *Procytheridea* sp.

Environment of deposition.—The Newmarracarra Limestone is built up for the most part of the remains of shallow-water benthonic organisms, predominantly pelecypods, which accumulated on the bottom of a shallow, warm sea. Currents introduced a certain amount of clay, silt, and sand, but the fact that these fossils show little evidence of wear, and the pelecypod valves are often closed, indicates that these currents were not very strong. There was also a certain amount of drift wood in the sea, which on becoming waterlogged, sank to the bottom and was incorporated in the limestone.

Following deposition of the Bringo Shale, there must have been a further subsidence (relative rise in sea-level) before deposition of the Newmarracarra Limestone. This subsidence explains the change in environment from one of restricted circulation during deposition of the Bringo Shale, to one of open circulation for the Newmarracarra Limestone. By covering or increasing the depth of water over the elevated Precambrian ridges, the region east of these ridges obtained good circulation.

(iv) *Kojarena Sandstone*

Definition.—The name Kojarena Sandstone was first published by Playford in Arkell and Playford (1954). He defined it as the Jurassic sediments, mainly sandstones, which overlie the Newmarracarra Limestone in the Geraldton district. The name is taken from Kojarena, a small railway siding on the Geraldton-Mullewa line. However, the limits of the formation have since been revised by Playford and Willmott in McWhae *et al*. (1958), the upper part of the formation as previously understood being included in the Yarragadee Formation.

The type section of the Kojarena Sandstone is in the Bringo railway cutting (28° 44′ 54″ S., 114° 50′ 54″ E.). The following is a description of this section:

Yarragadee Formation. Conformably overlying—

Kojarena Sandstone (33′)

	Thickness feet.
(2) Sandstone, reddish brown, the lower half being mottled grey, brown, and yellow; bedding indistinct; marine fossils in a lens up to 6 inches thick, 19 feet above the base	31
(1) Claystone, greyish white, mottled red; poorly bedded	2

conformably overlying Newmarracarra Limestone.

Lithology.—The Kojarena Sandstone is composed predominantly of brown ferruginous sandstone, with a little claystone at the base. The sandstone is medium- to coarse-grained, and is generally very well-sorted. The unit is poorly bedded to massive, though cross-bedding is sometimes present.

The sandstones are composed of subangular grains of quartz, with little or no felspar, and small quantities of heavy minerals. Compared with the preceding marine formations the heavy mineral suite is marked by an increased percentage of the ultra-stable minerals zircon and tourmaline, and a corresponding fall in the quantity of metamorphic minerals.

Stratigraphic Relationships.—The Kojarena Sandstone is found overlying the Newmarracarra Limestone, with apparent conformity, throughout most of the area examined. In one area near Wicherina (945350) the Newmarracarra Limestone is sometimes overlain directly by the Yarragadee Formation, while in bores around Eradu (to the east of the area covered by Plate 4) the Kojarena Sandstone appears to rest on the Bringo Shale. Further north, near the mouth of Kockatea Gully, the Kojarena Sandstone disconformably overlies the Upper Permian or Lower Triassic Kockatea Shale.

The Kojarena Sandstone is overlain, with apparent conformity, by the Yarragadee Formation.

Distribution and Thickness.—The Kojarena Sandstone is the most widely distributed of the Middle Jurassic marine formations. It extends from Howatharra Siding (off the map) to Mt. Hill, and inland it is found all along the valley of the Greenough River north and south of Eradu and the lower reaches of Kockatea Gully. The unit is probably present in the Geraldton Racecourse Bore between 154 and 186 feet.

In the area around Eradu the unit probably reaches its thickest development. The thickness from bores and exposures in this area is probably about 110 feet, whereas in the Geraldton area it does not exceed 33 feet, the thickness of the type section. It is not present in the 47¼ mile peg bore (off the map) which is situated close to the Urella Fault. In this bore the Yarragadee Formation rests directly on the Kockatea Shale.

Fossils and age.—The Kojarena Sandstone contains few fossils. In the Bringo cutting section at 20 miles 5 chains from Geraldton, there is a thin fossiliferous lens up to 6 inches thick containing moulds of marine fossils. At several other localities, such as Round Hill and 1½ miles east-north-east of Eradu, a few similar marine fossils have been found. Those which have been identified are *Trigonia moorei*, *Cucullaea* sp., *Isognomon* sp.,and *Belemnopsis* sp. These fossils are also present in the underlying Newmarracarra Limestone, which is of Middle Bajocian age. As the two formations are conformable, it is likely that the Kojarena Sandstone is also of Bajocian age.

Fragments of wood occur occasionally in the unit, and worm tubes are also sometimes found.

Environment of deposition.— The Kojarena Sandstone is interpreted as being a shallow-water marine deposit. The presence of marine fossils in typical sandstones of the formation shows the marine origin, and the high degree of sorting probably indicates that it was deposited below wave-base. It represents the final phase of the Middle Jurassic marine cycle.

Yarragadee Formation

Definition.—The Yarragadee Formation was first named "Yarragadee Beds" by Fairbridge (1953). He used the name for exposures of sandstone and siltstone on Yarragadee property, 7 to 8 miles north of Mingenew. His usage was followed by Johnson *et al.* (1954). The name was raised to formation rank by Playford and Willmott (in McWhae *et al.* 1958). They included the "Monksleigh Beds" of Fairbridge (1953) in the formation. Fairbridge's type locality of the "Yarragadee Beds," 1½ miles south-south-east of Yarragadee Homestead, is retained as the type of the Yarragadee Formation. However, the section exposed there is complicated by faulting (it is adjacent to the Urella Fault), and a satisfactory section cannot be measured.

The section of Yarragadee Formation exposed in the Bringo railway cutting is proposed as a reference section for the formation in the Geraldton area. This section is as follows:

Yarragadee Formation (51½)

Top of formation not exposed, overlain by Quaternary deposits.

	Thickness feet
(13) Sandstone, silty, coarse-grained, light yellowish brown; poorly sorted	1
(12) Claystone, white, unbedded, lenticular.	½
(11) Sandstone, silty, coarse-grained, light yellow-brown, unbedded, poorly sorted.	2
(10) Claystone, silty, white, unbedded; contains rare cannon-ball concretions; lenticular	1½
(9) Sandstone, silty, coarse-grained, conglomeratic in part, light yellow-brown unbedded, poorly sorted; quartz grains subangular	8
(8) Claystone, greyish white, unbedded, lenticular	1
(7) Sandstone, medium-grained, yellow-brown, well-sorted, unbedded; quartz grains are sub-angular; contains a few dark brown cannon-ball concretions ...	3
(6) Siltstone, sandy, with some interbedded fine-grained silty sandstone and claystone; variegated yellow, white, and red, thinly-bedded, partly cross-bedded; contains some thin ferruginous bands and cannon-ball concretions	6½
(5) Shale, silty in part, grey, grading into siltstone, white to light grey; contains a few thin jarositic bands ..	5½
(4) Siltstone, sandy, white to yellowish white, thinly bedded to fissile, grading into fine-grained silty sandstone; contains thin beds of grey claystone, which is partly carbonaceous	6
(3) Claystone, dark grey, carbonaceous, grading into siltstone; poorly bedded, containing carbonaceous wood fragments; yellow jarositic beds, irregular in shape, are present; an efflorescence of minute gypsum crystals is present in places	5½
(2) No exposure, due to channel filled with alluvium	4
(1) Claystone, sandy, silty, greyish white to grey, mottled pink, poorly bedded, weathered; contains few thin yellow-brown ferruginous beds	7

conformably overlying Kojarena Sandstone.

Lithology.—The Yarragadee Formation is an interbedded sequence of sandstone and siltstone, with lesser thicknesses of shale, claystone, and conglomerate. The sandstones are mainly poorly sorted, and are very coarse- to medium-grained. They are partly felspathic, though the felspar is usually kaolinized at the surface. Exposures of the sandstones are commonly white, with a mottled red-and-yellow colouring. The siltstones are micaceous, and are usually white at the surface, though in the subsurface they are often dark grey and carbonaceous. Bedding in the sandstones is generally poor, though cross-bedding is sometimes developed. The siltstones are often thinly bedded to fissile.

Stratigraphic relationships.—In the Geraldton area the Yarragadee Formation rests with apparent conformity on the Kojarena Sandstone, and the top is eroded or capped by laterite.

Distribution and thickness.—The Yarragadee Formation is known to extend from near Howatharra Siding in the north to the Moore River in the south. In the Geraldton-Mingenew area it is known to extend no further inland than the Urella Fault. It seems that no Jurassic sediments occur to the east of this fault, which is believed to have been active in Jurassic times.

Exposures of the formation are sporadic, and are generally thin. Individual beds in the unit are markedly lenticular, and the differential compaction associated with this results in very variable dips.

No exposures of the Yarragadee Formation in the Geraldton area are more than 80 feet thick, and it is doubtful if more than 100 feet of the formation is present in this area. However a study of the Dongara, Yardarino, Mingenew, and Moora bores shows that the unit probably exceeds 4,000 feet in thickness in the deepest part of the Perth Basin, near the Darling Fault.

Fossils and age.—The only fossils known from the Yarragadee Formation are plants, but none have been recovered from exposures of the formation in the Geraldton area. However in the type area of the formation, 6½ miles north-north-west of Mingenew, there are numerous well-preserved fossil leaves in a white siltstone. Walkom (in McWhae *et al.* 1958) has reported the following forms from this locality: *Otozamites bengalensis*, *Otozamites feistmanteli*, *Otozamites bechei*, *Otozamites* cf. *bunburyanus*, *Araucarites cutchensis*, *Pagiophyllum* sp. *Brachyphyllum expansum*, *Elatocladus plana*, and *Retinosporites indica*. Walkom considers that these fossils are of Middle or Upper Jurassic age. However Balme (1957, and written communication) has examined samples from the Mingenew bores and from a shaft only 2 miles north-west of the type locality, and he finds a probable Lower Cretaceous spore and pollen assemblage. These samples are in a similar stratigraphic position in the formation to Walkom's fossil leaves. Balme has also reported on the palynology of samples from the Yarragadee Formation in the Dongara, Yardarino, 47¼ mile-peg, and Moora bores. These suggest that the unit ranges from Middle Jurassic to Lower Cretaceous in age, with no evidence of a break within the unit.

Environment of deposition.—In the Geraldton area the Yarragadee Formation is believed to have been deposited under continental, fluviatile conditions, associated with movement along the Urella Fault. A continental environment of deposition is indicated by the rapidly alternating lithologies, the lenticular nature of individual beds, the lack of marine fossils and presence of plant fossils, and the variegated colouring of the unit.

Continental sedimentation is frequently associated with faulting, which results in continuing elevation of the source area. As the Yarragadee Formation is not known to occur east of the Urella Fault, it seems quite likely that this fault was active during Jurassic times. The Urella Fault dies out to the north, and in this area the Yarragadee Formation thins, and eventually disappears. The Urella Fault also dies out to the south, but there the Jurassic and later movement is taken up by the Darling Fault.

Structure

The Jurassic sediments of the Geraldton district are practically horizontal, showing only very small dips, measured in terms of a few feet per mile.

The base of the Newmarracarra Limestone is taken as a marker horizon, and in the area mapped in detail this is found to decrease in elevation from 660 feet above sea-level in the Bringo cutting to 539 feet at (690297). This is a fall to the south-west of just over 20 feet per mile, equivalent to a dip of only about 1/5°. This is the maximum regional dip found anywhere in the area, and is apparently due to differential compaction over the sloping Precambrian basement. In the Bringo cutting the limestone is only 14 feet above the Precambrian, whereas at (690297) there are about 220 feet of sediments beneath the limestone.

The major structural feature of the Geraldton area is the Geraldton Fault. It was named by Jutson (1914), and has also been referred to as the "Moonyoonooka Fault" (Woolnough and Somerville 1924). The evidence for the existence of the fault is based on geomorphology and the deep bores at Geraldton. The fault itself is not seen at the surface.

Geraldton is situated on a coastal plain which is backed by a dissected scarp of Jurassic sediments overlying the Precambrian basement. Jutson suggested that this is a retreated fault scarp. The scarp in itself is not sufficient evidence for the existence of a fault, but the hypothesis is confirmed by two deep bores in the Geraldton area—the Racecourse and Municipal bores. The Racecourse bore was drilled with calyx equipment in 1896-98, and was abandoned at a depth of 1,531 feet without reaching basement. Some of the cores were preserved from the bore, and these have been examined. The section in the bore is interpreted as: 0-53 feet, Quaternary; 53-400 feet, Jurassic; 400-1,531 feet, Lower Triassic or Upper Permian (Kockatea Shale). A few cores were retained from the Newmarracarra Limestone, which is believed to be present between 186 and 233 feet. As the Newmarracarra Limestone is flat-lying in its area of exposure (east of the bore) and the nearest exposure is about 540 feet above sea-level, the throw of the fault since the Jurassic can be expected to be of the order of 750 feet. However, the throw on the fault at the unconformity between the Kockatea Shale and the Precambrian, is believed to exceed 1,500 feet, based on the depth of this unconformity in the bore and its elevation at the surface. Hence it seems likely that there were two distinct periods of movement along the Geraldton Fault, the first during the Lower Triassic or late Permian, or between the Lower Triassic and the Jurassic, and the second after the Middle Jurassic.

The Geraldton Municipal bore struck granite at 1,435 feet. As the Racecourse bore was still in sediments at 1,531 feet, the unconformity must dip east, i.e. into the fault.

It is difficult to position the fault accurately owing to the lack of outcrop on the coastal plain. Hence the position of the fault shown on the map must be regarded as being only approximate.

In the Bringo cutting a series of small faults are exposed which fracture both the Precambrian and the overlying Jurassic sediments. They are normal faults, throwing down to the west, with the downthrown block usually dipping east (Plate 3, 1 and Plate 6). There are seven of these faults, the largest throw on any of them being only four feet, and the total throw about 14 feet. The faults tend to die out in the soft Jurassic sediments, sometimes passing into monoclines. These faults cannot be traced either on the ground or on air-photos, and are probably only local features. They may have formed when movement occurred along the main Geraldton Fault. Their age is evidently pre-laterite, for the contact between the hematite rock and the leached limestone (which are products of lateritization) is almost unaffected by the faulting.

One small pre-Jurassic fault was also noted in the cutting, displacing a vein in the Precambrian rocks.

Minor faulting has also been found in the Chapman Group sediments exposed in a cliff-face near "Ellendale" (895228). At this locality a west-dipping normal fault, having a throw of about five feet, is clearly visible.

At the eastern end of the Bringo cutting there is a small faulted anticline (Plate 3, 2). The faults are apparently due to tension at the crest of the anticline, and a small block of sediments has fallen between them. As there is no evidence of compressive movements elsewhere in the area, this anticline may well be due to folding over a tilted fault block at depth. Alternatively it may have formed by differential compaction over a buried ridge of Precambrian rocks.

At (724298) a series of well-developed landslides is visible. The sides of the hills around this locality are steep, and the hills are capped either by laterite or by Newmarracarra Limestone. The unconsolidated sandstones and shales of the Moonyoonooka Sandstone have failed, resulting in four main faulted blocks and many minor ones. They are classical examples of landslides, with the typical concave outline at the top of the hill, and a series of back-tilted blocks. The complex manner in which the Moonyoonooka Sandstone has been faulted during this landsliding can be seen in a nearby gully (723300) where the formation is well-exposed. The total throw of the landslides is about 170 feet.

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CONTENTS OF VOLUME 42

Part 1 *(published 19th March, 1959)*

Part 2 *(published 2nd June, 1959)*

Part 3 (Rottnest Island: The Rottnest Biological Station and Recent Scientific Research. Edited by E. P. Hodgkin and K. Sheard) *(published 15th August, 1959)*

Part 4 *(published 21st October, 1959)*

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