OIL-FINDING

Photo. by M. Crouliansky

General View of the Twingon Oil-Reserve, Yenangyoung Field, Burma.

OIL-FINDING

AN INTRODUCTION TO THE GEOLOGICAL STUDY OF PETROLEUM

BY

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LATE OF H.M. GEOLOGICAL SURVEY

ILLUSTRATED

SECOND EDITION

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TO

ARTHUR SANKEY REID

IN GRATEFUL MEMORY

OF HOW MUCH I OWE TO HIM

PREFACE TO THE SECOND EDITION

"OIL-FINDING" has been so kindly received that the author makes no apology for attempting to bring it up to date.

In the last few years so much new evidence has been collected, and so much further experience in different oilfields acquired that it is possible to deal with many of the questions relating to petroleum with much greater confidence. Chemical research hand in hand with geological, a combination that has not been so frequent as might be wished, has thrown light upon points hitherto somewhat obscure, and promises to give even more important results in the future.

Several new books upon the subjects of petroleum, petroleum geology, and the development of oil and gas-fields have been published both in Britain and America; our knowledge of the laws governing the formation and concentration of petroleum has been greatly increased, and, perhaps inevitably, a certain amount of turgid unscientific nonsense has been added to the literature of the subject. Yet, to the author's regret, the vital question of the origin of petroleum has been as heretofore discreetly temporized with, if not, in vulgar parlance, "funked." No one has seen fit to champion the cause of the animal-origin theory and seriously bring forward evidence for its defence. For that theory is now definitely on its defence, the rival vegetable-origin theory having decidedly gained ground especially among the younger generation of practical geologists and those who are intimately associated with the winning of the precious fluid. Several authors, however, still hesitate to give a decided opinion on the question of origin, preferring to quote previous works and opinions, now long out of date, resuscitating old second and third-hand pieces of evidence now largely discredited, and contenting themselves with maintaining a non-committal attitude that does more credit to their judicial faculties than to the depth of their researches.

On the other hand, the mystery-mongers, who were wont to dilate upon the difficulty of petroleum problems, are, with the advance of knowledge, finding it more and more difficult to wrap such a practical subject as the finding and winning of oil in vague and general verbiage, warning the student to beware of heterodox opinions without giving some clear indication as to what they consider orthodox.

"Oil-finding" in its new edition will be found to contain many important additions; every chapter contains much new matter, and new chapters upon the subjects of gaseous petroleum, oil-shales and torbanites have been introduced, since recent research work has shown that evidence on these matters has a direct bearing upon phenomena formerly believed to be exclusively associated with liquid hydrocarbons.

It is hoped that most of the mistakes in the hurriedly written first edition will be found to have been corrected.

Some of the more purely scientific aspects of petroleum phenomena are treated at greater length, more with the hope of stimulating research on special lines than of claiming to have discovered complete explanations of obscure problems.

While still only professing to be an introduction to the geology of petroleum, it is hoped that the new edition of "Oil-finding" will tempt the student somewhat deeper into the intricacies of the subject and point to the necessity of a closer liaison between geologist and chemist, while at the same time not driving away the general reader by an excess of technicalities.

And the author has some grounds for confidence that his efforts to attain to clear scientific views and definite established truth, if perhaps sometimes expressed in a manner more uncompromising and dogmatic than politic, will meet with a welcome as frank and as critical as they deserve.

E. H. C. C.

THE DUTCH HOUSE,
BEACONSFIELD.
March, 1920.

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CHAPTER I

THE ORIGIN OF PETROLEUM

The importance of petroleum has at last impressed itself upon the world, and even in Britain, where it is to be feared the subject is as yet far from being generally understood, the necessity of controlling adequate supplies of mineral oil is being more fully recognized every day. The world-war was won largely by the help of petroleum and its products; civilization owes it a debt that it is impossible to estimate. But, with an irony that is not uncommon, the value is being appreciated just as the future supply begins to appear doubtful. Not that there is at present any difficulty in supplying the world's wants, but demand is increasing far more rapidly than supply, and a world's shortage of mineral oils is inevitable within a few years, unless new and prolific sources can be discovered and the greatest economy practised in the use of what is available.

The finding of oil, therefore, becomes an ever-increasingly insistent problem, to the solution of which the minds of scientific men are naturally turned, and in order that that problem may be approached with greater certainty and greater hope of success, it is necessary to have some clear idea as to what petroleum is and how it has been formed. The most ambitious aim of this little book is not so much the recounting of practical details that may prove useful in the search for oil as the attempt to lead the student into the paths along which success in elucidating the more theoretical questions may best be realized.

It has been the custom in treatises upon petroleum, the one bright exception being the work of Engler and Hofer, to regard the origin of the mineral as an interesting academic but unimportant question, which is fully dealt with when the various theories have been stated, the least popular summarily dismissed, and a few pages of carefully guarded general statements written round about without ever touching the root of the matter.

That this unsatisfactory state of things has arisen from lack of accurate information on definite points is the misfortune rather than the fault of the authors, but all geologists will agree that to leave a question of such vital importance unsettled is to blindfold the student or prospector at the very start. How, if one does not know, or cannot prove, from what material and under what conditions petroleum is formed, can one tell where to look for it or ever be confident as to its presence beneath the surface?

This question of origin, in fact, absorbs and includes nearly every other question as to the occurrence, distribution, and winning of oil.

The theories that have been brought forward from time to time to account for the origin of petroleum and its congeners divide themselves naturally into two classes, which again may be subdivided as follows:—

A. Inorganic Origin	1. Hypogene Causes. 2. Volcanic Action.
B. Organic Origin	1. From Animal Matter. 2. From Vegetable Matter.

A. Theories of the **inorganic origin** of petroleum are essentially the ideas of chemists and indoor students of the subject. They are founded on assumptions and built up by theoretical considerations, none of which have been tested by application to actual facts and conditions as observed in nature.

(1) The most ingenious of the *hypogene* theories suggests the origin of petroleum by the condensing and polymerization of hydrocarbons formed by the action of water upon supposititious masses of metallic carbides deep within the crust of the earth. Such vague hypotheses are almost invariably rejected nowadays, and it is needless to enter upon a detailed

examination of the various arguments *pro* and *con*. The conditions under which petroleum is found in nature furnish sufficient grounds for the dismissal of any theory involving a deep-seated origin.

(2) *Volcanic action* has occasionally been suggested to be responsible in some ill-defined way for the occurrence of petroleum. At first sight there appears to be some direct evidence favourable to this idea. For instance, oilfields are found in many parts of the world at no great distance from, and even running parallel with, lines of volcanic activity. Japan and Sakhalin, Mexico, Burma, and the West Indies are cases in point. Again, mud-volcanoes of solfataric type, an evidence of undoubted volcanic action usually in the obsolescent stage, have been confused with mud-volcanoes due to the discharge of gas from underlying oil-rocks. These are two entirely different phenomena, but if no distinction be made between them it might be erroneously claimed that there is evidence of volcanic action in very many oilfields. When the question is examined in detail, it is seen that both the lines of volcanic activity and the structures which are conducive to the formation and storage of petroleum are merely separate and independont effects of the same cause. Volcanic lines are developed near to or along the margins of continental masses, or, more correctly, between continents and deep oceanic basins; that is to say, in belts where active earth-movement is taking place. Many oilfields also lie along belts where active earth-movements have been experienced, but there is no evidence to suggest that the vulcanicity and the formation of petroleum are essentially connected in any way. The distribution of land and water may be vastly different now from what it was when active vulcanicity obtained; and it can frequently be proved that the oil was formed before vulcanicity commenced, and may have remained after all such action had ceased. Interesting evidence of this nature is to be obtained in Burma and Barbados.

To go into the matter more closely, it is difficult for a geologist to realize exactly what those authors who have promulgated the idea of a volcanic origin of petroleum really mean by "volcanic action." As evidence they bring forward the well-known cases of distillation caused by the intrusion of igneous rocks through such strata as the coal-measures or the Scottish oil-shales—phenomena which are not necessarily connected with true volcanic action. That such local distillation has frequently taken place is proved by abundant evidence, and the igneous rock may be found to contain in small cavities soft or elastic bituminous compounds. In Fife and in the Karoo, South Africa, such evidence may be obtained, especially in the latter. When the writer was engaged in an examination of South Africa for the Union Government with the view of ascertaining whether there were any possible oilfields in the country, he found that over vast areas the igneous intrusions contained small quantities of hydrocarbons. Intrusion of dolerites are very frequent throughout the Karroo, both as dykes and sills, the latter being sometimes very irregular and of good thickness. There are also in places volcanic necks more or less filled with intrusive rock. Wherever the igneous rock has traversed carbonaceous strata it has distilled a certain quantity of oil, which is now found filling vesicles, joint planes, and crush planes in the intrusions. The hydrocarbons are sometimes hard and solid, sometimes plastic, but more frequently, especially in fine-grained compact dolerites, they consist of fairly light oil. In some cases in very compact sills traversing the carbonaceous shales of the Dwyka Group a hand specimen when broken open shows in vesicles a very volatile oil which evaporates in the course of a few minutes, in fact a natural petrol. Dykes ascending from a depth through coal-measures or strata containing oil-shales or torbanites bring these liquid or semi-liquid hydrocarbons up among strata from which no such natural distillation could be obtained.

The discovery of these hydrocarbons by the odour of freshly broken specimens, or the formation of films of oil on the waters of creeks and in excavations, naturally gave rise to the belief that there might be oilfields beneath, and there have been many experimental wells drilled in Cape Colony and the Orange Free State in the hope of striking oil. All these borings were visited by the writer, and the logs of most of them were available for examination. Gas in small quantities has occasionally been encountered in such borings, all of which have been made in the immediate vicinity of igneous rocks, either dykes or sills, and in strata lying practically horizontally.

All such borings gave some signs of oil or gas in igneous rocks or at the margins of igneous rocks, but none struck oil in a sedimentary formation and needless to say none had the remotest chance of proving successful. One enterprising company, using a diamond boring machine, drilled through all the sedimentary strata and for over one thousand feet into the metamorphic granite beneath.

It is sometimes possible to collect in excavations a few gallons of oil for examination, but all the hydrocarbons so collected, whether solid or liquid, are easily distinguishable from true crude petroleum by being "cracked" products. They are formed by natural destructive distillation, and consequently contain large percentages of unsaturated hydrocarbons. Similar cracked oils, often very viscous, are well known in or in proximity to dolerite sills in the oil-shale fields of Scotland: they resemble shale-oil very closely, and are easily distinguishable from the crude petroleum, which is occasionally found in different environment in the same fields, by the bromine absorption test. The cracked oil with a high percentage of olefines, etc., takes up bromine readily to satisfy the valency of the carbon atoms, while the true crude petroleum does so to a much smaller extent, since it consists much more largely of saturated hydrocarbons.

These distillation effects are purely local, and no instance of such action on a large scale has been brought forward; the limits of the distilling action are usually well defined. Even were such evidence on a large scale available, the occurrence of the bituminous compounds only demonstrates the presence of organic matters contained within the sedimentary strata so affected, and the igneous action cannot be considered the *origin*, but merely the process which has happened to call attention to the potentially bituminous nature of the strata.

That volcanoes themselves should produce petroleum has not been suggested, since in spite of the minute care with which volcanoes have been studied, no observer has obtained evidence favourable to such an hypothesis. Except Mexico, in no large and productive oilfields have igneous rocks, either intrusive or volcanic, been encountered to any considerable extent, and to use the term "volcanic action" in a vague sense to account for phenomena which are not associated with any such action is merely to beg the question, and at the same time to disregard a mass of relevant evidence which has been gradually accumulated ever since petroleum first became of commercial importance.

A modification of the volcanic theory has been put forward by Mr. Eugene Coste, in a paper entitled "Rock-Disturbances Theory of Petroleum Emanations *versus* The Anticlinal Theory."

The main points of this thesis may be stated briefly as follows:—

(1) That traces of hydrocarbons are found in many crystalline, intrusive, and volcanic rocks.

(2) That impregnations with petroleum are found in certain instances throughout great masses of strata, including different formations separated by unconformabilities, and that even crystalline gneisses beneath the sedimentary strata may be found containing oil.

(3) That the wide differences in gas-pressure, or in production of oil in different fields, "pools," and horizons in a series, cannot be accounted for by any theory of the formation of petroleum within the series.

(4) That the one essential factor in the occurrence of oil and gas in strata is the faulting, uplifting, fracturing, fissuring, and jointing always accompanying even slight rock disturbances.

From these premises, which will hardly be accepted by geologists, Mr. Coste deduces that petroleum and natural gas are of deep-seated or hypogene origin, and have been brought upwards by solfataric action through joints, faults, "chimney-like channels," etc., into the porous sedimentary strata in which we find them.

In support of this theory he brings forward a number of heterogeneous facts and a few very sweeping assertions, but much of the evidence is of so contradictory a nature that it can be used as effectively in attack upon as in defence of the theory. It is perhaps unnecessary to deal with this theory in detail, but it may be pointed out that in the great oilfields following or flanking lines of tectonic disturbance it is in the less disturbed and less faulted zones that the most productive areas occur, that faults, fissures, and joint-planes are only open channels when near the surface, except among very hard crystalline rocks, and that migration of hydrocarbons across bedding, the difficulty or impossibility of which is made much of, is a very different thing from migration along bedding in strata with any appreciable porosity.

The occurrence of salt, sulphur, and gypsum in association with petroleum in such cases as the Texas fields is claimed as evidence of solfataric action, yet the mode of occurrence is in reality very different, as any geologist who has worked in a volcanic area can testify.

The possibility of impregnation downwards, a phenomenon of very frequent occurrence, does not seem to have been considered, or the occurrence of a light filtered oil in crystalline rocks beneath the oil-series in Placerita Canyon, Los Angeles County, would hardly have been adduced as evidence of a deep-seated origin.

As explained above, South Africa affords countless instances of the presence of liquid hydrocarbons in igneous intrusions, where their origin is sufficiently obvious; while, as will be shown later, the great gas-fields and "prospective" oilfields of Western Canada furnish abundant evidence to refute all idea of a deep-seated origin.

At the February, 1914, meeting of the American Institute of Mining Engineers Mr. Coste and Dr. Hans von Hofer brought forward their respective theories, and in the discussion that ensued, continued by written contributions, a great deal of interesting evidence was adduced. Though it can hardly be claimed that the result of this discussion has been to settle the origin of petroleum, the weak points of the two theories under discussion were certainly pointed out, and while Dr. von Hofer, with weight of authority and greater scientific care than his opponents displayed, seems to have disposed finally of the theories of solfataric, volcanic, deep-seated or rock-disturbance *origin* for petroleum, he failed to answer the most trenchant criticisms of his own theory (that of animal or diatom origin) expressed by Mr. Eugene Coste.

The papers read by Dr. Hans von Hofer and Mr. Coste, however, have served a very useful purpose in calling attention to the importance of arriving at a clear and decided view as to the origin of petroleum, and the necessity of marshalling evidence for each theory not from the published works of others, not by generalizations from second-hand sources, but from detailed study in the field of each cited country or district.

B. Organic Origin.—In considering the theories of the formation of petroleum from organic matter it is necessary to examine a vast mass of evidence, chemical, geological, and experimental. The views of many experts are still undecided, and the relative importance of animal or vegetable matter as the material from which petroleum and petroleum compounds can be formed is a question that is handled very gingerly in recent publications. Yet, as stated above—and it cannot be stated too often and too strongly—unless we can make up our minds upon this question, the search for new oilfields must necessarily become to some extent a groping in the dark. Before asking himself if there is oil to be found in any district or locality, the geologist must consider why there should, or should not, be oil; how it could have reached such an environment, and whether it can be relied upon to be present, if drilled for. To enter into such inquiries without knowing from what material the oil has been formed, is to adventure upon a search with one eye bandaged.

The question is not merely of academic but of great practical importance, and it is in the author's experience that great sums of money have been fruitlessly thrown away by petroleum companies solely because those responsible for the selection of possible new fields to be tested had not mastered this first essential question of the origin of petroleum.

B. (1) *Animal Origin.*—The theory that petroleum is formed by the decomposition or destructive distillation of animal matter entombed in the strata has many adherents at the present day. It has arisen largely from the wish to find a marine origin that will be acceptable to scientists. As oil occurs in sedimentary strata, and most sedimentary strata are to some extent at least marine in origin, there was a natural tendency to seek for some mode of origin for petroleum compatible with the manner of accumulation of ordinary sedimentary rocks.

The evidence upon which this theory rests is largely chemical, many chemists having conducted researches with the object of ascertaining whether oils with the characteristics of natural petroleum can be formed from animal matter.

Its existence has been maintained more by argument than by active research, and, as will be shown in a few instances noted below, many of the arguments advanced are mutually destructive, and even the defenders of the theory do not invariably agree among themselves with regard to the theoretical considerations they rely upon to convince the sceptics.

Let it be granted at once that under conditions easily reproducible in a chemical laboratory animal matter of almost every kind can be decomposed and separated out into various classes of compounds, some of which can, when properly treated, be converted into mixtures of oils closely resembling petroleum as found in nature.

A short account of the chemical processes which Engler and Hofer believe to have taken place in the formation of petroleum from animal matter is given by Messrs. Bacon and Hamor, and is very instructive.

They state that four stages can be distinguished, though there may be some overlapping of the chemical reactions in the different stages.

The first process is of the nature of putrefaction or fermentation, by which albumen and celluose are eliminated, while fatty matters, waxes, and a small quantity of other durable material, and possibly fatty acids formed from albumen, remain.

The second process, which may occur partly during the first stage, is a saponification of glycerides, and the production of fatty acids, either from the action of water, ferments, or both. Waxy esters are wholly or partly hydrolized.

In the third process carbon-dioxide is eliminated from acids and esters, and water from alcohols, oxyacids, etc., leaving hydrocarbons of high molecular weight containing oxygen compounds. This is comparable with the theory of Krämer and Zaloziesci, who hold that an "intermediate product" like ozokerite must be formed, and regarded ozokerite as representing an early stage in the development of petroleum.

The fourth stage calls for a violent reaction in the breaking up of hydrocarbons of high molecular weight by "cracking" them into light hydrocarbons and gaseous products.

In these processes Engler and Hofer assume that time and temperature *compensate* each other, a somewhat more cautious manner of stating that processes requiring a high temperature may be brought about at low temperatures, given sufficient time. They also hold that pressure has had no action beyond raising temperature slightly.

It must be admitted that this is a most ingenious theory, and that reactions such as those suggested could no doubt be brought about in a laboratory where temperature can be varied rapidly and the necessary reagents supplied as required.

But it does not require much knowledge of either chemistry or geology to prove that such a series of reactions could not possibly take place on a large scale in nature under the limiting conditions which we must postulate.

The first two stages presumably take place at or near the surface under normal temperatures and pressures to allow of fermentations and putrefactions, but whether cellulose could be eliminated entirely is open to doubt.

In the second stage the saponification is somewhat mysterious; what reagent could be present to bring about saponification? Could alkalis be under any conceivable condition set free to act upon the organic compounds, and if such action were possible how could the alkalis be finally eliminated from the saponified products?

The third process is even more mysterious. It has presumably taken place at considerable depth and under pressure, but not under effective sealing, since carbon dioxide is supposed to be released. The removal of water from alcohols and oxyacids in the presence of excess of water is perhaps even less intelligible, and that water must have been present in an unsealed deposit is hardly open to doubt.

The idea also of an intermediate product resembling ozokerite is difficult to understand: it has been conclusively proved that ozokerite is a *final* product, the last residues of an inspissated oil of paraffin base, and not an initial or intermediate product in the formation of oil.

The fourth process is perhaps an even less justifiable assumption than the earlier ones. It necessitates a high temperature, sufficient for the breaking down of saturated hydrocarbons, the cracking by destructive distillation with formation of uncondensible gas, the formation of lighter hydrocarbons, both saturated and unsaturated, and the probable deposition of free carbon. When a saturated hydrocarbon is cracked equal numbers of saturated and unsaturated molecules are formed, but petroleum, and especially petroleum of paraffin base, contains but a small percentage of unsaturated hydrocarbons instead of a quantity approaching fifty per cent. This fourth process must have taken place at depth and under efficient sealing and under high pressure, so that the resulting oil could be preserved, but the temperature necessary for such cracking, probably at least 400° C., cannot have been obtained by depth, and it is only depth temperature that can be considered. To assume that time and temperature are interchangeable, *i.e.* that lengthy periods at low temperature can effect reactions that require high temperatures, is merely begging the question.

It is perhaps unnecessary to deal with this ingenious theory and series of processes more fully, their inherent improbability is sufficiently evident, even without a consideration of the limiting conditions with which we have to be content in dealing with the formation of petroleum. Unless a more plausible series of reactions can be suggested the animal origin hypothesis may be summarily dismissed. The bare possibility of forming petroleum-like compounds under carefully selected conditions really does not bring the investigation much further forward. It is interesting and instructive to know that by selecting suitable material of animal origin, and eliminating such material as is unsuitable, by treating the selected material by special processes, the desired result, a mixture of oils, can be obtained. But it is commencing the investigation from the wrong end: it should rather be the chemist's task to learn what conditions are possible in nature among stratified sediments, and then to attempt to reproduce in the laboratory the same or similar conditions to ascertain whether petroleum can be the result of such treatment of animal matter. To do this the chemist must have recourse to the geologist, or must study geology practically in the field with great detail and thoroughness, a task for which it is probable that few chemists have either the time, the opportunity, or the qualifications. It is often only too evident that the exponents of the animal origin theory have started out with the idea and the evident intention of making oils in their own empirical fashion from material selected by themselves and have disregarded nature and her methods. Thus, though their researches be elaborate, valuable and interesting, though their treatises be ponderous and painstaking, they may never have approached the outskirts of the problem which they set out to solve.

Having once accepted the possibility of forming hydrocarbons by these special methods, many authors, pointing to the indubitable evidence of the former existence of living organisms among the strata in which petroleum is now found, seem to consider that further proof is unnecessary. Each author has probably his favourite class or order of organism which he would make responsible for the raw material in each particular oilfield of which he has special knowledge. Thus at one time or another almost every class of organism, from the fish of Mr. Winda, the Russian geologist, to the foraminifera of the United States Geological Survey (California, Texas and Louisiana Oilfields) has had special attention drawn to it in this connection.

If foraminifera have anything to do with petroleum it might be expected that the most highly foraminiferal deposits would show some sign of impregnation. But they seldom show any such sign, and when they do it can generally be shown that the oil is derived from some other formation (*e.g.* Barbados).

When we consider the extreme slowness of accumulation of a foraminiferal deposit the entombment of animal matter in such circumstances is absurd, while in more rapidly accumulated sediments the proportion of foraminiferal tests will necessarily be much smaller.

In some of the oil-sands in Trinidad, foraminiferal fossils have been identified in microscopic slides: it is remarkable in these cases that the oil filling the interstices between grains and impregnating any argillaceous matter that may be present seems to avoid the calcareous foraminiferal debris, none of which shows any signs of impregnation. The point is not of importance, but is perhaps worth recording.

Sometimes the chemical theorists carry their speculations even further, and suggest that the characteristics of the oils formed, *e.g.* whether of paraffin or asphaltic base, may be determined by the nature of the raw material.

Of the geological evidence, however, little that will bear careful scrutiny has been adduced to support the animal-origin theory. A statement such as the following, "this series is oil-bearing, and at intervals throughout it the hard parts of animal organisms are found," seems to be regarded by many as sufficient evidence upon which to base a generalization of such enormous importance.

In the discussion before the American Institute of Mining Engineers Dr. von Hofer quotes as follows two somewhat ambiguous and at best second-hand pieces of evidence: "Bertels found in the Kuban district of Russia, in a bunch of mussel-shells, a substance partly 'petroleous,' partly animal remains still undecomposed. R. A. Townsend reported a similar observation from the Tertiary oyster-banks of Assam, in Asia."

As both these districts are oilfields, and impregnation with petroleum may be found anywhere in an oilfield, in the sea, along the shore or inland, the evidence cannot carry great weight. But if reasoning of this nature is to be admitted as argument, Messrs. Wall and Sawkins' discovery of fragments of wood near the pitch lake in Trinidad, and especially along the shore, impregnated with sticky asphalt or embedded in it, must also be taken account of; these observers suggested that such evidence demonstrated the gradual conversion of wood into asphalt. These are merely cases of impregnation or accidental association, but if they are to be considered of importance the writer can furnish the animal theorists with a more striking piece of evidence from his own experience. He has frequently come across *live* oysters so impregnated with petroleum as to be inedible. These were found in the Trinidad oilfields, either after a flow of oil from one of the wells had been carried down a river into the mangrove swamps, or when seepages of oil had been unusually active along the shore where the oysters abounded.

To return to the chemists' theories, the occurrence of oil in limestones is often brought forward as a clinching argument, even by authors who, perhaps in the next chapter, deal with the migration of petroleum through vast thicknesses of strata and its appearance naturally in the most porous rock available. "Here," one will say, "is a coral limestone formed chiefly of the debris of coral and other organisms often in the position of growth, and it is impregnated with petroleum," leaving it to be inferred that the oil has been formed from the soft parts of the coral polyps, and oblivious of the fact that a similar argument might be made to apply to a Recent beach, full of shell fragments and similarly impregnated, such as may be seen in many localities in the Island of Trinidad.

Much of the evidence brought forward is distinctly amusing, more particularly the field evidence. A good instance of this comes from Egypt, and is worth recording.

A Teutonic chemist, Sickenberger, observed along the shores of the Gulf of Suez and the Red Sea that coral limestones of Recent age lapped by the waters contain drops of sticky petroleum, and are in places partially impregnated. Another chemist, Fraas, subsequently confirmed the observations. The deduction these chemists arrived at was that the oil was being produced by the decomposition of the animal remains of coral polyps.

Disregarding the inherent improbability of such an hypothesis—*i.e.* that it would mean the formation of petroleum at ordinary temperature and pressure—Engler and Hofer claimed the occurrence as evidence of the formation of petroleum from animal matter, and strange to say this remarkable tale has been repeated in book after book on the subject of petroleum, no one having apparently taken the trouble to verify it.

The writer is able from personal experience to give this remarkable story its quietus. In the first place, the coral beaches in the Gulf of Suez and the Red Sea are in some places of Miocene age, and in others Recent; both may be found containing traces of oil, though in the former case the animal matter of the polyps must have been decomposed for some hundreds of thousands of years. Again, when the north winds blow for months on end and lower the water level of the Gulf of Suez some two feet, the coral polyps die and decompose, so that on the shores dead coral to a depth of two feet is frequently noticeable.

There are many seepages of petroleum, often of considerable dimensions, both along the shores of the Gulf and from beneath the waters, frequently from Miocene limestones. From these seepages films of oil and even patches of large size are evolved and drift about upon the water till washed up by waves upon the rough coral, to which the inspissated petroleum naturally adheres. Since the time of the Romans Jebel Zeit has been known as Mons Petroleus, on account of the seepages at its base. Off Gaysum Island, off Ras Mesala, and at other localities, submarine eruptions of oil are known to occur. And all along the shores of the Gulf every here and there traces of oil may be found, often far from any known seepage, drifted by winds and currents to the rough coral which protects it most effectively from being washed away again. But this oil is at the latest of Miocene age, and may have its origin in the Lower Cretaceous (Nubian sandstone).

If the animal origin theory depends upon such absurdities for field evidence, its defenders will find it difficult to meet any attack founded upon accurate observation of geological facts. And moreover the bringing up of such questionable evidence and the constant repetition of the same can only have the effect of making the impartial student or observer look with doubt upon other items of evidence advanced no less confidently.

The geologist demands detailed and definite evidence; it is not enough for him to know where the oil is found, he must assure himself on many points, such as the lateral and vertical distribution of the petroleum in a geological series, the conditions under which the series has been deposited, the manner in which sufficient raw material to form the oil has been accumulated, and the process by which the oil has been concentrated and brought to its present position. When such questions are gone into carefully, one possibility after another is disposed of, and by a process of elimination an inevitable conclusion is finally reached.

In such inquiries the golden rule is *never to postulate or suggest any condition or any mode of deposition or accumulation which cannot be shown, or proved, to be actually in operation at the present day.* It is by the study of the present that the secrets of the past are revealed.

In justice to the chemical theorists it must be admitted that they have occasionally attempted to meet the objections of geologists by reference to actual facts.

Samples of sludge or slimy mud containing organic matter more or less decomposed have been taken from harbours, estuaries, or mud-flats, analyzed and distilled, and petroleum-like compounds, in minute quantities, it is true, separated out. The fallacy lies in the assumption that these samples from the upper layers of the sludge are typical in chemical composition of the mass of slowly accumulating material beneath. The upper layers teem with animal life, no doubt, but there is a rapid change downwards. When a dredger is working in the sludge of a harbour or estuary, it will be observed by any one who makes a study of the material removed that the lower layers differ very considerably in colour from the upper layers, and that at a depth of two or three feet almost all trace of organic matter, with the exception of the hard parts of mollusca, has disappeared. The change of colour is almost entirely due to the reduction of iron compounds, ferrous salts replacing ferric, and this process is effected principally by the decomposition of organic matter. The author had occasion at one time to note day by day samples of the slowly accumulating fine sludge of Port of Spain Harbour, Trinidad. These samples were taken on the Government dredger, and a selection of them was analyzed by Professor Carmody, Government Analyst of Trinidad. The environment is an ideal one for the accumulation of animal matter and its entombment in impervious argillaceous sediment. But in the specimens analyzed the percentage of organic matter was infinitesimal, though the remains of the hard parts of mollusca were by no means uncommon. Such sludges will become in time blue clays, precisely similar to those which are so frequent among the Tertiary strata of Trinidad, and which, though they often contain rich molluscan faunas, are almost entirely free from organic matter.

It is doubtful, indeed, if it is ever possible for the soft parts of animal organisms to be entombed to any considerable extent among accumulating sediments. In seas and estuaries the waters and the upper layers of whatever sediment is being formed teem with life, but as each organism dies it is eaten or decomposed—in most cases it is certainly eaten alive. Its soft parts become absorbed into the bodies of living organisms, only its hard parts (and often not very much of them) go to swell the deposit of sedimentary material. Thus equilibrium is maintained; the mass of organic matter does not go on indefinitely increasing, but remains a practically constant quantity; the inorganic matter is continually being extracted by the living organisms from the water and the sediment brought into it by rivers and by denudation of the coast-line, and this organic matter, after a longer or shorter period in which it is part of a living organism, is being passed on to take its part in the formation of future strata.

Thus the first great difficulty that upholders of the animal-origin theory have to face is that of proving that animal matter can be entombed in sufficient quantity to account for the vast stores of petroleum contained in sedimentary strata. It is possible, of course, under special local conditions, to preserve and entomb the soft parts of animals, but throughout the geological record instances of such preservation are very few and far too insignificant to serve as evidence against the known facts as to the almost universal destruction or decomposition that overtakes each organism sooner or later.

To point to highly fossiliferous strata as proof that animal matter has been entombed in large quantities is to disregard facts for the sake of an attractive theory. The hard parts of diatoms and foraminifera cannot sink and become involved in a sedimentary deposit till the animal matter has been destroyed, and similarly nearly every fossil that is preserved in strata can be proved to have lost its soft parts before becoming incorporated in a bed that is being formed.

A good example of this type of reasoning may be studied in the published accounts of the oil-shale beds of the Kimmeridge Clay in Dorsetshire. These are thin fossiliferous tough shales containing occasionally more than five per cent. of free oil or bitumen, as well as a considerable proportion that has reached the "Kerogen stage," *i.e.* has become insoluble in carbon disulphide. A freshly fractured piece of the shale has a distinct odour of sulphurous petroleum. A view frequently expressed about this oil and kerogen is that they have been formed from the animal matter of the mollusca, the remains of which are to be seen on almost every bedding plane in the oil shale, as well as in the dark clays associated with it. This view is subscribed to in the most recent Geological Survey memoir dealing with oil-shales, lignites, etc.

And no one seems to have taken the trouble to examine this theory critically to verify it or to try to find confirmatory evidence for it.

A careful examination of the oil-slade beds made in the field, in the chemical laboratory and under the microscope has brought to light many interesting facts. For instance, they are slightly more porous and sandy than the surrounding clays, and distinctlv more fossiliferous. The fossils are chiefly comminated fragments of a large number of species of both littoral and laminarian zone, and possibly even pelagic, types. Lamellibranchs with the two valves joined are rare, and when such are detected the valves are almost invariably open. "How were such beds formed ?" is the first question to be asked, and the answer is too obvious to be in danger of contradiction. They were shelly mud-banks formed on a low and muddy shore or estuary. The molluscan remains were washed about by tides and currents till reduced in most cases to fragments, which were concentrated by waves and tides upon the surface of each minute bed as it was formed. Probably a large part of each bedding plane was uncovered at low tide. On any low-lying shoreline where argillaceous sediment is accumulating and where the receding tide leaves large areas uncovered, similar accumulations of molluscan detritus may be seen, and the hard parts of the mollusca are not distributed evenly through the beds, but are concentrated on bedding planes. It is quite obvious that under such conditions there cannot have been any entombment of animal matter in these beds, with the exception, perhaps, of the remains of cartilaginous material where the hinge of a lamellibranch is preserved intact. These Kimmeridge oil-shales are only impregnated with bituminous matter now because they are more porous than the surrounding clays, and thus have been able to absorb and adsorb a higher percentage of petroleum.

Thus the idea of the oil or Kerogen contents being formed from the fatty constituents of the animal matter of this molluscan debris will not bear careful scrutiny, and another source of the petroleum must be looked for. This is to be found in the Portland Sand, which lies above the Kimmeridge Clay and was at one time impregnated with a sulphurous asphaltic petroleum. Vegetable matter formerly present in the estuarine muds may have been the source of much of the oil, but animal matter cannot have contributed more than an infinitesimal fraction of the former petroleum contents.

Many other instances of such or similar false reasoning could be cited were it necessary: they emphasize the importance of studying how beds have been formed and under what conditions before proceeding to found generalizations upon the data they furnish.

An interesting illustration of what happens in nature may be studied in almost any fine argillaceous rock rich in fossil evidence; a clay for instance that has accumulated slowly and that now contains perfect specimens of the hard parts of mollusca, such as lamellibranchs with the two valves joined and closed or gasteropods. In such a case, if anywhere, it might be expected that entombment of animal matter might have taken place. But what do we find? Almost every perfect specimen bears the "death-mark" (Plate II), the small round hole drilled by the predatory gasteropod, which has fastened upon its victim, pierced its outer armour, and devoured its fleshy part. Fossiliferous clays in the Pegu Series of Burma, a series in which oil-bearing strata occur at intervals throughout a thickness of 4000 feet in some localities, afforded very abundant evidence of this nature.

The most fossiliferous beds, however, are almost invariably littoral deposits in which there is a mixture of forms from deep and shallow water. Whether whole or fragmentary, many of the fossils show the death-mark, while the fragmentary nature of most specimens proves that they have been washed about the shore with every wave and tide long after they have lost all traces of their soft parts. The abundant evidence of crustacea and fishes, the scavengers of the sea, included in such beds serves to remind us that organic material is not wasted, is not rejected to pass with inorganic matter into the sediment, but is, so to speak, continually kept in circulation. "Eat and be eaten" is a law of nature, and from these little life tragedies of the mollusc we may realize the difficulty in the way of the accumulation of sufficient animal matter, a difficulty which the animal-origin theorists gloss over so light-heartedly. But even for the worst criminal nowadays an apologist seems to be forthcoming, so it is not surprising that the predatory marine gasteropod, the Hun among mollusca, has been defended. A prolific writer, possibly better endowed with the milk of human kindness than the faculty of scientific observation, has taken up the cudgels on behalf of this lower organism, and has solemnly declared that the gasteropod is a sort of Conscientious Objector. It would be horrified at the very idea of taking life; it is a pacifist, a vegetarian and an anti-vivisectionist. Pressed upon the subject, the said author would doubtless be prepared to add that his client is also a teetotaller, a non-smoker, an Esperantist and an anti-vaccinationist.

Well, in matters of fact of this kind it is necessary to depend on observation: moralizing on the subject will never lead to tangible results. Any one who wishes to learn the habits of the predatory marine gasteropod must rely upon his own observation, must disect his quarry and study it in its behaviour towards other organisms and towards its own order and species. And he will find not only that the instincts of the gasteropod are criminal and depraved, but that it is admirably adapted by nature for its nefarious activities. It is equipped with an elaborate apparatus, a very "string of tools," for boring through the hard parts of its prey and feasting upon the defenceless living organism within. In fact its Kultur is eminently efficient. It is essentially a burglar and a murderer, it preys not only upon the defenceless lamellibranch but upon its own order, its own family and its own species. It is a cannibal. And not only does it take life, but it devours its victims alive, even as we superior human beings eat oysters.

To sum up, these predatory organisms have reached a height of Kultur, or depth of criminality, amply sufficient to win for them the Iron Cross, if not even the title of All-Highest among the mollusca.

Thus though under certain favourable but rare conditions a small quantity of animal matter may undoubtedly become entombed and preserved in accumulating sediment, the quantity at best must be so small that it is entirely out of proportion to the enormous masses of liquid hydrocarbons which any productive oilfield furnishes from a relatively small area. To overcome this difficulty a regional migration of pretroleum has been suggested, viz. that though formed in very minnte quantities petroleum has been concentrated by migration from enormous areas and enormous thicknesses of strata through countless ages towards the strata in which it is now found. In how far local migration can be postulated will be seen in a subsequent chapter: in this connection it is only necessary to note that Dr. Hans von Hofer agrees with Mr. Coste in rejecting the theory of "regional migration of petroleum," holding that "migration of oil can take place only in cracks, joints and fissures, the source of motive energy being the accumulation, in the primary deposit, of natural gas under high pressure."

Quite apart from this initial impossibility of proving a sufficient supply of raw material from which petroleum might be formed, there is also much chemical evidence against the animal-origin theory.

It is only from the fatty parts of animal organisms that the petroleum could be formed, so it is only a portion, and often a very small portion, of the soft parts that can be utilized. The elimination of nitrogenous compounds and at the same time the preservation of the fats must be presupposed, and such an assumption may be said to beg the whole question. The theory is that the animal matter decomposes in such a manner that, before it is entombed, practically all nitrogenous matter has been removed (since only the merest traces of nitrogen compounds have ever been found in natural petroleum), and the preservative action of salt water has even been adduced to make such a retarded decomposition appear less improbable. But can we find any evidence of such a selective decomposition in nature? Are fats preserved, even in sea-water, while flesh is decomposed and dissipated as gases?

Let any one who has studied the formation of guano, or who has been unfortunate enough to have the processes in the decomposition of a dead whale forced upon his senses, answer.

A very special and peculiar form of decomposition must be postulated, and furthermore, one that does not eliminate the sulphur content, since sulphur compounds are in many cases present in petroleum, sometimes in large quantity. The high pressures necessary to favour the formation of paraffin hydrocarbons from fats are inconsistent with conditions that will allow the escape of nitrogen in gaseous compounds, while the high temperatures necessary for the destructive distillation of fats, the only methods by which oils resembling petroleum can be obtained from them, are, as will be seen in the next chapter, inconsistent with what we can ascertain as to the actual temperature conditions obtaining in geological strata within the depths at which it can be proved that the formation of oil has taken place. An attempt has been made to circumvent this difficulty by the ingenious suggestion that time may take the place of temperature; or to put it more lucidly that though the requisite temperature necessary for such destructive distillation be not reached, a lower temperature maintained for a long, indefinite period may have the same effect. Were the difference in temperature between that required and the maximum that can be postulated very small, this suggestion would be worthy of consideration. As it is Mr. Eugene Coste remarks very pertinently, if with a slight exaggeration pardonable on account of its humour, that it is like saying that "by leaving a turkey long enough in cold storage, it will cook itself."

To return once more to the golden rule, as it is neither expedient nor justifiable to assume the existence of conditions of which we have no actual evidence in nature, much of the interesting laboratory evidence can only be regarded as experimental rather than explanatory.

Another difficulty which the animal-origin theorists have to encounter is the disposal of the phosphorous contents of the animal matter. This, of course, on the decomposition of the animal organisms naturally takes the form of phosphates. Now of all salts formed in nature the phosphates, whether

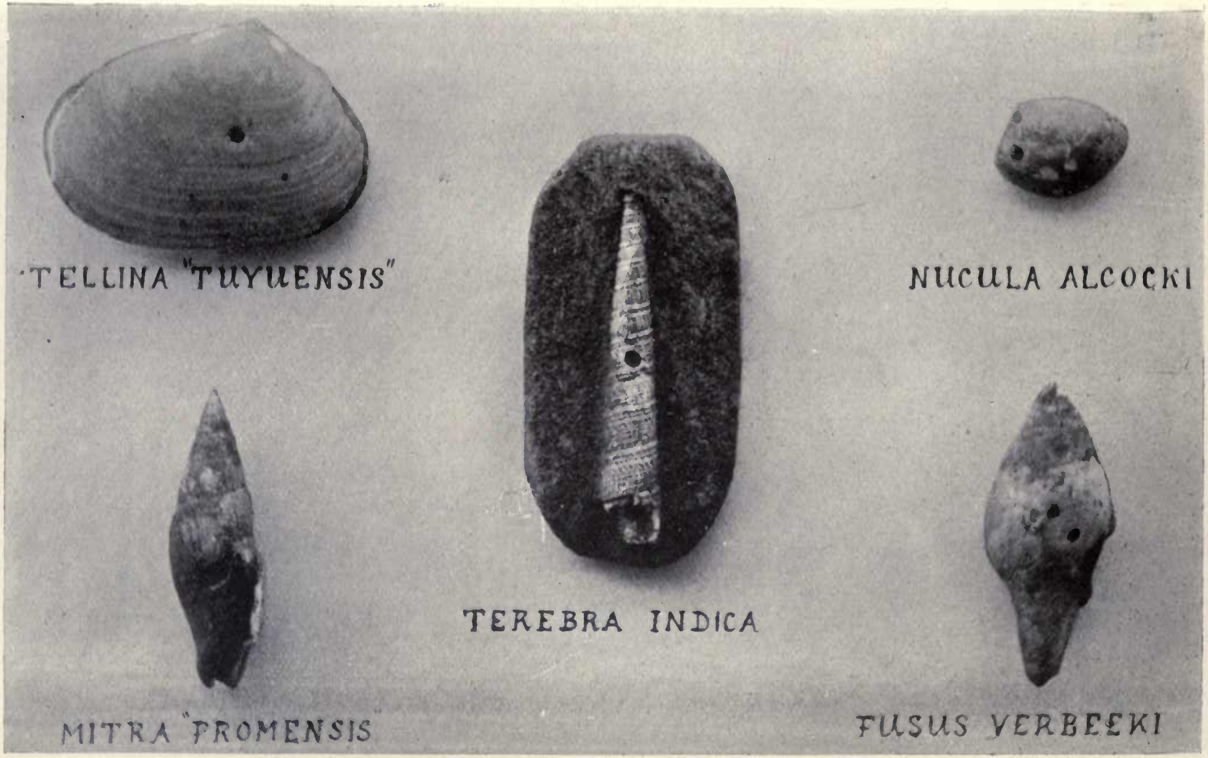


Photo. by S. L. James

Mollusca from the Pegu Series of Burma, showing the death mark.

of iron or calcium, or double and compound phosphates, are among the most difficult to dissolve and remove in solution. Hence, phosphatic beds or lines of phosphatic nodules may be expected near or among those beds where animal organisms have been most abundant. The phosphates indeed remain chiefly as, or in, the hard parts of the organism when the softer parts have been decomposed or absorbed into the economy of other living organisms. The proportion of derived phosphates to animal fats is very high in nearly all marine and fresh-water organisms. If, then, we are to contend that the petroleum of our great oilfields is derived from animal matter, vast stores of phosphate must be present somewhere in the vicinity of the place where the oil has been formed. But we know of no great phosphatic deposits associated with oil-rocks or within the confines of oilfields.

This objection is partially met by the suggestion that the oil is formed in very minute quantities throughout very widespread deposits of enormous thickness, and has been gradually concentrated, migrating drop by drop to where it is now found; and as phosphates occur in small quantities in practically every rock, sedimentary or igneous, and in an oilbearing series as elsewhere, it may be claimed that the quantity of petroleum formed in any given area is not out of all proportion to the quantity of phosphates in that area. No calculations as to the proportion of phosphates to oil have been put before the scientific world as yet. The calculation, however, is simple. The area from which an oilfield can have derived its petroleum can be demarcated in many cases with considerable accuracy, the weight of oil in the field can be estimated, as has often been done, and the average phosphate content of the strata can be obtained by a series of analyses.

If fish, as has been suggested, are the source of origin of the petroleum, the proportion of phosphates to oil must be very high, and even if lower organisms are made to do duty as the source of raw material, the proportion of phosphate to animal fat is still large. It will be found that such an enormous mass of phosphatic material would have to be postulated as existing in the strata, that its presence would be continually demonstrated by bed after bed of nodules or masses, which would be of too great commercial value to have been overlooked.

It is unnecessary to allude to more of the practical difficulties which beset the animal-origin theory when it is tested by reference to geological field evidence. To sum up, those who believe in an animal origin for petroleum have to call to their aid methods of accumulation of material of which we have no evidence, and chemical processes easily arranged for in a laboratory, but of, to say the least, very doubtful occurrence in nature. The theory, attractive as it may be from the chemist's point of view, fails utterly when applied practically: the artificial light of a laboratory is more favourable to its development than the cold light of facts gathered in the field.

Of late years the theory has undoubtedly lost ground among practical geologists, who have to deal with the facts as they are ascertained in the field, though amidst academic geologists and experts whose duty it is to advise oil-companies from a distance, those holding the staff billets rather than positions in the fighting line, the animal origin may always be sure of sympathetic consideration if not actual acceptance.

It is perhaps in Germany and Austria that the theory of an animal origin has found most adherents, and ponderous works teeming with the elaborate detail so dear to the Teutonic mind have been published on the subject. Yet, in spite of the care with which such treatises have been prepared, they are all open to the objections that theorizing, however elaborate, will never settle a question of practical importance, that the professors who would master any subject must not only delve in the libraries among the works of others, must not only carry on research in the laboratories under empirical conditions imposed by themselves, but must put their theories to the proof in the field, where battalions of the most beautifully stereotyped and polished generalizations may be shattered by contact with a few hard and rugged facts.

B. (2) *Vegetable Origin.*—There remains the theory of formation from vegetable matter. In one form or another this theory has been in existence from a very early date in the history of oilfield discovery and development, and it is held now by many observers who have had to study oilfields, but I am not aware of its having been stated at length in any geological treatise. Consequently the opponents of the theory not uncommonly seem to labour under a totally wrong impression as to what the vegetable-origin theory is, and it has even been stated that distillation from coal or lignite is relied upon by the vegetable-origin theorists to account for the presence of petroleum, an idea to which no practical geologist at the present day would attach any importance.

It would not be necessary to allude to this point, were it not that Dr. Hans von Hofer, the champion of the animal origin theory, in discussing the possibility of a vegetable origin seems to be under the impression that a distillation from coal is the only hypothesis which he has to meet, an hypothesis which he very rightly declares soon to have been recognized as inadequate. The evidence he advances to combat such an hypothesis is that petroleum often occurs not underlain by coal-beds, that in fact coal and petroleum, *e.g.* on the northern border of the Carpathians, are mutually exclusive, and that the products of the distillation of coal are entirely different from petroleum. With none of these facts will any believer in the vegetable-origin theory be inclined to disagree; they are well anthenticated and familiar to any experienced geologist, but they are far from being evidence against the theory of the production of petroleum from vegetable matter.

Yet in spite of this certain exponents of the animal-origin theory seem still to believe that a distillation from vegetable deposits is seriously suggested as the origin of petroleum. A little knowledge of the chemistry of the subject makes such a view appear quite untenable. It is true that coals and lignites can be made to yield hydrocarbons of the paraffin and olefine series by distillation, and the lower the temperature of treatment the greater the yield of these hydrocarbons, but tars, tarry acids and aromatic hydrocarbons are also formed, the last-named increasing in quantity with the temperature. There is no difficulty in distinguishing chemically between such distilled and naturally partially "cracked" tarry oils and crude petroleum. The respective odours alone are sufficient as a practical test, and the percentage of unsaturated hydrocarbons, detected by the bromine absorption, gives a certain method. Naturally distilled oils formed when igneous intrusions have penetrated a series containing oil-shales or carbonaceous strata are distinguished in the same manner, the distilled oil always being richer in unsaturated hydrocarbons than the crude petroleum.

Once a deposit of vegetable matter has reached the lignitic or coal stage all possibility of its being completely transformed into petroleum under any conditions of temperature or pressure is past. This brings us naturally to the need of a definition of the lignitic and coal stages. It is a matter of very much greater difficulty than it would appear to be at first. There has been much experimental work and much controversy, but a satisfactory definition of coal that will explain its constitution has hardly yet been arrived at. In the exhaustive memoir by Marie C. Stopes and R. V. Wheeler on "The Constitution of Coal" all the relevant evidence is gathered, and the reader cannot do better than study that work; but coals and lignites vary so greatly in chemical and physical properties that any simple definition to include all grades of coal is well-nigh impossible.

Some facts, however, are well established. Coal is formed from vegetable matter of all kinds, all more or less modified by its subsequent history. Not only have organic structures been broken down, but the chemical compounds of the materials forming these structures have also been changed. Ulmic, resinic and cellulosic material are all represented, and are given greater or less importance by different observers and in different coals. Hydrocarbons probably exist in small quantities in many coals, and possibly there is much free carbon, but on this latter point there has been much controversy, the "mother of coal," once believed to be practically free carbon, is now known as "fusain" derived from cellulosic compounds. Vegetable remains, wood, cortices, spores, spore cases, etc., can be identified in nearly all coals, in some of course more than in others, but the compounds forming these bodies may be profoundly modified.

To come to practical points about which there can be no mistake, in a coal the water in the original vegetable matter has been almost entirely eliminated; this means the loss of nearly all the oxygen and a certain amount of the hydrogen, and so the relative percentage of the carbon is increased. In a lignite much of the water still remains. The oxygen probably passes off to some extent as carbon dioxide and monoxide, and some free carbon may be released, the quantity increasing with the time during which the process is in action and with the increase in temperature and pressure. Every gradation from a lignite to an anthracite can be produced in the same series of beds from the same raw material, the carbon percentage increasing and the vegetable structures being broken down more completely till the carbonaceous deposit becomes almost amorphous.

It is convenient to speak of this process as a kind of carbonization, though it does not resemble the carbonization that coal undergoes in retorting or coking. It follows that when this carbonization has reached a certain point the carbon-hydrogen ratio is raised to such an extent that it would be impossible to form the mixture of hydrocarbons that we know is crude petroleum from the coaly or lignitic mass. Thus it is seen to be impossible under any conditions to make petroleum from coal or lignite without a process of destructive distillation leaving a carbon residue, and a sufficient temperature for such a distillation cannot be admitted as possible under the conditions, now fairly well ascertained, in which petroleum is formed.

Perhaps, therefore, it will be as well to state briefly what is the vegetable-origin theory as understood and followed by the scientific prospector or field geologist, before proceeding to give a review of the mass of evidence which leads inevitably up to it.

Petroleum is formed from the remains of terrestrial vegetation accumulated in clays, sands, or actual beds (which under other conditions would develop into carbonaceous shales, sandstones, and seams of coal or lignite), by natural processes which can be not only reproduced in the laboratory, but can also be proved to have taken place in the past and are taking place at the present day.

In weighing this theory, as in the case of the animal-origin theory, there are first of all some general considerations to be dealt with to ascertain whether there be any inherent improbability in the hypothesis as stated. For the present the actual processes by which petroleum can be formed, or is formed, need not be considered.

The first question to be asked is, "Can sufficient material be accumulated ?" In other words, is it possible for terrestrial vegetable remains to be distributed throughout sedimentary strata, or to be formed into beds which can afterwards be entombed to play their part in the geological record ? To this question every coalfield or lignite-field, every carbonaceous shale or sandstone, every peatbog or buried forest, returns an emphatic affirmative.

The second question follows naturally: is it possible from accumulations of vegetable matter to form bituminous compounds or hydrocarbons by natural processes? The coalfields again furnish us with a very definite answer. In nearly every coalfield of importance, and especially, be it noted, where deep coals in little disturbed strata are worked, there is a considerable proportion of bitumen in one or more seams. Where the coal measures are most disturbed and the seams crop out, the least traces of bitumen are found. Where the coals are most completely sealed up by impervious shale beds, where they are buried deeply or do not crop out at the surface, the proportions of bitumen and gaseous hydrocarbons are, *ceteris paribus*, greater.

Recent researches on coals have established their relation to petroleum more clearly than has been recognized hitherto, and the evidence from torbanites (see Chapter VIII) has supplied another important link in the chain of evidence.

During the war the possibility of obtaining a supply of petroleum by boring in Britain was discussed very thoroughly and criticized both favourably and adversely. Much interesting evidence was collected, and a tabulation of the recorded instances of natural seepage of petroleum in coal-mines and among carboniferous strata was attempted. The number of such seepages is very large, and it is noteworthy that the best examples occur in anticlinal structures, and usually from slightly porous beds above coal-seams. Association of the oil with brine has been observed several times.

Numerous examples of such petroleum, almost invariably of paraffin base, came through the hands of the writer during his tenure of the position of Chief Geologist and Deputy Director of the Petroleum Research Department. Cumberland, Derbyshire, Staffordshire, Shropshire, Nottinghamshire, Yorkshire, Linlithgow and Mid-Lothian all furnish undoubted occurrences of crude petroleum or residues of former impregnations in carboniferous strata, and in some instances the transition stage between the petroliferous and carbonaceous phases seems still to be in evidence.

But this is a different matter from the occurrence of a workable oilfield. It is hardly open to doubt that there have been oilfields in Britain in the past, or that the former productive horizons can be identified. But adsorption, inspissation and lixiviation have, it is to be feared, removed and dissipated the petroleum, leaving mere residues and gas where there was once an adequate supply, and light filtered shows in some lower horizon. This subject will be dealt with in Chapter X; the point to be noted here is the natural relation of coal to oil.

To this it may be objected that we are now dealing with oil and not with coal, and that coal and oil are not, as a rule, found in intimate association. This point will be dealt with later; for the present the possibilities alone are under consideration.

There is, then, no difficulty about the accumulation of sufficient material, and material of a suitable kind.

The next point to be considered is, under what conditions have the strata associated with coal or lignite seams or carbonaceous shales and sandstones been deposited and consolidated, and under what conditions the strata associated with petroleum? This is a matter that is not always obvious except to the practical geologist. It used to be objected to the "growth-in-situ" theory of coal formation that the fauna of the coal measures is largely marine, but when stated more correctly this objection is seen to have little weight. It should be read as follows: In the coal measures, among the constant alternations of thin beds of shales, sandstones, coal-seams, etc., occur here and there beds containing a marine (usually a littoral pelecypod) fauna, while the other strata are mostly unfossiliferous except for the occurrence of terrestrial organisms. These marine beds are frequently mere shell-banks of sandstone, calcareous sandstone, or even limestone or ironstone (*e.g.* "blackband"); they are thin, and liable to rapid lateral variations, as miners of the blackband seams can testify. Speaking generally, our Carboniferous Coal Measures, or, indeed, any coal or lignite measures in any part of the world, consist of rapid alternations of thin beds of rapidly accumulated sediment, varied with occasional bands truly marine in origin, and horizons denoting terrestrial conditions. To the geologist such evidence spells littoral, estuarine, or deltaic conditions on a large scale.

But following our method of interpreting past conditions by what we can actually see in operation at present, let us consider in what parts of the world great accumulations of vegetable matter are being formed, where by a slight change of level marine conditions may be brought into play over wide areas, and so marine strata made to alternate with terrestrial. The only places where such an environment obtains on a large scale are in the deltas of great rivers such as the Amazon, Orinoco, Mississippi, Ganges, and Brahmapootra, Irrawaddy, etc., and in neighbouring areas where the same phenomena on a smaller scale may be studied with a greater facility. Within the mazes of a great delta, what are known in South America and the West Indies as "lagoons," *i.e.* swamp-forests growing at sea-level, separated from the sea only by a fringe of sandbanks or a belt of mangrove swamp, cover vast areas. In these swamps and lagoons the accumulation of vegetable matter is remarkably rapid, while in times of flood much of the land is under water, and any slight movement of depression would cause a great advance of the sea-margin and cause marine strata, littoral sands, and fine silts and clays to be deposited over the beds of terrestrial origin.

In the much-written-about, but little known, Island of Trinidad, there is an ideal area to study such conditions at the present day—mangrove swamps, forest lagoons, delta formation, and retreat and advance of the sea under differential earth-movements of very recent date. At sea-level can be seen in process of formation terrestrial deposits separated by a strip of littoral sands from truly marine silts and clays, with occasional coral banks in reef formation which will eventually form limestones. Furthermore, a study of the excellent coast sections in that island makes it clear that precisely the same conditions existed throughout the Tertiary period. The same rapid alternations in sedimentary types are seen, lignite seams and oyster beds, littoral sandstones and marine silts, thin calcareous bands and ironstones, in fact all the phenomena of Carboniferous Coal Measures may be studied in Miocene and Pliocene strata under the simplest conditions. The higher Tertiary strata on the eastern and southern and western coasts of Trinidad, where excellent and almost continuous cliff sections can be studied and mapped, afford perhaps the finest examples in the world of deltaic conditions on the margin of a Tertiary continent.

One very instructive section in the Sangre Grande Ward may be instanced here. An abundant, though not very rich, fauna of fresh or brackish water mollusca occurs in a grey littoral sand, which also contains the remains of twigs and leaves. On the one side this sand bed passes gradually into fine sands and silts undoubtedly marine in origin, and on the other side into carbonaceous shales with strings and thin beds of lignite. The fossils are undisturbed as they lived, the lamellibranchs having both valves joined and closed. It is quite evident that we have here the sandbank at the mouth of a lagoon, littoral and marine conditions on the one hand, and fresh water or terrestrial conditions on the other. The whole section is not more than 200 yards in extent, and as the beds lie almost horizontally there can be no mistake as to these different conditions existing at the same horizon.

Evidence such as this leaves no room for doubt as to the manner in which these Tertiary lignites and their associated strata have accumulated. Occasionally the evidence is so complete that the course of a Tertiary river near its mouth can actually be traced through the strata, the lagoons on both sides of it roughly demarcated, and the sand and pebble banks that intervened between lagoons and sea mapped. It is even possible by a study of the effects of current action in the sandbanks to determine that the prevailing wind was, as it is now, from the east, and by a study of the finer sediments to prove that the climate was wet, the lagoons liable to fresh-water floods, and, in fact, that conditions were very much the same as at present.

The fact that the accumulations of vegetable matter were formed in lagoon formation or in a water-logged condition is important. Under sub-aerial conditions the aerobic bacteria bring about the decay of woody matter fairly rapidly, and consequently no great deposit of vegetable matter, with the exception of cortex, seeds, and the more resistant materials generally, can be formed. But if the deposit be to a great extent water-logged, the aerobic bacteria cannot attack the woody matter, which may thus accumulate in vast quantity.

Now let us turn to the evidence from oilfields to ascertain under what conditions the strata associated or impregnated with petroleum have been formed. So far as lithological evidence goes, the strata of many Tertiary oilfields are exactly the same as those associated with coals or lignites; there are the same rapid alternations, the same constantly repeated minor succession of clay ("underclay" in the case of coal or lignite) followed by sands sometimes conglomeratic, passing upwards into marine silts and clays, "underclay" again, and so on.

Considered in detail the resemblance is as striking. It is in the thick littoral sands which overlie the lignite seams, that shell banks occur, and not infrequently ironstone nodules and concretions, suggesting that a concentration of iron compounds under current action may have taken place. Bands of calcareous sandstone, the "hard shells" of the driller's logs, occur not infrequently in these sand groups, and especially at the top of them. These represent littoral deposits in which there was sufficient shell sand to form a cement for the whole bed; when the calcareous material is insufficient for this purpose it occurs in round or disc-shaped concretions often of large size and distributed in more or less regular lines. All these phenomena are as characteristic of the carbonaceous as of the petroliferous phases.

In fact, the only difference is that in the one case we have abundant evidence of vegetable remains in underclays, leaf beds, carbonaceous shales and sandstones, fossil tree-trunks, and seams of lignite or coal, while in the oilfield phase not a trace of vegetable matter is observed, but the porous beds are more or less impregnated with oil or bitumen, which may often be seen exuding at the outcrops.

The next point to be noted is that careful stratigraphical mapping has proved that the same horizons that are carbonaceous in one locality are petroliferous in another, often within quite a short distance; the only variation being that bands of impervious clay are sometimes more conspicuous among, and especially above, the petroliferous strata than among or above the carbonaceous.

This point has been established over very wide areas in Burma, Trinidad, and other countries, by careful geological mapping on the scale of six or more inches to the mile, and the change from the petroliferous to the carbonaceous phase can in some cases be shown to take place within three hundred yards.

First of all, taking evidence on a large scale, Burma furnishes an excellent field for study. The stratigraphical and palæontological work of the Geological Staff of the Burma Oil Co. has proved that the great productions of oil in the Yenangyoung, Yenankyat and Singu fields are all obtained from horizons which are represented by the Yaw Sandstone Group and the strata immediately overlying it, which have been mapped and examined over very many miles of their outcrops in the foothills of the Arakan Yomas to the west. These great arenaceous groups exhibit on their outcrops both the petroliferous and carbonaceous phases, the latter, however, predominating, and the remains of terrestrial vegetation are very common throughout. Traced eastwards these groups are found to become more or less split up by bands of clay and their total thickness perceptibly diminishes, while the petroliferous phase replaces the carbonaceous.

Similarly in other countries where oil and coal or lignite occur within the same series, the same phenomena are to be observed, and it is possible to work out generally the provinces of oil-belt and coal-belt in strata of the same horizon. The Ghasij Shales in Baluchistan afford a striking example; a bituminous coal is worked in one district, while another is characterized by oil-shows derived from the same strata.

To follow this inquiry in greater detail, particular beds may be selected and mapped till the actual transition between the two phases is observed. In Burma, in several localities, lignite beds have been traced into oil-bearing rocks containing no trace of vegetable remains. In the Yaw valley, about fifteen miles south-west of Pauk, is one of the best instances, the lignitic phase being completely superseded and replaced by the petroliferous within a distance of three hundred yards, the outcrop being followed easily as the strata dip steeply, and a hard sandstone bed enables the horizon to be followed without the possibility of mistake. In this case the oil is a light one with a paraffin base and containing a high percentage of solid paraffin.

In Trinidad similar detailed evidence as to the equivalence of lignite seams and oils of asphaltic base is not far to seek. In mapping the southern coast section in that island the author came on a series of lignites and lignitic shales intercalated with sandstones near Grande Riviere. The dip of the strata is vertical, and the strike coincides generally with the coastline which consists of an almost continuous cliff, so that the following of horizons was a matter of the greatest simplicity. Within a mile to the westward the lignitic phase was replaced by the petroliferous phase in the same horizons, the overlying strata becoming at the same time slightly more argillaceous on the whole through the thickening of intercalated bands of clay. All traces of vegetable remains were lost before the Rio Blanco was reached, and seepages of oil out of the porous beds were observed in several places. This point is important as it has been frequently urged as an argument against the vegetable-origin theory that traces of vegetable organisms are not found among oil-bearing strata. From this section on the southern coast the name Rio Blanco Oilbearing Group was given to the strata at this horizon in the Tertiary series, an horizon which has been proved to be not only petroliferous, but very richly productive in many parts of the island. In only two other localities, and these widely separated, are lignitic strata known to occur at this horizon. It is noticeable that where the petroliferous phase is in evidence impervious clays of greater or less thickness directly overlie, or are observed at no great distance above, the oil-bearing sands.

Where the transition stage between petroliferous and carbonaceous conditions is well defined some very interesting evidence may be obtained. A good instance is afforded in the State of Falcon in Venezuela. Here there is a Tertiary series of at least eight thousand feet, the lower part of which is distinctly petroliferous, while the upper half contains lignite seams, lignitic clays, and carbonaceous sandy beds. Near Cao de Ralito, where the series is dipping at about 30 degrees, there is a bed that shows both the lignitic and petroliferous phases.

It contains flattened tree-trunks preserved as bright lignite, while the rest of the bed is impregnated with oil, which by inspissation forms a small deposit of asphalt on the outcrop.

In this case the oil may have found its way up the dip from some distance below the surface, but it seems more probable that it has been formed *in situ* from vegetable debris contained in the bed, only the purer and solider masses of wood, such as tree-trunks, having been able to reach the lignitic stage before increasing pressure due to the rapidly accumulating sediment above brought about the necessary conditions for the formation of petroleum. The coal or lignitic stage is always reached first by the purer vegetable deposits; those containing much sediment retaining their normal vegetable characteristics for a longer period. In this connection a shore section on the southern coast of Trinidad is instructive. It occurs high in the Tertiary series, where the beds are practically horizontal, and shows a thin lignite bed with tree-trunks in the position of growth and their roots in an under-clay. In the seam the wood of the tree-trunks is a bright lignite, but the roots, though in places slightly lignitic, are still chiefly tough wood.

Had such a bed been subjected to efficient sealing and high pressure after the seam had reached the lignitic stage the woody matter might have been changed to liquid hydrocarbons, but that part already changed to lignite would have remained unaltered.

Below the Cao de Ralito section described above oil seepages are seen at several horizons, especially in association with argillaceous rock or just below impervious clay beds, and lignitic beds are absent. Above the section the lignitic phase becomes steadily more conspicuous as we ascend in the series, the strata, however, showing no other essential difference above or below for some thousands of feet. It is a striking illustration of the transition from oil-bearing to coal-bearing conditions, the former characterizing the strata that have been subjected to the greatest presure and the most effective sealing so as to prevent loss of gaseous compounds.

Still more remarkable evidence is furnished by the so-called "porcellanites" of the western and southern districts in Trinidad. These are naturally-burnt shales which have become ignited spontaneously, just as the bituminous Kimeridge clay in coast sections in the south of England has done on many occasions. The brick-red burnt outcrops of these porcellanites make very striking features in the scenery of the Wards of Oropuche and Cedros, a thickness of as much as thirty feet of strata exposed in a cliff being sometimes burnt and indurated.

When examined closely many of these porcellanites are found to be leaf beds, being a mass of beautifully preserved leaf impressions; the leaves are those of ordinary terrestrial vegetation, similar, if not actually belonging, to the same flora that flourishes at the present day in the colony. Veins and strings of clinker are seen ramifying through the masses of burnt shale, and occasionally some remains of sticky asphalt may be observed lining joints in indurated but not oxidized portions of the outcrop.

In several cases lignitic seams are observed not far below an outcrop of porcellanite, and Messrs. Wall & Sawkins in their Memoir upon the Geology of Trinidad state that the combustion of lignite has burnt the overlying shales. The author, however, has found no evidence for this; he has never observed a naturally burnt lignite. It is the shales themselves, either bituminous or in a transition stage between bituminous and carbonaceous, that have ignited spontaneously and burnt. The ignition is probably due to the heat engendered by the oxidation of sulphides, as in the case of the Kimeridge clay; every stream draining a porcellanite outcrop is beautifully clear, and the cause of this is soon ascertained when the water is tasted. It is full of alum, proving the oxidation of sulphides.

One very important point in connection with these porcellanites remains to be mentioned. Their dip is always very gentle, and though the outcrops may be traced for miles along the coast or through the forest, no case of a steeply dipping porcellanite has been observed.

The relation of porcellanites to oil-bearing strata is interesting and carries us a step further in the inquiry as to the cause of the phenomenon. The lower part of the cover-clay of the La Brea Oil-bearing Group is burnt to a typical porcellanite for a distance of nearly two miles along its outcrop. In this case leaf impressions are absent or very rare. Some patches

Photo. by Sir J. Cadman

i. SMOULDERING OUTCROP NEAR LA BREA, TRINIDAD.

Photo. by Sir J. Cadman

ii. MUD-VOLCANO IN ERUPTION, TRINIDAD.

along the outcrop may be seen occasionally smouldering at the present day; Professor Cadman has photographed a smouldering outcrop near La Brea (Plate III). Other occurrences of the burning of the clay above an outcropping oilsand may be seen in the forest south of Siparia and in Burnt Cliff in Barbados, where a petroliferous shale has been burnt along the outcrop for a considerable distance.

This establishes the fact that these porcellanites are as much associated with the petroliferous phase as with the carbonaceous. It might be suggested, indeed, that porcellanite is more characteristic of a petroliferous than of a lignitic series, were it not that leaf-beds are essentially phenomena of the carbonaceous phase; while the occurrence of procellanites in a lignitic series, where no signs of petroleum have been detected, is very frequent, *e.g.* on the southern coast of Trinidad near Chatham and in the eastern Lignite District near Sangre Grande. In both these localities thick beds of the porcellanite have been traced for miles where no oilsand is known to occur, but where lignites are common.

One coast section west of Irois is specially significant (Fig. 1). A porcellanite outcrop is seen dipping at an angle

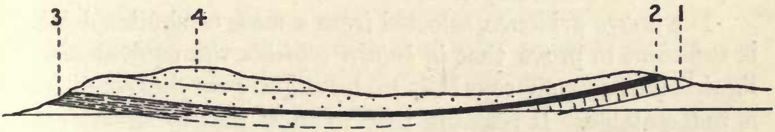


FIG. 1.—Coast section west of Irois (Trinidad). (Length about 200 yds.)
1. Porcellanite; 2. Clay; 3. Impure lignite and shale; 4. Sandstone.

of some three or four degrees at right angles to the coastline, and covered by argillaceous beds. This dip brings the outcrop below tide mark, where the strata become horizontal. At a distance of less than one hundred yards the strata emerge with a low dip in the opposite direction, thus forming a very gentle local syncline. Where the strata emerge the argillaceous beds have thinned out or become replaced by arenaceous strata, and the beds beneath are no longer burnt but consist of carbonaceous shales with one seam of impure lignite. This section can be observed from the local gulf steamer on its daily route from San Fernando to Cedros and back, and can be studied in detail during a walk along the beach. The whole section is some two hundred yards in length, and is so well exposed that there is no possibility of misunderstanding.

Such evidence places beyond doubt the connection between the lignitic and petroliferous phases of these Tertiary strata, and emphasizes once again the point that a slight difference in environment, the change from an arenaceous, that is to say, a porous, cover to an argillaceous or impervious cover, seems to determine whether the strata have ignited and burnt to porcellanites or have remained as unburnt lignitic shales. It is obvious that where strata lie at low angles the presence of an impervious cover will tend to preserve any combustible or volatile matter that may be in evidence in the underlying strata from being rapidly dissipated or removed by weathering, and thus will favour a slow combustion if a temperature sufficient to cause ignition be reached.

We may safely conclude, then, that these "porcellanites" of Trinidad represent a transition stage between the purely petroliferous and the purely carbonaceous phases, they have been more or less bituminous shales, and to attribute their combustible matter to an animal origin would be the most unjustifiable of assumptions.

The above evidence, selected from a mass of similar details, is sufficient to prove that *in known oilfields* the equivalence of lignitic and petroliferous beds under slightly varying conditions is indisputable. It remains now to show that *in known coal-fields*, the association of petroleum with carbonaceous strata is, though perhaps rare, by no means unprecedented. The point to be considered is the environment, the conditions to which the vegetable matter has been subjected. There are very many instances on record of a series being petroliferous in the lower beds, and lignitic or coal-bearing in the upper members. In such cases it will always be found that a greater or less thickness of comparatively impervious strata intervenes between the two phases. The section at Point Ligoure on the western coast of Trinidad shows this very clearly, while in Borneo, Russia, West Virginia, and many other countries, lignite or coal characterizes the less loaded or less perfectly sealed horizons of a series. In the latter country oilwells are sometimes drilled through workable coal-seams, and the bores have to be cased carefully to prevent water entering the coal-seams and flooding the coal workings.

The evidence as to environment is confirmed by recent researches on the nature of coals, and the conditions under which they are found. It was until recently the accepted view that anthracites are characteristic of the most disturbed, contorted, and faulted parts of a coalfield, and that bituminous coals are characteristic of the less disturbed portions. This theory, though there seemed at one time to be ample evidence for it, can no longer be held owing to the careful researches of H.M. Geological Survey in the South Wales and Staffordshire coalfields. Anthracites occur in comparatively slightly disturbed strata in South Wales, and bituminous coal at the same horizons in less disturbed areas. It has been suggested that differences in the original conditions of deposition may account for this, particularly as the amount of ash—inorganic material included in the coal—varies at the same time, being greater in the bituminous coals. Probably a truer explanation is to be sought for in the fact that the anthracites occur where the coal has been open to the influence of deep-seated weathering, and where the structure and nature of the covering have favoured the loss of volatile constituents. The greater original purity of the deposit is also a factor to be reckoned with; a pure coal will readily give up its volatile or bituminous contents, while an impure coal, owing to the "adsorptive" capacity of finely divided inorganic matter for bitumen, retains it to a much greater extent and will not part with it altogether, even under the action of organic solvents.

Thus it is in deep mines where the seams do not crop out at the surface, but are well sealed up beneath impervious strata, no matter how contorted, that we must look for evidence of petroleum. And the evidence, though somewhat scanty at present, and unfortunately not always recorded, is not wanting. Miners who have worked in deep workings of bituminous coal tell of "tarry oozings" from the neighbourhood of seams, or along joints in hard close-grained strata. Not long ago a seepage of petroleum was recorded from the Sovereign Pit of the Wigan Coal and Iron Co. at Leigh, Lancashire, at a depth of some 600 yards.

The oil-shales of Scotland, though not oilrocks in the strict sense, add their quota to the mass of evidence connecting petroleum and coal. The evidence concerning the relations of petroleum to oil-shales is dealt with briefly in Chapter VIII, in which some account is given of the writer's latest researches upon the subject. Suffice it to say here that the animal-origin theory of the so-called Kerogen of oil-shales is now rejected in the most recent works on the subject, and in a paper before the Geological Society of Glasgow, Mr. R. J. Conacher gives cogent reasons why no importance can be given to such animal matter as may have been entombed in or near the strata now found as oil-shale.

Thus we see that though coal and lignite are very different substances from liquid petroleum, they are inextricably connected; coalfields give evidence of oil and oilfields of coal, transitional stages can be searched for and found, and both asphaltic and paraffin oils are seen impregnating the same strata which at no great distance are carbonaceous in character. Such evidence, almost always forthcoming as the result of careful and detailed stratigraphical work in any part of the world where petroleum is to be found, makes it hardly possible to doubt that it is to terrestrial vegetation that we must look for the raw material from which our supplies of petroleum are derived.

But while stating this conclusion it must be borne in mind that in certain cases, as for instance gas coals and oil-shales, it is quite probable that such animal matter as may have been preserved has borne its, very minor, part. The ammonia derivable from a gas coal or some of the oil-shales might be taken as evidence that some animal matter may have been present, but a study of chemical analyses makes it plain that deposits of vegetable matter are quite rich enough in nitrogen to give good yields of ammonium sulphate without having recourse to problematical animal remains. For each 1 per cent. of nitrogen in a coal or oil-shale the theoretically possible yield of ammonium sulphate is rather over 100 lbs. per ton, a yield which it is impossible to obtain in practical working. All coals and oil-shales, all petroleum and even peat contain nitrogen. In peat a percentage of more than 2 has been recorded, and in coals that percentage is rarely exceeded. In petroleum as much as 1 per cent is known in some highly inspissated heavy asphaltic oils, though in light paraffin-base oils it is usually very much less.

B. (2) *Vegetable Origin.*—Before leaving this branch of the subject, it is necessary to refer to an idea or hypothesis frequently put forward in a rather indefinite manner, but which has found favour with many, especially those who have little field experience.

This hypothesis is that petroleum is formed from marine vegetation; in other words seaweeds or fucoids. It was apparently the desire to find some marine origin for oil that caused this theory to be taken up, and allusions to "fucoids" by writers on the subject of petroleum were at one time very frequent.

But the origin of the theory was a series of observations made on decomposing seaweed on the coasts of Sicily, Sardinia, Norway, and other countries, where a "jelly-like substance" was found to be formed at one stage of the subaerial decomposition. This "jelly-like" matter was somewhat loosely described as "substances resembling petroleum," and the theory of a seaweed origin for oil sprang to birth in the minds, not of the observers themselves, but of others who read about it. The theory was again revived by the discovery of "Nhangellite," formed in Portuguese South Africa by the decomposition of fresh-water algæ in dried-up shallow lakes, and the claim that this Nhangellite was evidence of the existence of petroleum in the neighbourhood. In 1906 the author was asked to investigate this claim in the field, but the evidence seemed insufficient to justify the necessary expenditure of time.

So far as geological field evidence has been adduced in favour of this theory, it has been confined to the production of a few specimens of so-called fucoids, but in most cases, as in the famous case of the Cambrian Fucoid Beds in the north-west of Scotland, examination has proved the so-called "fucoids" to be worm tracks and burrows. The exposure of this evidence, however, has not entirely removed the theory from currency: a theory can, it appears, survive the loss of the last piece of direct evidence in its favour.

Let us again appeal to the facts and consider what evidence can be brought up for and against a seaweed origin for petroleum. In the first place, are there any inherent improbabilities in the theory? Is it possible for seaweed to be accumulated in vast quantities and entombed in sediments as they are deposited? That vast quantities would be required will be admitted, as by far the greater part by weight of seaweed, about seven-eighths, is water.

Under what conditions do seaweeds flourish most luxuriantly? It is a simple matter of observation. On rocky coasts, in comparatively clear water, and in stagnant marine areas such as the Sargasso Sea, seaweed can grow abundantly. But in neither case is there any probability of the seaweed sinking and becoming entombed in sediment. On rocky coasts the weed is torn off by storms and cast on the shore, *e.g.* in the west of Scotland and Ireland, where kelp-gathering is a regular industry. In the Sargasso Sea the weed is floating or attached to floating timbers, the remains of derelicts, etc.

In deep water, beyond the laminarian zone, seaweeds are rare, small, and insignifiant. In muddy estuaries, under deltaic conditions, which have been proved to be the environment in which strata now oil-bearing have accumulated, where in fact sedimentation proceeds apace, there would seem to be some possibility of weeds becoming involved and preserved in the rapidly forming deposits, but in such conditions the waters are singularly free from seaweed growth. Thus the initial difficulty of postulating the possibility of a sufficient quantity of raw material is, perhaps, even greater in the case of the marine-vegetation theory than in the case of the animal-origin theory.

Turning to chemical evidence, there are facts even more difficult to explain away. When the water is removed from seaweed, of the remaining solids a considerable proportion is bromine and iodine in the form of salts. In fact, it is from the ash of seaweeds that these elements are extracted commercially. If petroleum is formed from the remains of seaweed, what becomes of these bromides and iodides which must be present in enormous quantity? In one case a trace of iodine has been detected in the water from a mud-volcano, but the proportion was quite insignificant compared with the trace of petroleum in the same water.

The marine-vegetation theorists must account for the loss or disappearance of these salts before they can justify the chemical possibility of their hypothesis.

The chemical difficulties to be surmounted are therefore as insurmountable as the initial difficulty of accumulation in sufficient quantity.

It has been suggested by American geologists that the organic matter of diatoms may be in certain cases the material from which petroleum is formed. These minute vegetable organisms have certainly existed in great numbers during the deposition of certain strata found occasionally in oil territory, especially above the deltaic rocks which contain the oil. The Texas-Louisiana and Californian fields have been claimed as instances, and it has even been stated that where the remains of diatoms are not found in the argillaceous strata above the oil-rocks the oil is also absent, or not present in such quantity. More definite evidence upon this point is required. But no serious evidence seems to have been brought forward in support of this ingenious and attractive theory. No proof of the entombment of organic matter, nor of the possibility of such entombment has been forthcoming, nor has the nature of the organic matter been inquired into.

The theory has to meet the same difficulties that make it impossible to accept the foraminiferal-origin theory, and even could the possibility of entombing sufficient material be proved the hypothesis could only apply to those fields where such diatoms are known to occur.

If field evidence of unimpeachable character were available, the matter would be worthy of serious consideration ; if fucoids and traces of fucoids were found in quantity throughout a series, and only disappeared among strata actually petroliferous, it would be necessary to give special attention to the rôle played by that class of organism and the strata in which the evidence occurs, but when most, if not all, of the so-called "fucoids" are worm-casts and tracks of animal organisms, the practical geologist is unable to treat the theory with respect.

Thus every hypothesis but that of the origin from terrestrial vegetation fails when tested by an appeal to the facts to be observed at the present day, and we may confidently state that the only source of origin which is at the same time adequate and within the bounds of chemical and physical possibility is terrestrial vegetation.

CHAPTER II

PROCESSES OF FORMATION

In the last chapter we have dealt with the material from which petroleum is, or can be, formed, and the various theories that have been put forward to account for its origin.

It now becomes expedient to consider the processes through which the raw material must pass in order to convert it into the mixture of saturated and unsaturated hydrocarbons which we know as "crude petroleum." The problem is to find out what these processes are, and how they have affected the raw material,

A simple distillation caused by heat will not meet the case entirely. We have seen already that such distillations take place in nature where igneous rocks invade coal or oil-shale measures. Instances of this are frequent among the Scottish oil-shales, and semi-liquid bitumen occurs as an impregnation in porous strata or along joints and in cavities for some distance from the shale bed or from the intrusion. But the result is not the reproduction of an oilfield on a small scale, nor could the process take place upon a sufficiently large scale.

What is required is a simple, slow, natural process which can take place over wide areas. It is, without doubt, more in the province of the chemist than of the geologist to make investigations with the view of determining under what conditions in nature it is possible to form petroleum from whatever raw material is available; but the geologist's evidence is necessary, if only to prevent undue attention being given to entirely artificial conditions which may be arranged for in the laboratory, but which can hardly be reproduced in nature.

Many chemists have conducted researches upon petroleum with a view to proving its mode of origin and the processes necessary for its formation, and no more careful and interesting work has been done than by Engler and Hofer. These observers state very clearly the conditions under which the reactions they observed and controlled took place, and the care and accuracy of their researches cannot be doubted. But they do not—and the same objection applies to the work of many others on the same subject—approach the inquiry from the point of view as to what conditions are possible in nature, conditions which the geologist in however rough a manner is able to define. Thus the work of these scientists, careful and painstaking as it is, is open to the charge of what might be called a form of special pleading in experimental work. Given the conditions they postulate, the results are certain, but if such conditions are practically impossible on a large scale in nature, the researches conducted in a laboratory become of little value to the practical man whose business is to find oil.

The geologist from his observation of the conditions under which petroleum occurs, knows the conditions to which the series of strata containing petroleum must have been subjected. Some universal process, subject to these conditions, is called for, and it is the duty of the chemist rather than of the geologist to reproduce as far as is possible the conditions so defined, and to prove whether it is possible to form the mixture of hydrocarbons known as crude petroleum from the raw material supplied and under the stipulated conditions.

Now the only conditions which the geologist has any right to dogmatize about are depth-temperature, pressure, the presence or absence of water, the nature of the raw material, and the question as to whether or not the strata in which the chemical reactions take place have been sealed and isolated from the introduction of extraneous material.

In the last chapter the nature of the raw material has been discussed at length, and, so far as is possible at present, determined. The calculation of depth-temperature is simple, and within reasonable limits the temperature at which oil may be formed can be deduced from incontrovertible evidence. The calculation of pressure is a matter of much greater difficulty, and there must necessarily be a very wide range between the minimum and maximum pressures postulated. The sealing up of the strata, in other words the determination as to whether the reactions have taken place in open or closed retort, is again a matter of easy determination, seeing that it is admitted by all observers that for the formation or preservation of oil impervious strata must overlie the petroliferous rocks. Similarly the presence or absence of water, argillaceous material, sodium chloride, and other material either active or inert in the chemical sense, can be deduced with a fair degree of certainty.

Here we must turn to the laboratory to learn what experimental investigations will come to our aid; it is a question of conditions favourable to chemical reaction.

The chemical reactions that take place in the vegetable matter can at present only be guessed at, but some idea of the general process may be obtained. A process that results in the formation of hydrocarbons from the fatty and waxy matter in vegetable debris can easily be understood, but when we consider the cellulose a more difficult problem is presented.

Loss of water alone, carried to its final stage, would leave free carbon as a residue. Yet that there is some loss of water, or at least of oxygen, is evident, and must be regarded as an essential feature of the process. A form of decomposition that would set free oxygen to react possibly with sulphides, forming sulphates, and thus make available hydrogen to bring up the hydrogen-carbon ratio to that characteristic of the mixture of hydrocarbons known as crude oil must be postulated. Under what conditions such a reaction or series of reactions could take place has still to be determined, but we have seen that high pressures and comparatively low temperatures are indicated. Sulphates, particularly lime sulphate as gypsum or anhydrite, nearly always characterize the strata of an oilfield both above and below the oil-bearing strata, while in coal-bearing rocks sulphides, *e.g.* pyrites, are often conspicuous and closely associated with the vegetable deposits. And, as has been shown, in the change from lignite to coal oxygen is released in combination with hydrogen as water and in combination with carbon as the oxides. The conditions under which such action occurs are clearly indicated as being pressures lower than those required for the formation of petroleum, and incomplete sealing of the deposit, so that gases may escape.

These, of course, can only be considered as the merest indications of the two processes that result in the formation from the same raw material of oil and coal respectively. It will be shown in a later chapter, in which torbanites are considered, that it is possible under somewhat unusual conditions to develop partially the oil-forming process before the coal-forming process is completed.

The elimination of mineral salts is another point to be considered. Vegetable matter contains considerable quantities of potash, which is left as the carbonate when the material is burnt, and in coal this potash is still retained to a great extent. But oil contains no potash or soda, though the brine so often found in association with petroleum contains both, the latter usually in great preponderance. Here is a problem which up to the present has not been solved, and any complete theory of oil-formation from whatever raw material must account for the elimination of these bases.

The occurrence of nitrogen and sulphur compounds presents no great difficulty. Vegetable matter contains both of these elements, and they are retained and to some extent concentrated in both coal and oil, though the percentages vary greatly in different oils and coals. In petroleum both the sulphur and the nitrogen contents are concentrated in the more complex molecules, helping to saturate compounds that are built up by polymerization from unsaturated hydrocarbons, and also probably associated with aromatic hydrocarbons in some cases. This is proved by the concentration of heavy hydrocarbons due to inspissation: for example, the nitrogen in a natural asphalt such as that of the pitch lake of Trinidad shows a progressive concentration from least to most highly inspissated fractions.

PERCENTAGES OF NITROGEN IN ORGANIC MATTER IN TRINIDAD ASPHALT.

Saturated Hydrocarbons in Malthenes.	Total Malthenes.	Total Bitumen.	Unsaturated Hydrocarbons in Malthenes.	Asphaltenes.	Organic Matter non-bituminous.
0·07	0·6	0·81	0·92	1·2	2·05

PERCENTAGES OF SULPHUR.

In the Malthenes.	In total Bitumen.	In the Asphaltenes.	In Organic Matter not Bitumen.
2·9	6·16	10·9	10·32

In experiments undertaken to try to determine how coal is formed from vegetable matter some very interesting evidence was obtained.

Spring in 1881 showed that peat under a pressure of 6000 atmospheres, but without any heating, could be changed into a bright homogeneous black mass, which was said to resemble coal, but seems to have been of a somewhat plastic nature when under pressure.

Fremy in 1879 announced the results of his experiments upon vegetable tissues of various kinds sealed in glass tubes and heated to 200°–300° C. for several days. Nothing resembling coal was formed; the vegetable tissues preserved their organized structure, but gave extracts of the nature of natural petroleum. These extracts, unfortunately, do not seem to have been completely investigated.

Stein at a later date repeated somewhat similar experiments. He sealed up wood with a small quantity of water in glass tubes and heated it for several hours, afterwards analyzing the solid residues. The temperatures varied between 245° and 290°, and the duration of the experiments varied from five to nine hours. At the higher temperatures the wood "fused," indicating the breaking down of all organic structures. Liquid extracts were found which for all practical purposes were petroleum, while the solid residues varied in composition according to the temperature. Those formed at the lowest temperature (245° C.) had a carbon-hydrogen ratio of 100 to 8·3, while at the highest temperature the ratio was 100 to 4·6. It is not stated what pressure was attained in the experiments, but it must have been high.

The points to note are that the temperatures are much higher than we can postulate in the formation of petroleum, and that the solid residues do not differ greatly in carbon-hydrogen ratio from those of bituminous coals. The liquid extracts, therefore, must have had carbon-hydrogen ratios of a lower order, *i.e.* must have been richer in hydrogen.

A series of somewhat similar experiments would be well worth making, using lower temperatures and if possible higher pressures, and placing some oxidizable material, some efficient absorbent of oxygen but otherwise inert, with the vegetable matter and water. The liquid extracts would be analyzed rather than the solid residues, if indeed any solid residues were left. To get sufficient pressure it would no doubt be necessary to raise the temperature above the boiling-point of water, but even that temperature is higher than need be considered in connection with the formation of petroleum.

The various attempts, however, to make commercial use of peat-mosses furnish us with valuable evidence. In Ireland, Sweden, the United States, and other countries, the problem of how to utilize the enormous accumulations of peat has for many years occupied the attention of practical chemists and chemical engineers, and after many failures it seems that some of the processes are within sight of commercial success. Without disclosing information confidentially received it may be stated that all these processes have this in common, that the peat after being dried and perhaps ground and again pressed into briquettes, is subjected to destructive distillation in the presence of a *limited quantity* of water, under great pressure, and at a comparatively low temperature.

The resulting products are various according to the end aimed at and the different pressures and temperatures in each case. Bituminous compounds, petroleum of almost every grade, and even coke may be obtained, while ammonium salts may be recovered as sulphate by a process similar to that used in the oil-shale and gas industries.

The important points for the geologist to note are that petroleum of various grades and in great quantity can be produced, and that the essential conditions are great pressure, comparatively low temperature, and the presence of a limited quantity of water.

Water is in any case present in the peat, even after drying, for it is as impossible, without destructive distillation, to remove the combined water in peat as it is in the case of a lignite.

It is obvious that similar conditions can easily be obtained in nature. The presence of water in greater or less quantity is almost inevitable in sedimentary rocks, the requisite pressure is amply provided for by a covering of a few hundred, or it may be thousand, feet of superincumbent strata, while as soon as decomposition commences the potential gas pressure may become so great that almost any hydrostatic pressure required can be obtained. The temperature, increasing as it does on a general average one degree Fahrenheit for every 55 feet of descent into the earth's crust after the first hundred, would soon be raised sufficiently to favour chemical reaction, while as pressure increased the temperature would also rise till the necessary equilibrium was reached. Thus once the process of petroleum formation has commenced, its action is probably automatic and must be complete, unless there is a change in conditions. The sealing up of the strata by impervious rocks, so that escape of gaseous or volatile compounds is entirely prevented or rendered so slow and gradual as to be quite insignificant, is, as has already been stated, a question upon which there is a general consensus of opinion.

It seems probable—but here we enter into speculation—that it is the *pressure* that is the determining factor, as it is in so many chemical reactions. Given the vegetable matter from which petroleum can be formed enclosed in a well-sealed deposit, given the presence of a limited quantity of water, and the necessary, but by no means high, temperature, as soon as the pressure reaches a certain point the action will begin. In a deltaic area undergoing earth-movement, as is almost invariably the case on the margin of a continent, sediment accumulates very rapidly. A geosynclinal on a large or small scale, in fact, is formed, and though sedimentation may occasionally outstrip subsidence, or subsidence outstrip sedimentation, the general result is the growth of the deltaic deposits outwards by progressive sedimentation over a continually increasing thickness of strata belonging to the same series. In such circumstances the requisite pressure for the formation of petroleum may easily be obtained in the strata sufficiently deeply buried.

Another probable effect of pressure also must be considered; *ceteris paribus*, the quality of the petroleum formed is likely to depend upon it. In the process of polymerization of organic compounds, it has been proved over and over again in the laboratory that pressure is usually the determining factor. Thus a higher pressure may determine a more complete condensation of the volatile compounds and gases into light oils, provided that such condensation is accompanied by a decrease in total volume. The fact that in many oilfields where several separate sands at different depths contain petroleum, the specific gravity of the oil generally decreases as the depth increases may not be due in all cases, as has often been assumed, entirely to partial and progressive inspissation of the shallow oils, but partly to the pressure under which the petroleum has in each case been formed.

On this hypothesis of oil-formation the importance of an impervious "cover" also becomes apparent. The "cover" is in effect the lid of the retort in which the chemical processes take place. If the lid be imperfect or imperfectly closed, escape of gaseous products, oxides of carbon, must ensue, pressure can never become very high, and the entire process of oil-formation may be prevented, arrested, or permanently stopped. Coals or lignites and carbonaceous shales and sandstones will be the result. This accounts for the occurrence of porcellanite beneath or forming part of a bed of shale or clay, while the lignitic or carbonaceous phase is in evidence where the cover is arenaceous and porous.

It has been suggested, on account of the association of oil-bearing rocks with clays or shales often of great thickness, that the argillaceous strata may have had some actual part in the formation of the petroleum. This is a point very difficult of proof, either for or against, since to bring actual evidence of the favouring of chemical action by the presence of argillaceous material which itself remains unaffected is well-nigh impossible. It is quite probable that much of the material from which petroleum is formed has been deposited with and included in argillaceous sediment: witness the leaf beds which have been burnt at outcrop to porcellanites. It is also certain, as proved by Mr. Clifford Richardson, that clays can absorb and "adsorb" bitumen to a remarkable extent, and can be used to filter solutions of asphalt and asphaltic oils. But these facts are not proofs of the argillaceous material taking any actual part in the chemical processes by which oil is formed, even as what used to be called a "carrier," a compound which, though itself apparently unaltered, enables chemical action to take place by continual decomposition and simultaneous re-formation. It is an interesting field for research for chemists to inquire into the possibility of argillaceous strata having some such essential rôle to play. For the geologist the matter of importance is simply that potential oil-bearing strata require an impervious cover if the oil is to be formed, and, when formed, if it is to be preserved from inspissation, and that argillaceous rocks, especially fine marine and estuarine clays and shales, are the best and most usual "cover-rocks."

By studying the subject of pressures in the earth's crust, and by careful measurement of sections where oil-bearing strata are exposed, it may be possible to arrive at some idea of the pressure necessary for the formation of petroleum. In many cases where large thicknesses of strata are exposed it will be found that the lower part of the series is petroliferous and the upper part carbonaceous, without there being any essential change in the character of the intercalated sediments associated with the oil-bearing and lignitic bands. It may be that the upper part of the series has never been under sufficient pressure to bring about petroleum-forming reactions.

Let us take a specific case and attempt, however roughly, to calculate the maximum and minimum pressures which can have been exerted during the formation of the petroleum. At Point Ligoure on the western coast of Trinidad, where the Guapo Oil Company operated, there s a very clear section exposing some 1300 feet of strata, the dip varying from vertical at the northern and lower end of the section to 56 degrees at the southern and upper end. The lower 600 feet are in the petroliferous phase, and several bands of oil-rock are exposed, especially near the base of the section. In the upper 200 feet of the section lignitic clays and sands with underclays aud thin seams of lignite are observed. In the lower part of the section the strata are somewhat more highly mineralized, concretions chiefly cemented with iron salts are more frequent, and there are several beds of fairly stiff argillaceous material intercalated with the oil-bearing sandstones and above them. In this case the mapping of the neighbouring districts has proved that probably not more than 800 to 900 feet of strata have ever been deposited above the uppermost beds in the measured section. Assuming that such a total thickness of beds has been deposited in a horizontal position, and again, assuming that the pressure can be calculated as a hydrostatic pressure directly due to the weight of the superincumbent strata —these being great, and perhaps hardly justifiable assumptions—it is possible to calculate the pressure to which the strata containing the raw material from which petroleum can be produced have been subject.

Taking the specific gravity of the strata to be on an average 2·7, we arrive at the result that the maximum pressure exerted and applied in this instance has been 189 atmospheres, or some one-and-a-quarter tons per square inch, and the minimum approximately 135 atmospheres or rather less than a ton per square inch on the strata now found to be oil-bearing, while a pressure of 99 atmospheres was apparently insufficient to determine the formation of petroleum. This calculation is, of course, open to many sources of error, and it is improbable that such high pressures have been exerted in this case, as earth-movement and denudation probably prevented the accumulation of any such thickness of strata in a horizontal position. The figures are only given to suggest a form of inquiry in which the observation of facts in the field may enable the geologist to obtain evidence as to the conditions requisite for the formation of petroleum. In this case the oil, as yielded at present, is of fairly high gravity with an asphaltic base. Another instance may be cited from a different region. In the valley of the Yaw, in Upper Burma, an excellent section through the entire Pegu Series of Burma may be studied, the total thickness being some 8000 feet. The lower 3000 feet exhibit here and there evidence of the petroliferous phase in seepages of a fairly light oil with paraffin base, but lignitic beds begin to appear on the same horizons as the oil-bearing rocks at about 3000 feet above the base of the series. Then, after passing upwards through some 1300 to 1400 feet of strata chiefly of solid clays, the lignitic phase is well represented by a series of seams with intervening underclays and sandstones, and up to the top of the section no further evidence of petroleum is forthcoming. In this case it is practically certain that earth-movement had begun long before the deposition of the higher beds, and that the strata were never superimposed upon each other in a horizontal position. Thus calculations of pressure and temperature from the data as given might be entirely erroneous. The points to be noted, however, are that a transition from the petroliferous to the carbonaceous phases takes place at a fairly definite horizon in the series, and that this change may not be due entirely to the sealing up of the strata in which petroleum is now found, but to a direct effect of different pressures.

Numerous other instances could be given, but these are sufficient to suggest a field of inquiry which might be followed up by laboratory experiments, the results of which might throw light upon the conditions governing the formation of mineral oils of every grade and nature.

Temperature.—The evidence as regards the temperatures at which petroleum may be formed in nature is no less interesting. It is evident that if depth-temperature alone is to be considered, and in the case of most oil-fields it is impossible to postulate any other phenomenon capable of causing a rise in temperature, there is no very great range of temperature available. In the case of Point Ligoure a rise in temperature of 40 degrees Fahrenheit would be all that could be granted. In the case of the Yaw Valley it would not be safe to calculate upon a rise in temperature of more than 52 degrees or 53 degrees.

Thus we see that the researches upon peat furnish an interesting and attractive suggestion as to the conditions under which mineral oils are formed in nature. High pressure and comparatively low temperature are the conditions under which petroleum can be produced from the vegetable matter of peat masses, and similar conditions are at the least easily obtained in the strata of what are now oilfields. The high temperatures required for the destructive distillation of animal fats to form distillates consisting of a mixture of hydrocarbons similar to natural petroleum, are not only unnecessary, but can hardly be assumed to be within the range of possibility.

Salt and Brine.—One other interesting and even puzzling feature about many oilfields is the frequent association of petroleum with brine or rock-salt.

The first oilwell drilled in America was intended to reach brine and not petroleum, and in many other countries it has been in the search for brine or salt that oil has been found. In very many oilfields, also, the water associated with the petroleum or occurring in porous beds below it, and also frequently above it, is brackish or even highly impregnated with sodium chloride. In mud-volcanoes, also, the water and mud discharged are almost invariably saline.

It has been claimed that the occurrence of this brine is confirmatory, in some unexplained manner, of the theory that it is in marine strata and from marine organisms that petroleum has been formed, and the well-known antiseptic properties of common salt, under subaerial conditions, be it noted, have even been adduced as being likely to favour the partial and selective decomposition of animal matters which would be necessary if petroleum is to be formed from them.

Into this speculation the author does not care to venture, for lack of sufficient detailed evidence. But it must be admitted that the terrestrial vegetation theory does not on the face of it explain the presence of these saline waters, nor does their origin from vegetable matter seem possible.

Without attempting an explanation, however, it is possible to review such facts as bear upon the problem and to consider how far these facts may indicate a possible solution.

In the first place it is necessary to ascertain whether brine and petroleum are always associated or not; in other words, whether the former is an essential concomitant, or whether its occurrence may or may not be due to causes not in themselves directly necessary to the formation of mineral oil. Unfortunately we are at present unable to answer this question with certainty. In some oilfields a strong brine underlies or accompanies the oil in every petroliferous band, in most cases what water is found is slightly saline or brackish, in a few cases there is little evidence of salinity. In the famous Yenangyoung field of Burma the waters met with in the upper oilsands, or in water-sands between them, are fresh or only moderately brackish, while a distinct brine has been struck in the lowest sands penetrated in recent years. In this case, however, it may be that the upper waters have been briny and have been diluted by the incursion of surface water. Thus the percolation downwards of fresh water may result in the occurrence of a small quantity of brine in the oilrocks being overlooked.

Many oilfields contain regular beds of rock-salt, *e.g.* Luristan, Persia and Texas, and these deposits may be found both above and below oil-bearing strata. Again, in Persia brine springs giving rise to saline rivers occur in outcrops of strata which are approximately on the same horizon as oil-bearing rocks in neighbouring districts. In the case where brine is most conspicuous, a suggestive subject for inquiry is the investigation of the evidence as to the conditions under which the strata now containing brine have been deposited, while it is also necessary to take into account the present climatic conditions under which the strata are observed.

In Persia, in the oilfields of Luristan, and more especially in the strata overlying the known oilrocks, we have almost every possible proof of a former desiccation during formation. Red-coated mudstones and sandstones, deposits of gypsum on a gigantic scale, Brockram-like breccias on the flanks of limestone outcrops unconformably overlaid, are the rule throughout a vast thickness of strata. Furthermore there is indisputable evidence of a contemporaneous earth-movement that shut off basins and allowed the desiccation to take place. The occurrence of beds of rock-salt, therefore, can readily be understood, quite apart from any suggestion of its being essentially associated with petroleum. Furthermore, the climate of this region (Plate IV) is very dry, absolutely rainless throughout a great part of the year, so that there is no excess of surface waters to dilute and disguise the presence of brine in the strata. The importance of this point concerning climatic conditions at the present day can be appreciated when the logs of the wells drilled in the Maidan-i-Naphtun field in Persia are studied. Hardly any water has been encountered at any depth in any of the wells. The significance of this point will appear shortly.

In Baluchistan in the Khatan oilfield, a region almost rainless, the waters associated with and accompanying the oil are impregnated with salts, but instead of sodium chloride it is largely the sulphates of sodium and calcium that are present. These salts occur frequently throughout great belts of the dry zone, and are characteristic generally of arid regions, quite apart from oilfields. Such evidence suggests that there may not be any essential connection between the occurrence of salt or brine and petroleum.

The whole question, however, requires exhaustive research before it can be decided whether or no the oil and brine are

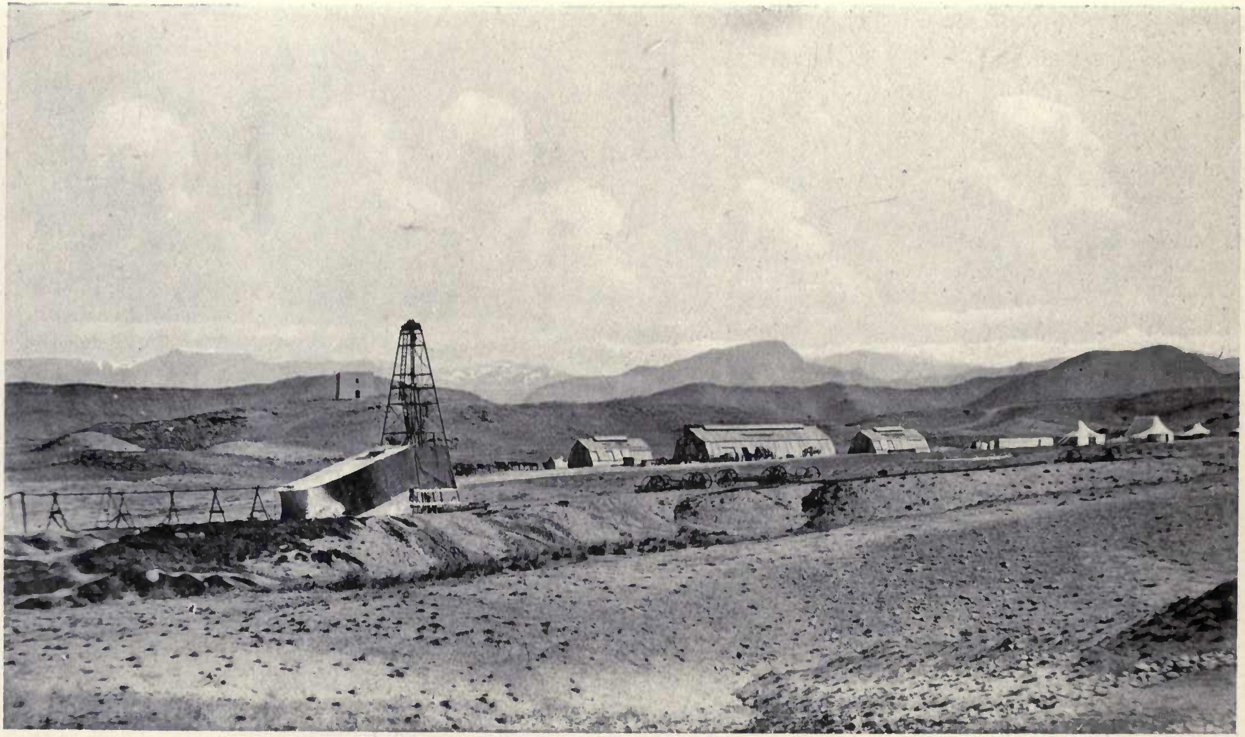


Photo. by G. B. Reynolds

THE MARMATAIN OIL-FIELD, PERSIA.
Shewing the bare nature of the country.

due to the same chemical action, whether they are different effects of the same causes, or whether their association is merely adventitious. In the answers to these questions probably lies one of the most illuminating generalizations yet to be made in the geological study of petroleum, and one which may be of great practical value to those who have to exploit new oilfields.

What is required is a large number of analyses of the brines and brackish waters found accompanying or underlying the petroleum in an oilrock or discharged from a mud-volcano. In each case it must be known from what depth the water was obtained, with what particular kind of oil it was associated, paraffin or asphaltic, high or low grade, whether sulphur compounds were present in the oil, and if so, in what percentage, and whether there has been any possibility of surface waters having percolated downwards and mingled with the brine or brackish water. Without precise data of this kind it is dangerous to generalize.

The only suggestion that the author would put forward is that it must not be forgotten that salt and petroleum may be entirely unconnected. Every sedimentary rock—and many igneous rocks for that matter—contains either sodium chloride or ingredients which could furnish that salt if the rock were sufficiently lixiviated. Where water is in excess, as in water-bearing strata, the percentage of sodium chloride is so small as to be inappreciable, but where water is in smaller quantity and has percolated through a considerable thickness of strata it is possible that a considerable concentration of saline matter in solution may have taken place. Now we have seen that one of the probable conditions under which petroleum has been formed is the presence of a *limited quantity* of water. Much of the hydrogen also may be utilized in the formation of the mixture of hydrocarbons which we know as crude petroleum, but this is very doubtful, as it would necessarily involve the oxidation of any oxidizable material in the vicinity. However this may be, it is evident that any residual water might become a fairly concentrated solution of saline matter. As we have seen that petroleum is formed in what we may consider a closed retort, circulation of subterranean waters and percolation of water from upper strata might be impossible or only possible to a very slight extent, and a brine associated with the oil or underlying it might survive without dilution till the oil-bearing strata are pierced by the drill. The evidence of desiccation in the strata overlying petroliferous rocks in many oilfields shows that excess of water is not a probable condition in the series containing oil, for where rainfall is scanty and evaporation rapid the absorption of water by the strata must be minimized.

This hypothesis as to the reason why saline water is usually found in association with petroleum is only put forward as a suggestion, which must be tested by application to facts as observed; it is merely stated now as a guide to the direction in which future research may prove profitable.

There is one other point in connection with the formation of petroleum which cannot be too clearly insisted upon. It is the common practice to distinguish between oils of asphaltic base and oils of paraffin base, and they are often spoken and written about as if they were entirely different minerals. In some cases it has even been suggested that they have been formed from different raw materials.

But there is actually no hard-and-fast line between asphaltic and paraffin oil; many asphaltic oils contain a percentage of solid paraffin, and many so-called paraffin oils can be made by careful distillation to yield a residue of asphalt. In fact, there is less difference between different crude petroleums than between different coals, which, as is well known, show every gradation from the least mineralized lignite with a high percentage of water, through bituminous coals and gas-coals to anthracite, and, perhaps, finally even to graphite.

It has been shown that the light paraffin oils of Burma, with percentages of solid paraffin up to as much as thirteen, and the heavy asphaltic oils of Trinidad can both be proved to have been formed from vegetable matter, while the paraffin oils of Trinidad, with percentages of solid paraffin up to six (though they occur under slightly different conditions from those in which the asphaltic oils are found, in the former case impregnating thin oilsands very well sealed up amidst thick masses of clay), give no evidence of an essentially different origin.

To account for the differences in grade and class of crude petroleum, we must look to variations in the conditions of formation; different pressures are probably the most important factors, but differences in temperature, relative quantity of water present, and many other local conditions probably all play their parts. In these questions there is need for much research and experimental work in the laboratory, and it is hardly within the province of the geologist to speculate upon the effects of the environment to which the raw material was subjected. It is, however, the geologist's task to deduce and discover as far as possible what that environment must have been, so that armed with the knowledge thus gained the chemist's task may be simplified.

CHAPTER III

THE MIGRATION, FILTRATION, AND SUBTERRANEAN STORAGE OF PETROLEUM

WHAT is crude petroleum?

It possibly has occurred to few practical men dealing with the precious fluid to ask themselves this question, or to attempt to answer it.

We are apt to take petroleum on trust, as we too often do in the case of milk, without ever considering its composition, chemical and physical. We speak of the oil of one field or another, of one well or another, and of the differences between them as shown by analysis, but we don't stop to ponder upon what petroleum is fundamentally. It is just oil. A very pertinent instance of this is before the reader: we have reached the third chapter of this little book, we have discussed the origin of petroleum and the conditions under which it is formed, but we have not begun to consider what crude petroleum really is.

The oil-refiner, however, has to consider this question, and he has by empirical methods, by experience often dearly bought, discovered a great many facts about the composition of crude petroleum, and devised and utilized many interesting processes the fundamental principles of which he may not have even troubled to investigate scientifically.

The prevailing idea is apparently that crude oil is a homogeneous mixture of various hydrocarbons and derivatives of hydrocarbons, simple and complex, which can be separated by their boiling-points into less complex mixtures from which again by fractional distillation and chemical means pure chemical compounds can be extracted.

This is a very simple and very practical definition; it is certainly true, so far as it goes, but it does not go very far.

For if crude petroleum be such a mixture of simple and complex hydrocarbons it is fairly evident from what we know of organic compounds that at each different temperature and pressure there will be a different equilibrium between the various constituents. Increased pressure or increased temperature will cause condensations or dissociations, and the respective weights and volumes of the organic compounds will vary accordingly. This is a point that seems frequently to be overlooked. The oil struck at the bottom of a two-thousand-foot well is *not* the oil that is collected at the surface. There has been a great change of conditions between oil-rock and surface, a great disengagement of light hydrocarbons as gas, and there must have been a simultaneous rearrangment of molecular groups. Crude oil under this theory must be frequently changing in composition according to the governing conditions.

This theory, however, may be partly but not wholly set aside if we consider crude oil as a solution, in which gas and other solutes are homogeneously intermingled in a common solvent, which, of course, may be itself of complicated composition. Thus we may look upon crude oil as solid asphaltic or aliphatic compounds dissolved in one or more of the lighter hydrocarbons.

But this theory in its turn is somewhat unsatisfactory, for it raises at once the difficult question of what is the phenomenon of solution. Now we know what happens when a salt, an electrolyte, is dissolved in a solvent; it is separated into its ions, positively and negatively electrified. It exerts an osmotic pressure, it reduces the surface tension of the solvent, raising the boiling point and lowering the freezing point, it conducts an electric current and by doing so is electrolyzed. This is crystalloid solution.

But there is another form of solution, or what appears to be solution, which does not conform to these rules at all. This is what is called colloidal solution, a subject which has occupied the attention of many scientists in recent years.

The writer offers the suggestion that crude oils are all colloid solutions, or, as they are called, "sols." There is much direct evidence for such a theory, and investigations which the writer has had in hand for some time will, it is hoped, throw some additional light upon the matter.

In colloid solutions the solutes are not ionized and do not exert osmotic pressure, raising the boiling and lowering the freezing points. This is not the place to go at length into a description of the phenomena of colloids, but it may be stated briefly that the accepted view of colloid phenomena is that they are due to the division of the solute, or as it is called the "disperse phase," into ultra-microscopic particles larger than molecules but which can be measured approximately. These particles are distributed homogeneously in the "continuous phase," the analogue of the solvent. A colloid solution, or sol, is called a "system" consisting of these two phases, and the system may under certain conditions become a "*gel*" or solid jelly-like mass without addition or subtraction of material, and may also be resolved or precipitated from the colloidal state.

Two varieties of sols are recognized, "*suspensoids*," in which the disperse phase is in solid particles, and "*emulsoids*," in which the disperse phase is in liquid particles. Each of these classes may be recognized in crude oils, and each has its own characteristics differing from those of crystalloid solution.

In crude oils the conditions must be somewhat complex on account of the various compounds present, but the phenomena of sol and gel are frequently recognizable.

The subject is only mentioned here because this view of the physical constitution of crude oil throws light upon many phenomena hitherto but partially understood; without going into a lengthy technical disquisition upon colloids it will be possible to explain with greater clearness the reasons for many well-known facts about crude petroleum, particularly underground, but also during some of the stages in refining. For instance, the fluorescence of certain crude oils can be explained, the gel formation during the extraction of solid paraffin from the lubricating fraction of a paraffin oil can be accounted for as well as the methods for freeing the solid wax from oil, and certain obscure combinations or associations between crude oil and other substances can be shown to be illustrations of the actions, typical between colloids, which lie upon the debatable border-line between chemistry and physics. The oiliness of oil, the viscosity, and indeed the whole theory of lubrication depends to a great extent upon the colloid nature of crude petroleum and some of its products.

It is necessary now to consider what may happen to the crude petroleum after it has been formed, what movements are possible for it, and the reasons for those movements, how it is concentrated and stored, and how it may be affected in grade or quality by the conditions to which it is subjected. The migration, filtration, and storage of oil in nature are subjects so inextricably connected that they can hardly be considered apart; they must all be understood by the geologist if he is to be capable of reading field evidence correctly and assigning its true significance to every indication which he may have to consider of the presence of petroleum, at the surface or in a well.

The causes for the migration of oil are earth-movement, hydrostatic pressure, and gas pressure. There are many factors which determine movements of oil, but directly or indirectly all movements are due to these three causes. The theory that oil is underlain by water or brine and has been floated up by the heavier liquid through porous strata, and thus by the hydrostatic pressure of the water forced towards the crests of flexures or to outcrop, is pretty generally accepted, and certainly in fields such as those of the Eastern States in America, where the strata often lie at low angles over great stretches of country with very small and gentle flexures and disturbances, and the porosity of the rocks does not vary sufficiently to hinder migration, there may have been a great lateral progression of petroleum towards the localities best adapted for storing it. But cases are not always so simple, and to assume that in any oilfield the petroleum contents have originated at a great distance, and have only reached their present position after a wearisome journey, is quite another matter. The insistence upon the migratory feats of petroleum has arisen to some extent, at least, from the desire to account for the formation of the hydrocarbons from animal matter. Thus, on the theory that the oil of the Californian and Texas-Louisiana fields has been formed from the soft parts of foraminifera preserved in thick masses of shales and clays, it is necessary to postulate a migration of each minute particle through almost impervious strata in a certain direction to form an accumulation in a porous stratum. To attribute such a movement to the hydrostatic pressure of water is perhaps to attach too great importance to an action which in porous and inclined strata does without doubt take place. But it has already been shown on what very doubtful evidence a foraminiferal-origin theory rests. If on the contrary the oil is formed from accumulations of vegetable matter, it is not necessary to postulate extensive migration as a rule; strata capable of containing the petroleum are usually at hand, and in these strata it will be found. The Tertiary Series in Burma and Trinidad, where great thicknesses of strata of estuarine origin are present, supply abundance of evidence on this point, while lignitic or carbonaceous beds contemporaneous with the oil-bearing strata, and at no great distance from them, give evidence of the presence of the raw material, and suggest that no great or extensive migration is necessary.

Hydrostatic Pressure.—It is the geological structure and the porosity of the oilrocks that determine the effects of hydrostatic pressure. The rocks must be sufficiently porous to admit of free, if slow, movements of the aqueous contents, and the strata must be sufficiently inclined to determine the direction of movement. Thus towards the crests of anticlines, both laterally and upwards, there must in nearly every case be a gradual migration of oil by the gradual replacement by water in the lower levels, when there is a sufficient difference in the specific gravities of the liquids. In a subsequent chapter the various structures that favour such migration will be dealt with.

The question of specific gravity becomes in some fields a matter of great importance. The fact seems to have been lost sight of occasionally that a heavy asphaltic oil of say 0·95 specific gravity or higher will be affected much more slowly than a light oil of 0·72 specific gravity. Consequently in considering lateral or upward movements of petroleum the particular grade of the petroleum must be taken into account. To overcome the friction and the viscosity of the oil which must necessarily retard percolation, a considerable advantage in specific gravity must be possessed by the water. Thus to generalize on the subject of migration of oil from facts ascertained in the Pennsylvania fields, where a light paraffin oil is found, and to apply the generalizations to such fields as those of California, or even Baku, where an asphaltic oil of heavier gravity is the rule, is, to say the least, very unsafe.

It has long been an accepted theory that when gas, oil and water are present—in a porous stratum—they separate out according to their respective specific gravities, so that on the crest of an anticline or dome gas only will be first encountered, then beneath and towards the flanks oil, and finally water at a still lower level. Diagrams illustrating such an occurrence are frequently seen in books upon petroleum, and the belief is fairly general that such an arrangement is the natural and correct one.

Oil and water certainly do separate out in this manner, especially when the oil is of fairly low specific gravity, but gas does not, and cannot, except under very unusual conditions. The gas-oil-water arrangement on the crest of a dome is absolutely impossible unless there be insufficient oil or water to fill the porous reservoir. In a syncline, waterless or

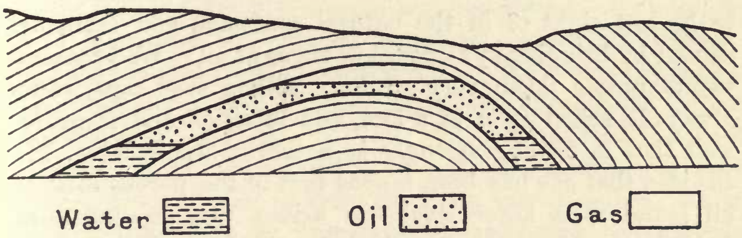


FIG. 2.

containing very little water, oil may be found at or near the base of a porous stratum, and if it be not present in sufficient quantity to fill the reservoir rock gas will be released from the oil to fill the upper layers. But in almost every other conceivable case oil and gas do not have a separate existence till a well is drilled into or almost into the porous reservoir. The case of the great gasfields, which might be considered as an exception to this rule, are dealt with in Chapter VIII.

The theory that gas lies above oil has been arrived at very naturally. Gas migrates more easily than liquid hydrocarbons, and tends therefore to spread all round an oilpool as well as above and below it, penetrating cover-rock and waterlogged strata to a certain extent. When a well is drilled to the upper surface of the oilrock, the release of pressure is so great and causes such a readjustment of equilibrium between the various hydrocarbons that the simpler and lighter compounds, chiefly gaseous, enter the well in great and increasing quantity before any oil, except perhaps the merest light filtrate, can reach the boring. This may take place, and very frequently does take place, before the oil-bearing reservoir is actually tapped. In the course of time the well may "drill itself in," *i.e.* the rush of gas may gradually loosen and disintegrate the few feet of cover-rock so that oil enters the boring and makes it an oilwell. In other cases it may be necessary to drill a little deeper—into the actual oilrock—before the well can become a producer of oil. The gas pressure may be too great at first to permit of further drilling, and the well may blow off gas for months before it can be deepened or drills itself in. The existence of a thin cap rock and the fact that the well is finally found to be a few feet deeper than previous measurements would indicate are apt to be lost sight of in the natural confusion and excitement caused by bringing in a good flow of gas or oil. Well-measurements, unless taken very carefully with a steel tape, cannot always be relied upon to a foot, and to sound and measure a well that is flowing strongly is naturally impossible. Thus the idea that gas has been tapped first in the porous rock and oil found at a lower level has arisen very naturally, and indeed seems in many cases to be justified.

Considering the question from the physical and chemical point of view, it is easily seen that in the presence of a body of oil under high pressure the *separate* existence of gas is impossible without some intervening membrane or stratum. Most petroleum geologists will doubtless recollect cases where it is possible to test this gas-oil-water theory and arrive at a definite conclusion. Yet this fallacy has got such a hold upon oil-drillers and geologists that it is doubtful if it will ever be entirely eradicated.

Gas Pressure.—Another cause of what may properly be called migration of oil is gas pressure. The gas may not exist as such in the strata, being dissolved and occluded to a great extent in the petroleum, or the pressure may be too great to allow of the existence of gas if it is below the "critical temperature." In that case the gas will be in a potentially gaseous state, and must exert an enormous pressure in seeking to find space in which to expand to the gaseous state. The terrific force with which such gas is disengaged on the striking of a prolific well is sufficient evidence on this point, as it is now admitted that gas pressure is the chief if not the sole cause of fountains or flowing oilwells. This gas, dissolved, occluded in or mechanically associated with the oil, must exercise pressure *in all directions*, and here again comes a point that has frequently been lost sight of. It is often assumed that the movements of gas and oil must be directly or indirectly upward, and this has often caused deplorable errors to be made in the location of oilwells and in the deepening of wells long after they have passed through the lowe t strata in which there is any hope of oil being struck. A "show" of gas in a well has only too frequently been understood as a sign that oil must lie beneath.

But if gas exerts pressure in all directions it will migrate in all directions till stopped by some impervious stratum. Thus both laterally and downwards there may be a migration of gas carrying with it probably small quantities of the lighter constituents of the oil. The oil will gradually be trapped during the migration, especially by argillaceous strata, so that the gas finally reaches furthest from the parent source. It is owing to this that we find gasfields spreading beyond the confines of an oilfield, and profitable productions of gas may be obtained near a prolific oilfield but in localities where no oil can be struck and where the strata may be substantially waterlogged. Instances of this are not uncommon in Burma.

Again, gas may be found beneath the oil-bearing strata, and may be evolved from clays and other almost impervious rocks long after porous oil-bearing strata above have been removed by denudation. The impregnation of strata unconformably overlaid by oil-bearing rocks has been observed in many parts of the world; good instances are recorded from Alaska, where metamorphic rocks have been impregnated from the Cretaceous above them, and from Galicia, where Cretaceous strata contain oil derived from an overlying Tertiary Series. Such cases of impregnation have also come under the writer's personal observation in Baluchistan and Trinidad. In Burma also there is some evidence of deep wells passing through the petroliferous Pegu Series and striking oil in the unconformable series beneath. In some of these cases the strata beneath are argillaceous, so that they contain little more than gas, and perhaps a little filtered oil, the exudation of which when exposed at the surface is naturally very slow.

In the south-eastern corner of Trinidad slow evolutions of gas may be seen from an outcrop of clay of the Cretaceous Series, which is not petroliferous in the district, but which is overlaid unconformably in the immediate vicinity by oil-bearing Tertiary sands. In the Piparo district of the same island the discharge of gas in one locality has been sufficient to form two small mud-volcanoes on an outcrop of Cretaceous clay which was not originally petroliferous. In this instance, however, the volcanoes may be fed from some more porous strata beneath, which have been more completely impregnated from the Tertiaries.

Surface Tension.—In recently published books upon petroleum, and especially those hailing from the United States, allusions are made to capillary attraction and the great effects it has in preventing oil from being drained thoroughly from its underground reservoir and in hindering or helping migration of oil. The writer must confess that he has been somewhat at a loss to understand clearly what certain authors mean to convey by their statements on the subject, so, in order to be perfectly fair to those authors, the following extracts are quoted verbatim, given in their order and not picked out at random, so that the reader may deduce for himself definite ideas upon this interesting subject.

In one book we find the following:

"Three forces are mainly responsible for the movement of oil through rocks and its segregation: (1) Gravitation; (2) Capillary Attraction; (3) Difference in Specific Gravity."

"Capillary attraction is much more powerful than gravitation, and is supposed to be an effective agent in the movements of oil."

"Diffusion of oil . . . in saturated rocks the capillary factor is likely to be overshadowed by the presence of water."

"Moreover, capillary attraction takes place only in rocks having extremely small pores, such as clays or shales."

"It is a great question as to whether capillary attraction, notwithstanding its great force, has been sufficiently widespread or continuous to be the most important factor in oil movements and accumulations."

In another work we find:

"A rock cannot be drained if it has very small pores, on account of friction, and, where gas and water are present, capillarity."

"Capillarity of the liquid gives it so firm a grip upon the surrounding small-pore rock that the gas in the large-pore reservoir cannot ordinarily force its way through. Similarly, though in a much more effective way, the lower capillarity of oil tends to retain it in the larger pores where the current is from the larger pores to the smaller."

"Immiscibility prevents the intermingling of the liquids, water and oil, which would otherwise by this means circumvent the action of capillarity already mentioned."

"Gravitational separation of oil, water and gas does not take place in porous bodies finer than a certain critical degree because of 'capillary interference.'"

"Resistance by capillarity is offered to the flow of liquids through a very fine porous medium which contains gas or an immiscible liquid."

Now in these extracts there are certain facts, clearly expressed if perhaps not fully digested; there are many suggestions that are interesting and worth consideration, and there are some mutually contradictory statements. The *tout ensemble* is confusing, and to arrive at a complete understanding of these phenomena it is necessary to consider briefly the complex subject of Surface Tension.

Capillarity or capillary attraction are useful but obsolete terms used to denote some of the best-known effects of surface tension, such as the rise or the depression of the surface of liquids in narrow or capillary open tubes partially immersed in a liquid, the rise or depression being measured from the normal surface of the liquid in the vessel.

Surface tension is a quantity that can be measured exactly per unit surface, and has been so measured for a great number of liquids. Briefly defined it may be described as a tension at the surface of anything, solid, liquid or gaseous. Properly considered, the very fact that there is a surface connotes tension.

The surface tension of a liquid as measured is the surface tension in air, *i.e.* the tension per unit area between the liquid and the vapour of the liquid in air at the temperature of the experiment. A rise in temperature reduces the surface tension; a drop in temperature increases it. The measurement of the surface tensions of solids is a more difficult matter, but the difficulties are not insuperable.

Any possible movement or rearrangement of mass that will tend to reduce the area of surface between two substances of different surface tension must take place. The rise of water in a capillary tube is due to the attempt to reduce the surface glass-air as far as possible, the surface tension between glass and air being greater than that between water and air. The rise only ceases when the potential of the weight of water raised above its true level is equal to the force of surface tension, which is proportional to the area of surface covered. Obviously therefore the finer the tube the greater the rise in level. Similarly, a drop of liquid immersed in another liquid which does not act upon it chemically, or a drop of liquid in air or gas, assumes a spherical form as giving the greatest cubical capacity with the minimum of surface.

Again, as the surface tension between a light oil and air is less than that between water and air, if a drop of light oil be allowed to fall upon a surface of water it will spread out into an infinitesimally thin film, covering the water as far as possible and thus reducing the surface over which air and water are in contact. These illustrations explain the phenomena in a very crude and unscientific way, but it is not necessary to state the mathematical formulæ involved and give the exact data on which they have been established. The principles, the decrease of certain surfaces of contact or the increase of certain other surfaces, are the points to be noted.

To apply these principles to the case of a liquid such as water or oil contained in a porous stratum is very simple. If the liquid be not sufficient in quantity to fill all the porous reservoir gravity will tend to keep it in the lower part, the upper part being occupied by the vapour of the liquid. But the porous stratum may be considered as an infinite number of vertical capillary tubes. The liquid will therefore rise in these tubes, *i.e.* in the pores of the stratum, to a height about what its normal level would be if affected by gravity alone. This height will be greater the finer the pores. In the case of an ordinary porous freestone and water the height is about three feet. Such a rise is of course contingent on the surface tension between the vapour and the solid particles of the stratum being greater than between the liquid and the solid particles.

The effect is that the level of the liquid will be raised; if this permits another heavier liquid with a greater surface tension to enter the lower part of the stratum, it is evident that in the course of time the first liquid will find its way to the upper surface of the porous reservoir, the heavier liquid gradually replacing it from beneath. In tubes the rise of the liquid due to surface tension varies inversely as the square of the radius, so it is evident that in a very fine-grained porous rock this movement due to surface tension may be of considerable importance.

In the case of crude oil a complication is introduced by the colloid nature of the liquid, and possibly of the strata also, but this will be considered below under adsorption phenomena.

But if oil and water be considered as two simple liquids, though with different specific gravities and surface tensions, it is easy to deduce what will happen when a porous stratum contains both these liquids as well as gas or air. The surface tension between water and air or gas being higher than the surface tension between oil and air or gas, the tendency will be to form a regular surface between water and oil so that the air or gas does not come in contact with the water. Thus, instead of hindering migration of oil, the effect of surface tension will be to assist it by separating oil from water. But if the surface tension between water and the particles of mineral forming the stratum is greater than the surface tension between oil and the particles the tendency will be for each particle to be surrounded by an infinitesimally thin film of oil separating the water from the mineral. Thus, in a porous rock where the pores are sufficiently large, oil and water may be inextricably intermingled under such conditions. Such a rock struck in a well will probably yield "roily oil," an emulsion very difficult to separate into its constituents, oil and water.

A similar effect will be brought about if the crude oil be a sol with a disperse phase of material with a greater surface tension than water. The water will tend to intervene between the disperse phase and the minerals of the stratum.

In very fine-grained strata, where the merest film of liquid is sufficient to fill the voids between particles, the liquid with the lower surface tension will tend to occupy all the pore space and prevent all migration of the other liquid through the stratum.

There are thus many conditions to be considered before any generalizations can be ventured upon, *e.g.* the nature of the strata must be known, and the surface tension between the various liquids and the mineral particles.

But so far as simple "capillarity" is concerned, if oil is considered as a simple liquid, the action is not one of interference but of assistance to overcome friction, and the extraction of oil from a bed is really favoured rather than hindered by the presence of water and the surface tensions of the two liquids. The flow of liquids through a porous medium may be helped by surface tension through the separation of the liquids which it brings about, as the tendency is always to reduce the surface of greatest tension.

Gravitational separation of oil and water is also assisted by surface tension, except under such conditions as are indicated above.

Surface tension is *not* more powerful than gravity, but its effects are limited by gravity, an equilibrium being established, as is done in experiments to determine the surface tensions of liquids in air, per unit area.

"Capillary attraction," which, as has been seen, is merely an effect of surface tension, takes place in any porous rock, whatever be the size of the pores: it is not only widespread but universal wherever there is a surface between two substances—solid, liquid or gaseous. So it is unnecessary to introduce complications in our ideas as to what happens underground when water, oil, and gas or air are present in a rock. But for surface tension there might be very complicated conditions to consider, but by its action everything is simplified and movements or migration of oil or water under gas-pressure, gravitation or hydrostatic pressure are rendered more easy of accomplishment.

Filtration Effects.—Any oil appearing with gas above the main oil source will probably be well filtered and to a large extent decolorized. Professor Clifford Richardson has proved that by continued filtration through clay solutions of asphalt and petroleum of any kind may be almost completely decolorized owing to the absorptive and "adsorptive" properties of the clay. The fraction "adsorbed" cannot be extracted again by treatment with solvents, and so is distinguished from that absorbed. This phenomenon is very suggestive, as similar conditions may easily be reproduced in nature.

The whole subject of such filtration and adsorption has been investigated within recent years by many scientists, and the phenomena may be said to be explained fully. The practical oilman does not require to be familiar with the theoretical aspect of the question; he knows that filtration does occur, and can detect when an oil has been filtered, and he may be content with that knowledge. But for those who desire to go deeper into the scientific reasons for such familiar facts a short account of the phenomena of adsorption will not be amiss.

It is entirely through the study of colloids, and the phenomena of colloid solution, that the facts as regards adsorption have come to light. Adsorption is a process of great importance in organic life, it is made use of practically in industry, but it is only within recent years that it has been explained. Many great scientists have studied the subject, notably Graham, Zsigmondy, Siedentopf, Hatschek, and others, and their conclusions are based upon actual and elaborate experiments which afford complete proof of many of the theories they have put forward. Perhaps the best book on the subject to give a clear, simple, and at the same time brief account of the colloid phenomena is "An Introduction to the Physics and Chemistry of Colloids" by Emil Hatschek, and the reader is referred to that work for more detailed information.

Adsorption is a surface action depending upon the surface energies of the particular materials dealt with. This has already been partially treated of above under the head of surface tension and "capillarity," and it is really the same action; it is impossible to distinguish between capillary effects and adsorption effects, both being due to the same cause. In all surface actions the greater the surface between two substances the greater the effects, and thus minutely porous substances, such as charcoal, or colloids which consist essentially of very finely divided matter, offering as they do a very large surface per unit weight or volume, are naturally more fitted to illustrate adsorption effects than matter not so constituted.

When a solution, whether crystalloid or colloid, comes in contact with matter of finely vesicular or colloid nature, and the solvent has a surface energy greatly different from that of the solid body, some effect of adsorption can always be detected. This adsorption is simply a concentration in one phase, *i.e.* the solution, at the boundary with another phase, *i.e.* the solid body. If the substance in solution has a surface energy intermediate between those of the solvent and adsorbent a concentration of the solute will take place at the boundary or surface between the two phases.

It has been suggested, and indeed almost completely proved, that the action is electrical, each particle in a colloid solution or sol and each ion in a crystalloid solution having a definite electric charge which will attract it towards the opposite charge at the boundary with the other phase. It is obvious that the effect is simpler with a colloid solution, which consists of a disperse phase of particles of a compound all with the same electrical charge, than with a crystalloid solution, which consists of ions oppositely charged.

Adsorption is decreased by a rise in temperature, which reduces the surface energy, and increased by a fall in temperature, which augments it. The whole effect of adsorption is to decrease the surface energy or tension at the boundary between two phases, and if such a decrease be possible adsorption will inevitably take place, it being impossible to decrease the area of surface.

The amount of substance adsorbed is proportional to the surface, and an equilibrium is attained when the maximum adsorption at the given temperature has taken place.

Now to apply these ascertained facts to the case of a crude oil in contact with a solid with a great area of surface for its volume or weight is very simple. The crude oil, to begin with, is probably a sol of the emulsoid order, *i.e.* it may consist of minute or ultra-microscopic particles of a very concentrated solution of certain substances dispersed in a very weak solution of the same nature. Thus an asphaltic oil for all practical purposes may be looked upon as a disperse phase of the polycyclical hydrocarbons in a continuous phase of the light oils. Suppose this oil to encounter a clay, itself a colloid, consisting of an infinite number of minute particles. The surface energy or tension at the boundary—the oil and the particles of the clay—is greater than that between the polycyclical hydrocarbon particles and the clay. There is consequently at once a concentration of the polycyclical hydrocarbons on every surface of every particle in the clay and the colloid particles of each phase will be held together by a force that can only be overcome by a great rise in temperature, *e.g.* by distillation. In fact a part of the asphaltic matter is adsorbed.

In papers dealing with the origin of oil-shale the writer has suggested that chemical action between unsaturated hydrocarbons in inspissated oil and the bases in the clay may be the cause of the intimate association of argillaceous matter and hydrocarbons that is known as oil-shale. Such action is just possible, perhaps, but it is not the *cause* of adsorption, since it has been proved that the surface concentration at the boundary between two phases, where chemical action is possible, takes place *before* any chemical action: the latter may supervene later.

The nature of the clay has to be considered; some clays have much greater adsorptive powers than others. It is found by analysis that clays rich in silica, alumina, and perhaps, ferric iron, give the greatest adsorptive effect, and clays rich in lime and magnesia the least. Now silica, alumina, and ferric hydroxide are colloids themselves, or rather can easily be brought into the colloidal state, forming stable gels also; thus the area of surface presented to a crude oil by a fine clay consisting largely of these compounds may be much greater than that presented by clays of different nature. Zsigmondy, it may be noted, gives as one of the essential characteristics of colloids that "they enter into reactions among themselves, which bear a deceptive resemblance to chemical reaction"; this is strikingly illustrated by the case of the asphaltic material in crude oil and adsorptive clays.

Where there are several different substances in solution the effect is no doubt complicated, but a selective adsorption must obviously take place, the substance that reduces the surface energy most effectively being absorbed first. Thus, if a crude oil is being forced by gas or hydrostatic pressure through a thickness of clay it may have its dissolved substances, or disperse phases, extracted one by one in order of surface energy and finally only a mixture of light oils, the almost pure continuous phase, may emerge from the "filtering" medium, the clay stratum, into a porous reservoir or at the surface of the ground. The Calgary field, with its wonderful assortment of different oils from different stratigraphical horizons, is an admirable example of the effects of such an adsorptive process.

It is unnecessary to pursue this subject further into the intricacies of physico-chemical science, but one or two points may be noted from the experience of investigators who have put our knowledge of adsorption upon a firm basis.

In the first place the chemical composition of the adsorbent is not a matter of the first importance; it is the area of surface presented that is the essential point. Thus silica, alumina, ferric hydroxide are not better adsorbents than calcium compounds on account of their chemical composition, but merely because being potential colloids they may exist in a more finely divided state. This is decidedly against the idea that any true chemical action takes place between the adsorbed component of the crude oil and the constituent minerals of the clay.

Adsorption no doubt takes place also in a sandstone, but owing to the grains being very large compared with the particles in a clay the amount absorbed, which is proportional to the surface, can only be very small compared with that absorbed by more finely divided material.

To illustrate this point consider a supposititious grain of one cubic inch in size and shape: it has a total surface of 6 square inches. Divide it into cubes of one-tenth of an inch side; the aggregate surface will now be 60 square inches. Thus when we come to cubic particles of one hundredthousandth of an inch side the aggregate area of surface will be more than 460 square yards. And the amount adsorbed is proportional to the area of surface. In Atterberg's classification of sediments sand grains are stated to be from 2 millimetres to 0·2 millimetre in size, and clay particles less than 0·002 mm., *i.e.* from one-hundredth to one-thousandth less.

Another point that must be noted is the effect of the concentration of the solution from which adsorption takes place. This is not so great as might be expected. If from a solution of a certain strength unit volume of the adsorbent removes or adsorbs a certain amount, then to ensure that double the amount is adsorbed the concentration of the solution must be quadrupled; to ensure the adsorption of treble the amount the solution must be made nine times stronger. In other words, the concentration of the solution varies as the square of the amount adsorbed.

The importance of this and other points with regard to adsorption will be seen in the chapter on oil-shales.

Probably one of the most remarkable examples of the effects of filtration is to be found in the foothills of the Rocky Mountains west of Okotoks, in what has been called the Calgary field. This field has failed to come up to the hopes and expectations of those who attempted its development, but a certain amount of oil has been struck and is being produced. All the necessary conditions for an oilfield were present, but there has not been found in any locality that has been drilled up to the present a sufficiently porous reservoir rock of sufficient thickness. A great mass of impervious shales, largely calcareous, overlie the presumed petroliferous horizons, and slightly more porous beds occur here and there in the argillaceous series. Numerous sharp corrugated folds, often accompanied by reversed faults, bring up fairly low horizons and make it possible to reach the presumed oil horizon without excessively deep drilling in several localities, but not in all. Brisk evolution of gas at the surface in one or two places indicated the probability of striking petroleum.

A number of wells were drilled on different flexures and different lines of strike to depths of about 3000 feet. All reached different stratigraphical horizons and several produced oil. But the oil varied very greatly in character according to where it was encountered. In only one or two wells was the parent oilrock reached, and but a small proportion of heavy oil—with residues up to some 40 per cent.—was obtained. But before such wells were drilled oil had been met with in several other wells. Generally speaking the further east the well and the higher in the argillaceous series the lighter the oil, always accompanied in such cases by very strong flows of wet and slightly sulphurous gas. The lightest oil, that from the famous Dingman well, was water-white or pale straw-coloured and contained 72 per cent. of petrol (including 42 per cent. of 0·68 spirit), only 6 per cent. of lubricating oil and no residue. It could be used crude in a motor-car, and gave greater power than the commercial petrol imported into the district from the United States, as the author, having tried it, can testify. But the sulphur content, though small, made this crude motor fuel unpleasant to use. It was sold for nine dollars a barrel.

Other oils, with from 45 to 25 per cent. of petrol and correspondingly higher percentages of residues, were got in different wells, and in fact a regular gradation from the heaviest to the lightest oil was proved. This interesting phenomenon is entirely due to long-continued filtration through thousands of feet of remarkably impervious strata. Only in the few slightly more porous bands was oil encountered, but gas was frequently very strong, especially accompanying or near a show of oil. In drilling some of the wells traces of absorbed or adsorbed petroleum were found throughout hundreds of feet of the shales, and such indications, often associated with gas in small quantities, encouraged prospectors to drill deeper and deeper in the hope, frequently vain, of reaching the primary oil-rock. Oil of different qualities, but not in great quantity, is now being produced from one or two wells, but the most promising localities have not been thoroughly tested yet.

Where oil is obtained from argillaceous rocks it is almost invariably light in gravity and colour, and productions are not as a rule large nor gas pressure great. The water-clear oil of Kaleh-i-Deribid in Persia (Plate V) is the most striking instance that has come within the writer's observation. This oil, which is perfectly "water-white," collects very slowly in small holes dug in the outcrop of a fine-grained, compact

Photo. by G. B. Reynolds

THE WHITE OIL SPRINGS AT KALA DERIBID, PERSIA.

Showing the steep flank of the asymmetrical anticline.

Photo. by G. B. Reynolds

THE WHITE OIL SPRINGS AT KALA DERIBID, PERSIA.

Showing the gently sloping flank of the anticline.

shale, exposed in a small stream valley. There is very little evolution of gas in this case, only a few bubbles being noticed, as compared with the brisk evolution so frequently observed from an outcrop of oilrock. The "show," though on the crest of a large and sharp asymmetrical anticline (Plate VI), is not concentrated towards the actual line of crest, but distributed for some 20 or 30 yards through the outcrop of the shale on the gently dipping flank of the flexure. This surface indication, in fact, differs essentially from the usual show of oil on an anticlinal crest; the petroleum does not seem to be forced up or carried up by gas, but collects particle by particle, just as water collects in an excavation in a water-bearing sand. The greatest yield is about four kerosine tins per day.

Close above the shales occur several outcrops of rather loosely compacted sandstone, which have all the appearance of weathered oilsands, but which, beyond traces of sulphur, contain no sign of oil. Such traces of sulphur are often the last surviving evidence (in a thoroughly lixiviated sand) of the former presence of oil which contained sulphur.

The author's theory with regard to this water-clear oil is that it is a filtered residue yielded slowly by the almost impervious argillaceous rock, that we must look for its origin in oilsands lying above the shale, and that it affords an instance of downward migration of oil, only the filtered remains of which have been preserved by the less easily weathered shale.

Filtered oils, varying in colour from water-clear to that of a well-matured brandy, which are obtained in small but payable quantities from shallow wells in the limestone of Ramri Island off the coast of Arakan, have probably a similar origin. The yield is steady and slow, the gas pressure small, while inspissation has, as in the case of Kaleh-i-Deribid, removed most of the more inflammable fractions, giving the oil a high flash-point, and enabling it to be burnt in ordinary lamps without distillation. In this case also the overlying series is petroliferous, and oilshows on a large scale with explosive discharge of gas from younger strata are not far distant, *e.g.* Faule Island.

In Baluchistan a somewhat different case of migration into older strata may be observed. The impregnation is only along joint planes and in beds of slightly greater porosity in a compact limestone, while the oil is a dark heavy residue containing sulphur and very little light oil. The shows occur on the flanks of a range of hills formed of limestone, anticlinal in structure, and overlaid by a thick series of shales. It is only at the edge of or beneath the outcrop of the shale that any appreciable production of oil has ever been obtained (*e.g.* Khatan), and the oil is very heavy, contains a large proportion of sulphur compounds, and is accompanied by warm sulphur springs. It seems perfectly clear that we are dealing with the inspissated residue of a partial impregnation which took place before denudation had laid bare the series so deeply, and that now only the all-but final results of inspissation are in evidence to indicate that impregnation of lower strata has taken place. The overlying shales are in places distinctly bituminous, and it is from their outcrop not many miles distant that a bituminous coal rich in pyrites is mined.

A more striking instance of much the same phenomenon, and one that can be more easily and completely studied, is afforded by San Fernando Hill in Trinidad. The hill is formed of an inlier of a peculiar rock called "argiline" by Messrs. Wall and Sawkins, and it forms the core of an anticline in the petroliferous Tertiaries which overlie it.

This argiline is an oceanic deposit probably pre-Andean in age, as similar deposits have been traced in Venezuela, Columbia, Panama and Ecuador, laid down in clear seas before the main Andean movement began or became conspicious; it is an exceedingly fine-grained rock and has been impregnated thoughout, and owing to its homogeneous nature and closeness of grain has been enabled to retain the impregnation under weathering influences for a considerable time. In the numerous quarries opened in this argiline, a crust usually some six to eight feet thick of the weathered material is observed, separated sharply from the part still impregnated; the line between weathered and unweathered argiline crosses the bedding obliquely in many places. At the north-eastern end of the hill sticky inspissated oil has exuded in considerable quantity, so much so that a syndicate was once formed to work it, but after doing some excavation the enterprise was abandoned as unprofitable. Similar attempts are often made to obtain oil where some such deceptive "show" has tempted men of enterprise, but without geological knowledge, to commence development work, and it is largely from such unsuccessful attempts that the popular idea of the great uncertainty of oil exploitation has arisen.

Within the last few years another test of the San Fernando anticline has been made and a well drilled at no little expense to a depth of between 2500 and 3000 feet. Needless to say the result was failure, and under competent geological advice no such well would ever have been commenced.

Another instructive example is furnished by the first well drilled by a company now operating in Trinidad. The well was commenced below the horizon of the oil-bearing rocks of the district, and, after passing at shallow depth through strata with slight indications of oil, entered a thick series of clay from which a certain quantity of gas issued. This gas assisted to puddle the clay, which caved badly, and made it rise in the bore-hole and thus cause great difficulty in the drilling. The clays at this horizon are of great thickness and only contain small, inconstant, and insignificant beds of oilsand. After struggling for months with these argillaceous strata and the gas, the well was abandoned, having reached a depth of only some 500 feet. It was probably the occurrence of gas that induced the company to persevere with the drilling, although they had been warned before the derrick was erected that the geological sequence of strata had been worked out carefully, and that the well would certainly prove a failure.

But of all examples of downward migration that the writer has had experience of the most remarkable is on the peninsula of Sante Elena in Ecuador. Here the older Tertiary strata, a petroliferous series, lie upon and are folded against a solid mass of oceanic strata of Cretaceous age. These oceanic rocks are largely siliceous, very fine-grained and not very porous, but are much fractured and jointed by the effect of the movement which has compressed the Tertiary strata into sharp folds. The Cretaceous mass forms the core of a large and irregular anticline now deeply denuded and even planed down by recent marine action and covered by a raised beach known as "tablazo." In many localities near the junction of Tertiary and Cretaceous strata the latter are found beneath the tablazo very fully impregnated with petroleum. Pits

10 or 12 feet square and 30 or 40 feet deep are dug into the Cretaceous outcrop and an inspissated oil collected, usually to the extent of five or six barrels per day from each pit. The life of each pit may be as much as three years, showing what large quantities of oil has penetrated the close-grained oceanic rock. The digging of these pits and collecting oil from them is quite a flourishing industry on a small scale.

It is to be observed that the conditions are in this case specially favourable: the region is almost rainless and the surface flat so that replacement of the oil by water is practically impossible. But Tertiary strata of greater porosity, the original oilrocks, may have lost their hydrocarbon contents to a great extent while the less pervious Cretaceous mass retains its impregnation. The oil can be seen trickling slowly from cracks and joints in the oceanic strata in the pits.

These instances are merely quoted to show of what practical importance it is that the probability of downward migration of petroleum and gas, even into almost impervious strata, should be recognized.

Another theory that is sometimes expressed regarding migration of oil is that it has been present in some particular area, but has escaped by means of faults in the strata, and so is no longer available nor can it be struck in a well. This is one of the many suggestions made about faults by those whose personal or practical acquaintance with geological work is small, but who make use of the idea of faulting as a sort of *deus ex machina* to account for something which they do not understand or have been unable to explain. It is reminiscent of an antique method in geological mapping, the observer when involved in serious difficulties boldly mapping a theoretical fault and starting afresh. In books on the subject of petroleum, when faults are mentioned the word is usually followed by the words "fissures" and "crevices." "Crevice," by the way, is a favourite word with the careless driller who has provided himself with a "fishing-job," and who lays the blame for the disaster upon a "crevice," which, suddenly entered upon, caused too great a strain to be put upon some part of his string of tools or cable.

Faults, fissures, and crevices are stated to have considerable effects upon the underground storage of petroleum by affording channels which allow the oil to escape upwards, downwards, or laterally, and to have disappeared from the rock in which it was stored.

But if oil does not disappear mysteriously *viâ* fissures to any important extent, the same cannot be said of gas, and as gas is the principal motive force in the delivery of oil towards the surface its loss by fissures may occasionally be a serious matter. As will be seen in a later chapter the gas-pressure in a porous rock is theoretically the same throughout, so any serious loss of gas by a fault-plane, along which the flow of liquid oil may be impossible, may so reduce the pressure in a field that wells may have to be pumped instead of flowing. That gas does escape along fault-lines is proved by many gas-shows, gas-wells and even mud-volcanoes, which are occasionally distributed along lines that cannot be outcrops or flexuring structures. These lines may be proved to be on or near faults even though the actual dislocation may not be visible. A fault also may enable gas to enter a porous stratum, at intervals along the outcrop of which it may make its presence apparent. Such escapes of gas, however, are usually found in localities outside the actual oil-pool: were they above actually productive strata some oil would probably be carried with the gas and might quickly close the minute fissures by becoming inspissated as it approached the surface.

Let it be admitted at once that faults do not infrequently affect oilfields either favourably or unfavourably, and have often a notable local effect in increasing production. Their effects are purely structural, and will be dealt with in a subsequent chapter on geological structure. As channels for migration of oil to any important extent they do not act, for the simple reason that a "fault-fissure," as the term is used in geological parlance, is not an open fissure in the ordinary sense of the word. Open fissures are in any case very rare in nature, and only occur in limestone formations or in hard igneous or metamorphic rocks, and then usually comparatively near the surface. Were any open fissure to be formed in soft Tertiary strata, the pressure would be sufficient to close it very rapidly, while if petroleum were to commence migrating by such a channel the fissure would soon be clogged by inspissating oil and the sand or clay brought with it. The storage of petroleum in any locality necessitates a more or less impervious cover, usually of considerable thickness, and this covering would require to be completely dislocated, a fissure opened and prevented from becoming sealed before there could be any possibility of the escape of petroleum in quantity. Where the covering is largely of soft argillaceous strata such a phenomenon is manifestly impossible. Another point also falls to be considered; even with an oil-bearing series entirely exposed at outcrop, the petroleum contents are dissipated by exudation at the surface very slowly. At the depth of some hundreds or even thousands of feet such action into a narrow open fissure could not but be very gradual.

Where one does obtain evidence of a form of migration to which the expression "intrusion" may be applied, is in veins of manjak, which term is used to include gilsonite and its congeners, and ozokerite. Manjak is to an asphaltic oil what ozokerite is to one of paraffin base. They are inspissated oil in veins which have actually been *intruded* usually in a vertical or highly inclined position from oil-bearing strata below, and the material has consolidated *without reaching the surface.* Occasionally such veins may be found along lines of fault, but all those with which the writer is familiar are either along bedding-planes or along minor slip-planes and joints in thick masses or argillaceous strata. The phenomena associated with manjak veins will be dealt with more fully later; the point to be noted at present is that if petroleum did migrate to any extent along fissures, cracks, or fault-planes, we should find abundant evidence of its having done so in veins of manjak or ozokerite. But these phenomena, though known in many parts of the world, cannot be said to be common occurrences in oilfields, while faults are frequent to a greater or less extent everywhere that earth-movement has been in operation, and there is hardly an oilfield that is without some evidence of faulting.

From all these considerations it will be seen that the migration of petroleum is a very circumscribed action, and cannot be called upon to explain any very widespread phenomena in oilfields. To put it briefly, petroleum goes where it can, but from the very nature of the conditions under which it has been formed and under which it is preserved its migrating movements are checked and hindered in almost all directions. Thus when earth-oils are discovered in any locality, we are almost justified in applying to them the famous conclusions of the gentleman who devoted his life to research upon the subject of the "fiery flying serpents in the wilderness," with special attention to their origin and subsequent history: (1) "They was there all the time," and (2) "they stayed where they was."

Subterranean Storage.—The relative porosity of strata is one of the determining factors in the movements of oil, and the selection of a reservoir rock. Oil will find the nearest available porous strata and will impregnate them. Given sufficient time and pressure it will impregnate, and even to some extent force its way through, an apparently impervious clay, but it will select the most porous stratum to impregnate. This is the reason that a gas-show, with a slight show of light and perhaps light-coloured oil, is so often struck in a well some little distance above the main oilrock. It is a filtered oil which has gradually accumulated in a porous band, after passing through the almost impervious cover of the true oil-bearing stratum. In most cases, however, it is only gas that is found under these conditions.

The importance of a good porous reservoir to contain the petroleum can hardly be exaggerated. As an illustration of this what is known as the Calgary field may be cited. That field was selected for testing upon almost purely theoretical grounds, that is to say structure, presumed presence of sufficient raw material to form oil, impervious cover, etc. The occurrence of shows of gas at the surface attracted some prospectors, but the main reasons that decided geologists to advise testing with the drill were theoretical.

Many geologists visited the field, and much was written about it before any successful results were achieved; a few observers condemned the field from the first, for various reasons. It was said, for instance, that the strata were too much "broken," *i.e.* faulted and crushed; it was said that there were no shows of oil such as any great oilfield might be expected to exhibit, and several other rather stupid ideas were promulgated against the prospects of the field. All these reasons proved in the end to be entirely wrong. The field has only failed to be a great oilfield for one reason, the lack of a good thick porous reservoir rock.

A great lateral variation has been proved. The porous sandstones of the Kootanie Group, as seen to the westward, thin out into a few small bands of calcareous sandstone eastward, and at the same time the shales of the overlying Dakota Group increase in thickness and impermeability. Consequently deeper drilling than was expected became necessary, and no great body of petroleum was discovered, though filtered oils were found at various horizons. It is true that some of the most promising localities have not yet been thoroughly tested, but it is to be feared that no great accumulation of petroleum is possible simply because there is no good reservoir to contain it. Theoretically the field is successful, and oil is being produced from one or two wells, but practically the field has proved a disappointment.

The great majority of oil-bearing rocks are arenaceous, sandstones of all kinds, grits or conglomerates, but some of the world's most famous oilrocks are limestones and dolomites. In the case of calcareous rocks it is probably merely because the limestone affords a porous reservoir that it is found impregnated with oil, just as in a manjak mine a nodule or nodular band of ferrous and lime carbonate, being slightly more porous than the surrounding clay, will contain more evidence of petroleum than the country rock. However, as the occurrence of oil in limestones has been made use of as an argument in favour of the animal-origin of petroleum, it is necessary to examine the evidence carefully. The famous Trenton limestone of North America is perhaps as good an instance as could be chosen. It contains barren areas and areas of partial impregnation, as well as areas where great productions of petroleum can be obtained, and it has been the subject of much research. It has been proved that in the localities where the rock is most productive it is cavernous in structure, containing innumerable small cavities which are often drusy, and which are found full of oil. Analysis has shown that the cavernous variety of the Trenton rock is dolomitized, the dolomitization naturally causing an increase in specific gravity, which connotes a decrease in volume, and thus causes the cavities. The rock, in fact, over wide areas, though sometimes only on selected horizons, has been formed into what may be compared to a sponge, and the oil contents vary in quantity directly with the degree of dolomitization. It is difficult, if not impossible, to imagine any chemical action which will bring about the dolomitization of a limestone and at the same time produce petroleum, and one is forced to the conclusion that the presence of the oil is accidental, and that it has occupied the cavernous limestone simply because the rock afforded room for it. Much of the impregnation, by the way, may be due to downward migration. In this connection we may bring forward confirmatory evidence from the cavernous limestones of Maidan-i-Naphtun and Marmatain in Persia. These are the oil-bearing strata from which the Anglo-Persian Oil Company is obtaining such remarkable productions, and they were first studied in detail by the writer. They are grey porous limestones, containing innumerable small cavities, generally lenticular in shape and attaining to a diameter of as much as one inch. The cavities are frequently drusy; their presence makes the rock in bulk exceedingly porous.

Careful mapping of the Maidan-i-Naphtun field proved that these are not ordinary limestones, but are of detrital origin; they vary from very coarse breccias consisting of large irregular blocks of limestone and sandstone in a calcareous matrix on the one hand, to thin calcareous sandstones and finally ordinary sandstones on the other. The thinning out of these calcareous masses, becoming sandier and occasionally more argillaceous as they thin out, is beautifully seen. Surface indications of oil occur in these strata even where they have thinned out into bands of sandstone a few feet thick, but the "shows" are greatest where the different bands coalesce into thick masses of calcareous rock. The origin of the limestone fragments, which are often most irregular, is the Cretaceo-Eocene limestone of Asmari, a very thick calcareous formation which is overlaid unconformably by the Tertiary petroliferous series.

These limestones, being of detrital origin, cannot be brought forward as evidence of the animal-origin of oil, as has been done in the case of the Trenton rock. Yet they present the same cavernous and drusy characters. Analysis to determine whether dolomitization has taken place or not has not yet been undertaken, but the rock has all the appearance of a dolomite, and the writer has little doubt about the matter: the drusy cavities certainly contain crystals of dolomite. The conclusion is obvious: the cavernous rock has become impregnated with oil, *because it is the most porous reservoir available* amidst a thick series of gypsum, shale, and mudstone beds.

At Jemsah, on the Gulf of Suez, very similar strata contain the oil-bearing beds, which are again cavernous dolomites.

Spindle Top gives another instance of a cavernous limestone or dolomite containing petroleum in quantity. In this case the impregnation is probably due to lateral migration aided by earth-movement.

It is perhaps not out of place to mention here that limestone oils frequently exhibit some differences from sandstone oils, and though those differences may not be essential, they may be of considerable practical importance. Thus many limestone oils are noted for the percentage of sulphur which they contain; their outcrops are often marked by sulphur springs and evolution of hydrogen sulphide, while crystals of pure sulphur may be found lining cavities in the oilrock. Spindle Top, Marmatain, and Maidan-i-Naphtun in Persia, and Khatan, Spintangi and Kirta in Baluchistan are instances. In these cases there is reason to believe that the sulphur compounds may not be entirely original in the petroleum, but may be due to the action of the oil and water on sulphides contained in the strata. In oilsands and their associated clays, pyrites and marcasite are not uncommon, but in the limestones of the above mentioned oilfields these minerals are apparently absent. It is possible that the petroleum may have absorbed and incorporated sulphur compounds encountered during its migration to and through the limestone which it now occupies. In the cases of Khatan and Spintangi the shales where the oil originated are full of pyrites in the area where the carbonaceous phase is in evidence, and the Harnai Valley Coal, as the bituminous coal worked in these shales is called, contains a large quantity of pyrites. This is absent at Khatan, but sulphur compounds are present in the oil, and sulphurous springs appear every here and there from beneath the outcrop of the shales.

Parallel evidence can be obtained within the confines of Great Britain; in the west of England where the Carboniferous limestone becomes slightly bituminous in some localities, the fœtid odour of a fresh fracture gives unmistakable evidence of the presence of hydrogen sulphide.

It is not suggested that sandstone oils do not contain sulphur compounds, many of them are unfortunately very rich in this, in oil, undesirable element, but there seems to be some condition affecting oils enclosed in limestone which makes it possible to decompose any sulphides present and to incorporate a percentage of the sulphur in the oil, which percentage naturally becomes more conspicuous as the sulphur compounds are concentrated by the inspissation of the petroleum.

In connection with this an interesting speculation is suggested by information supplied to the writer by Mr. W. A. Guthrie. Asphalt may be formed by heating paraffin wax with sulphur. This may indicate the lines on which to seek an explanation of the fact that it is asphaltic oils rather than oils of paraffin base that are most commonly sulphurous. It is not suggested that such a process as heating in the presence of sulphur could be possible in nature, seeing that petroleum must be formed at a fairly low temperature, but if the raw material from which oil is formed contains sulphur in quantity the series of compounds that finally form asphalt by polymerization may be more readily formed than those that characterize an oil of paraffin base. This is the more probable, as it is the olefines and unsaturated hydrocarbons generally from which the polycyclical hydrocarbons forming asphalt are built up, and sulphur to enter into combination with a hydrocarbon must either replace its equivalent in a saturated hydrocarbon or combine directly with an unsaturated, thus satisfying the carbon valency. It is suggested that the sulphur being present in some combination determines the formation of such compounds as require the sulphur to saturate them.

In a limestone the sulphur compounds may be unable to attack the lime, and so are confined to the hydrocarbons, while in a sandstone or shale there is usually sufficient iron present to form pyrites with any sulphur that may be available.

Pyrites is frequently associated with oil-bearing strata of clay and sandstone.

Further research is necessary upon this point, but the suggestion of the effect of environment on the oil after its formation is made here, as it may be of practical utility. The same oil that impregnates a limestone in one locality, where it is associated with abundant evidence of the presence of sulphur, may be found in a locality not far distant impregnating a sandstone, and containing a smaller percentage of sulphur compounds and consequently being of higher quality and better value.

It is to sandstones, however, that we owe our principal supplies of petroleum, and almost every variety of sandstone may be found acting as an oil reservoir.

Here one of the popular ideas of the driller may be summarily dealt with. In oilfield work one is frequently informed that there are oilsands, gas-sands, and water-sands, and that they have essential and different characteristics, while some informants will even go so far as to state that they can tell by examination of a clean sample of sand to which of these three classes it belongs. These are men often of acute observation, and they may be perfectly right for a particular field, or in a particular locality, but to generalize, in one or even several oilfields from the evidence, and to expect the generalizations to prove true of another field, perhaps in a different country, is notoriously dangerous. True, in one field the oil-bearing horizons may be composed of a certain kind of sand of characteristic coarseness, colour, contour of grain, and porosity, while gas or water may be found in the same locality in arenaceous strata of different types, but a sand may change almost entirely in character within the space of a few hundred yards, and yet remain none the less an oilsand, gas-sand, or water-sand as the case may be, Proceeding down the flank of an anticlinal flexure, or down the pitch of a dome structure, what was the oilsand near the crest may be found destitute of oil and full of water.

Again, some sandstones, especially those with calcareous cement, may be so compact as to be hardly capable of containing appreciable quantities of oil, but may contain gas. But when one considers the conditions under which such sands have been deposited, it becomes obvious that the calcareous cement may vary in quantity in different localities, and the porosity of the rock may vary as much. Thus the same sandbed may be rich in oil at a comparatively short distance from where it was merely a gas-sand. A low-lying shore, such as may be seen on the eastern coast of Trinidad, is an object lesson in arenaceous deposition. There every gradation from a shell-bed, formed almost entirely of fragments of broken shells, to a pure siliceous sand, a muddy sand or a sand containing vegetable matter, which will eventually be a carbonaceous sand, may be seen accumulating under the action of waves and tides. Each variety will differ from the others in size and contour of grain, chemical composition and porosity, and all are being formed simultaneously within a distance of, perhaps, less than a mile of coastline.

It cannot be too clearly stated and understood that *an oilsand is a sand containing oil, a gas-sand one containing gas, and a water-sand one containing water*. Remove the contents, and they are no longer entitled to the names, though they may still be mapped geologically and designated as the horizons of such and such oil-, gas-, or water-sands.

Contour of Grain.—On the subject of the contour or shape of the grains in an oilsand there has been some confusion of opinion. Mr. A. Beeby Thompson in his book on the "Oil-fields of Russia" gives microphotographs of sands from Baku oilwells, calling attention to their fairly well-rounded character, on the strength of which he suggests that they are wind-blown. On the other hand, Professor Clifford Richardson in his book on "The Modern Asphalt Pavement" gives microphotographs of the sand extracted from the asphalt of Trinidad's famous Pitch Lake and washed, calling attention to the sharpness of the grains, on the strength of which he suggests that the silica has been deposited from solution. Now the sand grains in Trinidad asphalte from the Pitch Lake are derived, as is the bitumen, from the La Brea oil-bearing group, on the outcrop of which that great asphalt deposit has been formed. Here then are two authorities who have examined the silica grains from different asphaltic oilsands, one calling special attention to the roundness of grain, and the other to the sharpness. This is quite sufficient to prove that oilsands differ considerably in the matter of the shape and contour of grains, but in this particular case the writer is unable to agree with either Mr. A. Beeby Thompson or Professor Clifford Richardson on the evidence which they have brought forward and figured. The Baku sands are neither so well rounded nor so evenly graded as typical wind-blown sands; it is more probable that any special degree of smoothing or rounding which these grains exhibit is due to the attrition they must necessarily have experienced in the well before being brought to the surface. In a flowing oilwell, where sand is brought up with the oil, there must be a great churning up of the siliceous material, quite sufficient to add a polish to the grains. Mr. Thompson's further suggestion that the sharpness of these grains may have caused an epidemic and rapidly fatal disease among shoals of supposititious fish, the carcases of which provided the raw material for the formation of petroleum, hardly bears out his contention as to the sands being wind-blown.

In the case of the La Brea oilsand, the grains are certainly neither so sharp nor so distinctly broken fragments of crystals as to suggest deposition from solution. It is a very ordinary water-borne sand.

There is, however, no reason why wind-blown sands or any other kind of sand should not become impregnated with oil: any porous rock will serve.

Porosity.—Porosities naturally vary very greatly in oil-bearing strata, and as it is on the thickness of an oilrock and its porosity that production ultimately depends, the subject is worthy of careful study.

If all the grains in a sand were spherical and of the same size and packed together in the best possible manner, so that each sphere touched twelve others, the voids in the rock would amount to 26 per cent. of its volume. This is of course an ideal case, and with smaller grains present and cementing material, not to mention the irregularity in the shape of grains, it is not to be expected that such a porosity is normal. But with irregularity in size and shape of grains there is always a possibility of greater porosity under normal conditions of pressure, so that if we take 15 to 20 per cent. of voids as representing the average accommodation for oil in a freestone or sandstone without calcareous or other cement we cannot be very wide of the mark.

It is said that only a certain proportion of the oil in a rock can be extracted by drilling: some authorities put it as low as 75 or 80 per cent. This, however, depends largely upon the nature of the oil and the oil rock and on the presence or absence of water. With a rock formed of such material that it is unable to adsorb anything more than a minute fraction of the heavier constituents of petroloum, *i.e.* a rock presenting a low area of surface per unit weight, with a fluid oil of low specific gravity and with water entering as the oil is removed, the extraction may be almost complete. With a rock containing colloid material, the extraction is naturally smaller, and if water be not at hand to replace the petroleum the yield of oil may fall far below the calculated percentage. Thus in argillaceous strata, even if they contain high percentages of oil, production must necessarily be small and slow.

The voids in a rock may be as much as 40 per cent. by volume, but that is exceptional and unlikely to be met with. Percentages of 20 and 25 of voids, however, are not by any means rare occurrences in sands, and given that the voids are completely filled with oil, a prolific production may be expected. Too porous an oilsand has its disadvantages, since on being struck in a well the cohesion of the stratum is liable to be completely broken down, and quantities of sand brought up with the oil. This may cause choking of the casing, the wearing away of flow-heads and caps put on to check or control the flow, and in extreme cases the derrick may even be half buried in sand.

In Baku the quantity of sand brought up by flowing wells has been a cause of great trouble and expense, and in California and Trinidad similar difficulties have been encountered. The oilsands of the latter colony have been analyzed by Professor Carmody, Government Analyst and Director of the Agricultural Department, samples being taken from outcrop for the purpose. Percentages *by weight* of from 15 to 18 of inspissated petroleum have been recorded from outcrops of the Rio Blanco oilsand. By volume this would mean nearly three times as much, so it may readily be understood that in some cases the surface of the outcrop actually shows signs of flow. Strata in this case cannot be broken by a hammer, being too soft, but small fragments can be twisted off in the fingers and rolled into pellets. Where the oil is not inspissated the percentage both by volume and weight will not be so high, but it is evident that strata so rich in oil will break down easily when struck in a well. The experience of those companies who have drilled into the Rio Blanco oilsands is that sand is always tending to fill up part of the casing, and the wells must be constantly cleaned if their production is to be maintained.

This "sanding-up" of a well when the gas pressure is great, and the flow of oil correspondingly rapid, is a more serious matter than it may at first appear. Where the oil-rock is so fully impregnated and so lacking in cementing material that it breaks down under release of pressure and the sand is carried up the bore by the flow of oil, a cavity is often formed at the bottom of the well. After successive cleanings of the bore and consequent flows, each ending in a sanding up, possibly of some hundreds of feet of the casing, the cavity may become so large that the strata above the oilsand, especially if of soft argillaceous material and not a hard cap-rock, collapse into the open space and restrict or stop the flow. Shooting the well with a charge of nitroglycerine may temporarily remove the obstruction, but as the casing has first to be withdrawn such drastic methods may only increase the cavity and bring down more of the impervious covering rock. In fact, in soft strata, such as are frequently encountered in a Tertiary Series, torpedoing a well is seldom of much benefit. A complete collapse of the covering may seal the bore entirely and no further production may be obtained. To guard a well subject to violent flows against such collapses it may be necessary to restrict the flow by throttling the well down to keep a high pressure on the sands, permitting flow only through a one-inch or half-inch pipe. In limestones and hard strata such methods are unnecessary.

The La Brea oilsands, the youngest oil-bearing rocks of Trinidad, also contain a very large percentage of petroleum, and it does not require the experience of drilling near the Pitch Lake to prove that the cohesion of the rock is very easily broken down; the Lake itself is sufficient evidence. The winning of oil from wells drilled to this oil-bearing group will always be subject to great difficulties on account of clogging of the casing by heavy oil and sand, and the wells will require constant cleaning out.

The most satisfactory oilsands are those which are sufficiently compact to maintain their cohesion even when the well is flowing. The greatest productions are not obtained from such sands, but wells drilled into them have a longer life and are worked much more economically.

Paraffin oils, perhaps because they are as a rule of lighter gravity than asphaltic oils, seem to disengage themselves more easily from the sands, and do not, as a rule, carry so much sand with them. This, however, may be partly due to incipient paraffination, the deposit of paraffin scale in the sand helping to maintain the cohesion of the rock. The sudden relief of pressure and consequent lowering of temperature when a prolific well is brought in in a paraffin-base oilsand must cause solid paraffin to be deposited. If a well in such circumstances be not carefully looked after, its life may be shortened considerably by the sand near the bottom of the bore-hole becoming completely clogged with solid paraffin.

The great advantage that limestone has over sandstones as an oil reservoir is that it does not break down and choke the bore-hole, and another advantage of almost equal importance is that it is possible to torpedo a limestone well, the production of which has fallen off badly, by exploding a charge of nitroglycerine at the bottom of the bore. This usually results in giving the well a new lease of life. It is seldom of any use to torpedo a well in sandstone, even if the rock be fairly hard.

The effect of earth-movements upon the porosity of strata has frequently been alluded to by writers on the subject of petroleum, possibly with the idea of pointing to the connection of accumulations of oil with particular structures. It is pointed out that during earth-movements the strata must be subjected to great pressure, and that this pressure may have affected the porosity by compressing the rocks is apparently indicated.

Also in actual folding of a mass of sedimentary material, if the mass be held so firmly that differential movement between beds is prevented, it is held that the crestal area on an anticline will be stretched in that part nearest to the surface and compressed in that part deeply buried.

A little consideration, however, will show that such effects can never be of any considerable magnitude. Strata under great and long-continued stress are relieved by flexuring, minute shearing or differential movement takes place between the beds, just as when a book is folded a shear-plane develops between each leaf, and the final result upon any specimen of a porous rock taken from a folded bed must obviously be infinitesimal.

Recently a writer upon the subject of petroleum has advanced a diametrically opposite theory, viz. that pressure, and especially crushing pressure, upon a sandstone must *increase* the porosity, and that in fact any force tending to deform a sand or sandstone enlarges the voids with respect to the whole mass, *i.e.* increases the size of the mass. The author somewhat naïvely attempts to support this ingenious view by a homely illustration. In walking over damp sand on the seashore it is observed that as each foot is put down and presses on the sand a dry patch spreads outwards from around the foot. This he attributes to the pressure of the foot having disturbed the sand grains and thus increased the voids between them so that the voids have been increased, and the same quantity of water is absorbed in a less bulk of sand, thus draining a superficial area on the surface round the centre of pressure.

It is hardly necessary to point out that the action is entirely different. The damp sand contains air as well as water. The sand is slightly depressed by the weight of the observer, and there is a corresponding rise in the area surrounding the actual footmark. Water drains into the depressed area under the foot and at the same time air is driven outwards into the relatively raised area.

But considering the subject seriously from a scientific point of view, it is obvious that porosity cannot be increased by pressure. Take a volume of sand or sandstone containing a percentage of voids, and put pressure upon it. It is obvious that the sand grains themselves cannot be increased in bulk. But if the voids be increased without the sand grains being affected, the volume of the sand or sandstone must be increased. If pressure can increase volume, where is such action going to cease? It is a very simple *reductio ad absurdum*.

It is true that if every sand grain were of equal size and each was perfectly spherical and packed in the closest manner, a shearing stress pushing each grain into a different relation to its neighbours would increase the percentage of voids. But no one who has ever examined sand or sandstone under the microscope could postulate such ideal conditions.

The late H. C. Sorby's work on cleavage and the effect of pressure upon strata of different natures is sufficient to disprove any theory of the increase of porosity by pressure.

But to show how little these simple physical facts are understood, the same author may be quoted where he states that in the proximity to a fault the porosity has been observed to decrease from 25·50 per cent. to 14·8 per cent. while "*the specific gravity and composition of the rocks remained practically the same.*" But for this useful word "practically" we might claim that the age of miracles had not yet ceased.

There are, of course, many and frequent changes in the porosity of the same bed when it is traced for any distance; of these the change in the amount of cementing material is probably the most important, and the next is the change in the size of grain. Near a fault infiltration by cementing material may increase considerably. But if one considers, say, a cubic foot of porous rock, and the forces that must act upon it to produce physical deformation even when it is involved in sharp and unbroken folding, it will be seen that except in flexures that can actually be comprised within the sample of rock considered the physical effect can only be infinitesimal. Movement takes place along bedding-planes, allowing differential movement between different beds, but very little rearrangement of constituent particles is possible. Hence, all theories that depend upon changes in porosity occasioned by movements, short of actual metamorphism, have little or no basis in observed physical fact, and need not be given any weight in the discussion of such practical questions as oil-content and production.

Oil occurs not infrequently in shales and clays where they have some degree of porosity, but the yield of wells drilled into such strata is always small and the petroleum accumulates very slowly. The oil is naturally well filtered and light in such conditions, but production is seldom sufficient to ensure a commercial success. In Java wells have been drilled into oil-bearing shales, yielding an excellent oil, but not in sufficient quantity.

There is some evidence suggesting that an oil may, under certain conditions, prepare its own reservoir by the removal in solution of cementing material in a rock. This probably applies only in the case of calcareous cement, and may take place only within the zone of weathering, but as that zone may extend downwards for some hundreds of feet, the results might be important.

On the southern coast of Trinidad there are many sections where the cliffs have been cut back by marine denudation, leaving a very gentle slope of clays usually much land-slipped —a plan, in fact, of former landslips. The strata dip steeply, and contain numerous thin beds of calcareous sandstone which stand out in lines above the clay surface, but are often discontinuous.

These sections, though washed twice a day by the tide, reek with the odour of petroleum, and a close examination shows that similar small reefs of brown oilsand are contained in the clay. These oilsands are seldom more than a foot or two thick, and they resemble the calcareous sandstone reefs in every way, except that they contain little or no lime, and are very much softer and consequently less prominent. They are quite full of petroleum, which exudes steadily and slowly, forming films upon the pools of water left by the receding tide. The oil is light, and is accompanied by very little gas.

Washed about on the shore, and sometimes embedded in the clays near the small reefs of sandstone, are large botryoidal masses of calcium carbonate. These masses are dark in colour owing to the inclusion of a proportion of clay, but the calcite is well crystallized, the crystals radiating from the centre of each rounded mass. These botryoidal masses are quite different from the ordinary fine-grained calcareous concretions of the clay. They occur in many parts of the island, but always near the outcrops of oil-bearing strata. Unfortunately, they are generally found loose, washed out of the clay.

In one locality near Galfa Point in the Cedros district, a bed of sandstone some six feet thick is exposed among clays on the foreshore. Part of it is hard and calcareous, and part comparatively soft, brown in colour, and highly petroliferous. In the calcareous portion petroleum is only seen along joints and bedding planes. The calcareous cement does not occur like a concretionary mass, but is quite irregular in outline and appears as if it had been attacked and eaten into by the petroliferous portion of the rock. Botryoidal masses of calcite are present close at hand, washed out of the clay series.

The suggestion is made that these botryoidal masses represent calcite that has been dissolved out of the sandstone and has crystallized out in the softer clay, thus leaving room for the oil to impregnate the sandstone beds. In the zone of weathering, carbon dioxide and water might be present in sufficient quantity to attack a calcareous cement, but the action must have taken place beneath the surface to allow the dissolved calcite to concentrate under concretionary action and crystallize out.

What part the petroleum and its accompanying gases can have taken in such an action it is difficult to determine; with the help of water they may have supplied the corrosive solution. The point to be noted is that these phenomena have only been observed where oil-bearing strata are present. Further study of such evidence may throw light upon the movements and storage of oil and especially upon the effect of oil and water in combination upon limestones, and may help to explain the selection of beds to form oil reservoirs, even when they are surrounded with almost impervious strata.

There are many minor points with regard to the underground storage of petroleum which might be cited, but all depend upon the principles already laid down, the selection of the most porous or potentially most porous stratum available. The migration through practically impervious beds must be very gradual, but, given sufficient pressure, it is sure, though it is probably only the lighter constituents of the mixed hydrocarbons that are able to migrate for any considerable distance.

CHAPTER IV

LATERAL VARIATION

HAVING now considered most of the more important theoretical questions concerned with the formation, migration and storage of petroleum, let us turn to the more practical matters of how oilfields are to be found, and how we can make as sure of them as possible. In the next five chapters facts as discovered and studied in the field will be considered, and theory as far as possible eschewed, while methods of approaching the various problems which have been found of value by the writer will be discussed.

The geologist whose task it is to prospect a new country, or a new area in a well-known country, for petroleum, will do well to prepare himself by the collection of as many previously known facts as he can find bearing upon the particular area, and by *the deliberate abstention from reading any opinions, generalizations, or theoretical matter* that have been published about it. By this the intention is not to cast aspersions upon any work done previously by explorers, geological surveyors, or travellers with a taste for science, but simply to enable the "field-student" to start work with a perfectly open mind. The line between opinion and fact must be drawn rigidly. There are very few countries nowadays which are not, at least partially, known geologically, and geological surveys, even if only of a pioneer type, have done much excellent and sometimes even detailed work in many parts of the world; but the generalizations into which the pioneer geologist is inevitably tempted are dangerous things, and lest they should impress, oppress, or antagonize his mind, the field-student will do well to know nothing about them. Ready-made generalizations fit the facts no better than ready-made coats fit the body; they are the bane of original work, and unless the observer can improve upon what has been done before, and can see a little deeper into the geological puzzles that await him than has been done by previous workers, he is unworthy of his task.

It is unfortunately not every scientific writer who is content to state the facts he has discovered, or has compiled from the work of others, first, leaving conclusions to be drawn and theories to be promulgated to a later section of his book or report. Explanations, suggestions, references to apparently analogous cases and even full-fledged hypotheses are often so mixed up with statements of fact that it is almost impossible to separate them, and a pet theory may, so to speak, be smuggled thus into a position to which it is hardly entitled and may be passed and accepted by the reader without critical examination. Truth to tell, it is almost impossible to arrange or marshal facts without some kind of theory, hinted at if not expressed. Even Government publications are not always free from this defect, and the theory suggested by inference is perhaps the most insidious form in which an attempt to influence opinion can be presented.

To get at recorded facts, however, without absorbing opinions is a matter of difficulty, but for this reason the writer would emphasize all the more the necessity of an open mind. After field-work has been done, new facts collected and correlated, new areas mapped, then comes the time for reading, for testing theories and opinions in the light of new discoveries, and one's own theories in the light of how such or similar facts appeared to trend in the minds of others.

Let a small-scale geographical map of the country be procured (if there be such a thing as a geological map it will also be necessary), and let the prospector sit down before them and study them, noting roughly on each such essential facts as the ascertained or reported occurrences of surface indications of oil. If only an unknown or unprospected district of a country is to be examined, a map of the said district will *not* suffice; a map of the whole country, perhaps with portions of neighbouring countries, is essential. The "field-student," as the writer prefers to call one who reads the rock rather than the printed page, who travels through countries rather than reference libraries, is now in search of a few general ideas.

What if they prove wrong? It is no matter; they will be tested in the field.

The orientations and extents of the principal mountain ranges, the courses of the main rivers, and the character and configuration of the coastline, if any, are naturally the first points to be noted. The first of these will probably give a very clear indication of the directions of the principal earth-movements to which the area has been subjected, or at least will show that one of two directions at 180 degrees is the main direction of the principal or latest movement.

The courses of the rivers can as a rule be divided into "consequent" and "subsequent" portions, and will thus in connection with the mountain chains afford considerable assistance in determining roughly the main strike-lines of the country.

A study of the coastline should indicate what parts are rocky and what parts flat and low-lying, and the presence of any delta of considerable size will be detected at once.

If the oilfields to be searched for or examined are in Tertiary strata, the methods of arriving at general ideas are simple, as it is only the latest earth-movements that have to be considered. If series older than the Tertiaries are to be examined the inquiry becomes more complicated, and it may not be possible to arrive at any general ideas of importance by a preliminary study of the map, unless some geological data are available. Most of the world's great oilfields, however, are in Tertiary strata, and of oilfields yet to be discovered in such countries as Galicia, Rumania, Russia, Egypt, Turkey, Persia, Baluchistan, India, China, Venezuela, Colombia, Brazil, Argentina, and Mexico, we may safely assume that very few, if any, will be in rocks older than the Cretaceous formation; so for the present let us consider that a Tertiary Series is to be prospected.

Some general ideas as to the probable main structural lines of the country having been obtained from the map, and the approximate positions of known and reported indications of oil noted on it, the prospector must ask himself why the oil is found in such localities and how it got there. These queries may take long to answer, or to obtain any light upon; when they have been answered, the prospector will be in a position to determine where else petroleum is likely to be found. The reason for considering such queries and attempting to find answers to them is that the general question of the occurrence of petroleum should not be lost sight of when practical field work is begun. To search for favourable structures in areas which are apparently outside the belt of country in which it is possible to find oil in paying quantity is not only a waste of time from the practical point of view, but, if experimental wells be drilled as the result of the prospecting work, other instances will be added to the long list of failures which have made the general public look upon oilfield work as on much the same level, in regard to risk, as gold mining.

The prospector is now ready to familiarize himself with the lithological characters of the rock with which he has to deal. For this purpose several lengthy traverses across the main strike-lines of the country are necessary, and also, if possible, one or more roughly along the strike. The object is not only to study the series as a whole, but to determine, if possible, the direction or directions of lateral variation.

This is primarily a more important matter than the study of structure, and accordingly it is considered first. In the author's experience are only too many instances of the following of structure in oil development work, while the lateral variation in the strata was neglected or lost sight of.

In many cases the working out of the directions of variation in the field may be a laborious task, necessitating the determination of the stratigraphical relations of different groups, but in some cases a clue may be furnished at once from the preliminary study of the map. There may be a great river in the country with a well-marked delta, and the evidence may point to this river having been represented in Tertiary times, while the ascertained main directions of earth-movement, or earth-waves, may indicate in what direction, laterally or otherwise, the course of the river has probably been changed between Tertiary times and the present day. In Persia, Burma, and Baluchistan, this method of approaching the subject proved of great value.

Deltaic Conditions.—If deltaic or estuarine conditions on a large scale can be proved to have occurred during the Tertiary Series in question, rapid and remarkable variations both along and across the main strike-lines are almost certain to be revealed. The field-student must look for constantly alternating types of deposit, *e.g.* shales or clays alternating with sands. Beds of undoubtedly marine origin, fine clays, marls and true limestones, must be differentiated from littoral or deltaic deposits. In every case when examining a bed the geologist must consider under what conditions it has been formed. The only satisfactory method of arriving at a conclusion on such a point is to consider under what conditions he has seen similar beds being formed at the present day, and failing such direct evidence from his own experience, he must consider under what possible conditions could such a bed be formed. In such an inquiry there is no piece of evidence that is too insignificant to note down. It may be that long afterwards much importance is found to attach to items of information jotted down in note-books, or better still on the field maps, items which at the time seemed to be entirely insignificant details. The presence of gypsum or selenite in the clays, of glauconite in the sands or argillaceous sands, and of remains of terrestrial vegetation in any bed, must always be noted. These all point to estuarine or deltaic conditions.

In a general way the main directions of lateral variation may be indicated from the very start by the records of former observers, *e.g.* the presence of thick clays or limestones in one district, and of coals or lignites in the same series in another, at once suggests that some variation may be expected in such and such a direction, even though the horizons of the particular deposits have not been ascertained.

In the deltas of great rivers, channels are continually changing their courses, so that sand-bearing currents trespass upon mud-flats, and the coarser and more arenaceous detritus thus alternates with the finer and more argillaceous. Sand-bars are continually being formed between sea and delta, cutting off lagoons or salt swamps. These sand-bars also are subject to sudden modifications through the action of tides and currents: they may be extended and increased, pushed forward or thrown back, cut off to form shoals or completely swept away. And with them the fate of the lagoons which they protect is inseparably bound up. They may be filled up with detritus to form solid ground, or may pass through a stage of mangrove swamp to become a forest-lagoon, a forest growing at or even under sea-level, where terrestrial vegetation flourishes, dies and accumulates in masses which, under favourable conditions, will in time be represented by coal or lignite seams or petroleum. Any slight set-back in deposition, any temporary gain of subsidence against sedimentation, and the lagoon will be invaded by the sea, the vegetation killed, though perhaps not washed away, and marine sediments may be deposited above the remains of forest or swamp growth.

Speaking generally, however, a delta is always advancing in one direction, in spite of the many deflections of the main river-channels. A delta in fact means a victory of sedimentation over subsidence, and in any area where deltaic conditions can be proved to have existed for a long period, littoral sediment will be found to have advanced over more purely marine or pelagic deposits. Set-backs no doubt frequently occur, owing to periods of more rapid subsidence, but a delta stands for continuous deposition, and till checked by a movement of upheaval which is sufficient to enable the river to denude its own deposits, or by the encounter with powerful ocean currents, it must continue to advance.

The Nile delta, the most famous and the actual origin of the word, gives very clear evidence of advance in the face of adverse conditions. It has advanced in spite of subsidence at its mouth. The whole Ægean Sea and neighbouring waters have deepened within the latest phase of the Tertiary and the Quaternary periods, and are probably deepening still, and land surfaces in Egypt have been affected also and have tilted northward. Flanking the delta to the westward of Alexandria there are strips of ground parallel to the coast and occasionally large areas that are below sea-level. They are separated from the sea by a succession of ridges, dunes and sandbanks, drifted along by wind and currents from the westward. Oolitic limestone grains are conspicuous in some of these sandbanks and the formation of such grains is apparently still proceeding. But for the advance of the delta these depressed areas could never have been cut off from the sea and desiccated. It is evident, therefore, that the quantity of sediment brought down by the Nile has been sufficient to enable the delta to advance against a tilting earth-movement. Borings through the Nile alluvium into marine deposits below confirm this interesting fact. The delta is probably neither advancing nor retreating at present, as currents off the mouths carry away the sediment rapidly.

In such circumstances it is obvious that rapid lateral variation must occur somewhere at every horizon. In some cases the variation is very remarkable. The Tertiary Series in Trinidad, formed as it is largely of fluviatile, deltaic, and estuarine deposits at the mouth of a great river, which is now represented by the Orinoco, affords some very striking instances. The island is situated on the margin of a continent with the deep Atlantic basin not far to the eastward, and the strata in the Tertiary Series represent a continual struggle between pelagic and deltaic strata, with the latter gradually becoming predominant, and variation on the same horizon is remarkably well shown. Thus near the Cunapo lignite field it is possible to pass on the same line of strike from a lignite seam through conglomerates and sands representing a littoral deposit into muds, fine clays, and finally a marine limestone within a distance of three or four miles. The lateral variation in that island is very complicated, and has not been fully worked out on all horizons as yet, but it seems to have been lost sight of by many of the energetic oil-prospectors who have visited the colony.

In examining a deltaic formation, then, variation in almost every direction may be observed locally, but the algebraic sum of all variations, supposing it were possible to measure these effects, would point to some general direction.

The concrete bits of evidence to be looked for are the splitting up and thinning out of sandstone beds, the decrease in coarseness of arenaceous sediment, the passage of sandstones into thin calcareous sandstones among argillaceous rocks or finely laminated alternations of sand and clay, the oncoming of finely laminated clays without gypsum, and the directions in which they thicken. Similarly the development and thickening of beds of calcareous marl, whether foraminiferal or not, and the first signs of true limestone bands must be noted. A shell-bank, formed of a mass of broken shells on a shore-line, must not be considered as a limestone, even though it may be composed almost entirely of carbonate of lime; it has been formed in the same manner as a littoral sand. Again, the thinning and splitting up of lignite seams among banks of sand and conglomerate, which were the bars between sea and lagoon, the passage of such seams into carbonaceous sands or clays, and the passage of shales into underclays and leaf beds, are of great importance. All these phenomena, if observed carefully, will give definite information as to which side the land lay and which side was open sea.

All evidence of shallow-water conditions or sub-aerial conditions, such as false bedding, ripple mark, sun-cracks, rain-pittings on fine sands and clays, and in some countries deposits of lateritic type, which were weathered and oxidized at the time of formation and represent what were at one time land-surfaces, are of value.

The directions of currents can frequently be made out from the arrangement of the longer axes of the pebbles in a conglomerate, and especially in clay-gall beds, and what have been called "clay conglomerates," which consist of pebbles of more or less soft argillaceous beds in a sandy matrix. This type of deposit is caused by a sand-bearing current impinging upon a partially consolidated clay or mud deposit and breaking up the bed, rolling the fragments into pebbles, and often bending the pebbles so formed. They pass, by the gradual decrease in the size of the argillaceous fragments, into sandy clays. Beautiful examples of this type of deposit can be seen on the western coast of Trinidad, and may be photographed in cliff sections, where the actual initial bending up and breaking of the argillaceous bed is sometimes observed, the current action having been checked exactly at this stage. In Burma also, and in Persia, where the detrital limestones have thinned out and become muddy and sandy, bands formed in this manner are to be seen.

A clay conglomerate indicates periodical desiccation. In desert country subject to occasional flooding in the watercourses the formation of such deposits is illustrated very clearly. For instance, in the deserts of Sinai there are numerous broad wadis, the continuation of stream valleys in the mountains. During storms these wadis may be suddenly flooded for a short time, possibly only an hour or two, and the flood water spreads over large areas, though it may never reach the coast some miles distant. A turbid flood spreads over the floors of the wadis carrying sand and stones of large size; as it subsides only fine argillaceous sediment is carried, and it finally settles in pools and along the lowest parts of the swept-out channels. In a few days the films of mud thus formed may be dried, forming a cake of mud as much as a quarter of an inch in thickness. Under the sun's rays the mud cracks and curls up and the flakes may be blown about by the wind and possibly embedded in blown sand. When the next flood comes the curved flakes of dried mud may be incorporated in a sandy deposit formed by the flood water, and this deposit if not again denuded will be a clay-conglomerate such as described above. Thus when we find such deposits we may deduce that alternate desiccation and flooding have been in operation during the deposition of the series, and shallow-water or even fluviatile conditions are indicated.

Finally, fossil evidence must be studied in connection with these variations, but the fossils must not be taken from the mixed faunas formed in littoral beds, where specimens from littoral, laminarian, and pelagic zones are washed about on the beach together, but from the actual deposits in which or on which the organisms lived. Oyster beds, for instance, may be noted as important; foraminiferal beds, thick clays containing lamellibranchs with joined and closed valves and gasteropods in perfect preservation, and assemblages of fresh and brackish water forms are all of help in determining directions of variation.

In well-exposed sections on river banks, sea cliffs, road or railway cuttings, and, if the ground be not too much obscured by vegetation, in any hilly ground, it is possible to study all these phenomena and to derive from each some link in the chain of evidence as to the sides on which sea and shore respectively lay while the deposits were being formed.

When this study is extended over wide areas and over many horizons in a thick series, the course of a delta can be made out with considerable accuracy at each successive epoch, and it can be shown to have pushed forward its littoral sediment, now rapidly, now slowly, with recurring intervals of retreat, and with perhaps slightly diverging directions at different times, but over all with a steady inevitable advance over the more characteristic marine sediments with which it was contemporaneous.

The Pegu Series of Burma, ranging from the Eocene far up into the Miocene according to our subdivisions of Tertiary time, furnishes perhaps the most conclusive evidence of the advance of a delta that has been worked out in any detail. All the phenomena of deposition mentioned above can be studied in this series, but for the most part the thinning out and splitting up of sandbeds, and the simultaneous thickening of clays, are sufficient to make the directions of variation quite clear, so that we are now enabled to elucidate the history of the series in almost all parts, and to give an idea of the conditions under which each particular bed was formed. The boring journals of oilwells have been of the very greatest assistance in establishing the history of the Pegu Series point by point.

A great river flowing from the northward entered a land-locked gulf, and hugging the western shore, gradually filled it up by its advance. Much of the axis of the Arakan Yonias was already land when the Pegu Series began to be deposited, and along the western shore thus formed great littoral sandstones with much evidence of terrestrial vegetation were deposited. On its eastern side the deltaic deposits were intercalated with truly marine beds. The advance of the deltaic deposits was not steady, but subject to many checks and retreats. During some of the checks vast accumulations of vegetable matter were formed in the swamps and lagoons near the river-mouth, to be aftewards buried under marine deposits of the invading sea or covered by coarser estuarine detritus as the delta was pushed forward. Thus in Lower Burma the oldest strata of the Pegu Series are entirely or almost entirely marine, while deltaic and even terrestrial conditions existed simultaneously in parts of Upper Burma. Earth-movement was in evidence, but not very active.

When the delta passed beyond the shelter of the western coast its course was to some extent deflected by ocean currents, but it continued to advance over the marine sediment. Now, after many changes of level, and the deposit of an overlying fluviatile series (which is usually uncomformable to the Pegu Series, but also has a marine phase that cannot but be conformable somewhere to the Pegu Series), the Irrawaddy has fallen heir to the former great river: and though it has a somewhat different course the general direction is the same, and we can still study the advance of a delta at its mouth.

In other countries the advance or retreat of deltaic fans of detritus may also be proved, but few cases are so simple as that of Burma. In Trinidad, for instance, earth-movement on a fairly large scale supervened during the deposition of the Tertiary Series and caused certain complications, so that the upper strata lie in a violent unconformity across the denuded strata of Middle Tertiaries. Yet the main directions of lateral variation can be proved with some degree of accuracy. During the deposition of the earliest Tertiary strata, sedimentation was advancing from the south-east, while marine conditions persisted for a longer period in the south-west. Towards the middle of the Tertiary period sediment was poured in from the south and west, and the arenaceous detritus is intercalated with and passes into pelagic strata to the north and north-east. Then followed a period of retreat when the advancing arms of the delta barely held their own, and fine clays and foraminiferal marls were deposited above strata of deltaic origin. Finally, sedimentation advanced again, and arenaceous strata were deposited by many currents flowing in various directions, east and west and north. The presence of islands of older strata, and the inception of a folding movement acting in a northerly direction, introduced many complications, but the main branches of the delta can be followed out, and seams of lignite and bands of oil-bearing rock at various horizons mark approximately the localities where accumulations of vegetable matter in forest lagoons or swamps were formed.

The same principles may be applied to the elucidation of the history of the Tertiary Series in many other countries, but it would weary the reader to enter into elaborate details of the evidence from one country after another that has served to confirm the theory and to associate oilfields with deltaic conditions.

The point of all this insistence upon the importance of studying lateral variation and determining the boundaries of a deltaic formation is simply that the probable petroliferous belt may be recognized. If oil is to be drilled for, it is as well to look for it as near as possible to areas where the conditions for its formation were favourable. On the one hand may be littoral and terrestrial beds where the carbonaceous phase is in evidence, on the other marine beds beyond the confines of the delta. Somewhere between we may hope for an area where the necessary alternations of arenaceous and argillaceous sediment are present, an area not too far from localities where accumulations of vegetable matter have probably been formed, buried, and sealed up. In that area we must seek for favourable structures to concentrate and retain the petroleum.

Much excellent work of competent geological surveyors, much arduous toil in opening up new districts and transporting plant to them, much fruitless expenditure of money and time could have been saved, had the facts concerning lateral variation been carefully studied and mastered.

It is, of course, a commonplace of geology that lateral variation occurs in rocks of all ages, but unfortunately in Britain, the birthplace of stratigraphy, the variations in most formations and series, with a few notable exceptions, are not very great, and much correlation of strata, it is to be feared, is still attempted chiefly on lithological grounds. Where we have evidence of continuous deposition on a large scale, and deltaic and estuarine conditions, as we have in the Carboniferous Formation, it has taken decades of field-work and controversy, and volumes of scientific papers written and discussed before it has been possible to arrive at a conclusive general idea of the conditions and variations. Even at the present day we find a classification based upon subdivisions established in some districts in England, including the well-known Millstone Grit forced upon Scotland, where such a classification is neither natural nor of practical benefit; and still "palæontological breaks" are inserted in a continuous series in order that a universal general arrangement may be adhered to. Similarly we have seen our local subdivisions such as Eocene, Oligocene, Miocene, and Pliocene forced upon other countries where their only significance is chronological, and where no natural groupings can be made to coincide with them. In our turn we have adopted Continental subdivisions, *e.g.* in the Cretaceous Formation, which are at the least very doubtfully applicable.

But if lateral variations during continuous deposition can be proved to be common and distinct among the primary and secondary formations, in the Tertiaries almost all over the world they become even more frequent and impressive, because it is those Tertiary strata which have emerged comparatively recently from beneath sea-level that we know; the great uniform Tertiary deposits, which perhaps future geologists will examine, are still beneath the waves. That is to say, we know only the margins of the Tertiary formations, and it is precisely along land-margins and on the fringes of continental areas that lateral variations must naturally be greatest.

We must take variation, then, as the rule and not the exception when studying Tertiary strata, and must not attempt the correlation of distant areas, as the author has often seen done, by similarity of lithological characters or the presence of some particular mineral or minerals. Such evidence only means similarity in the conditions of deposition, a similarity which during progressive sedimentation must migrate from one area to another. Thus oil-forming and oil-bearing conditions may be transferred from the lower beds of a series to the upper beds as we proceed from one province to another.

CHAPTER V

GEOLOGICAL STRUCTURE

It will be noticed that what is usually considered the most important matter in oilfield work, the study of geological structure, is given a secondary place. This has been done, not because its importance is not fully recognized, but because the study of lateral variation comes first naturally, and may render unnecessary a great deal of detailed work in discovering and mapping favourable structures. The field-student has now advanced sufficiently in his knowledge of the country which he is examining to be able to predict in what districts, and possibly also at what general geological horizons, conditions were favourable to the formation of petroleum. His next task is to discover in the indicated districts suitable structures to contain and preserve the petroleum from inspissation, and to ensure sufficient concentration to make paying productions probable.

Earth-movements.—The elucidation of geological structure naturally depends on a study of the earth-movements that have been experienced. Here, again, an examination of the general map of the country is essential; it is advisable to get a broad view of such evidence of folding, faulting, and unconformabilities as has been obtained before details of structure are attacked.

In the preliminary traverses made to gain an insight into the lateral variation, the geologist has doubtless obtained some evidence of folding and the direction of folding movements. In many cases only one earth-movement will require to be considered; in others two, or even more, of different ages, directions and degrees of severity may have to be distinguished and delineated. Earth-movements are instances of relative movement, but as a rule it will be found simpler to consider them as movements in a definite direction towards some central axis of folding, the force being applied tangentially to the earth's crust. There is no structure produced by flexuring or faulting that cannot be explained by the application of this simple principle.

The movement to be considered, then, resolves itself into a horizontal push, and in the majority of cases the direction is from the seaward towards the mountain ranges. Again, the oldest strata exposed will be found as a rule in the heart of any axis of folding that may be present. This gives another method for determining on *prima facie* evidence the direction of movement.

Where flexuring attains to great dimensions, and a series of well-marked parallel folds is produced, the steep sides of asymmetrical folds will be found almost invariably on the side from which the movement took place, and vertical or even inverted limbs of flexures are not uncommon in such circumstances, even among comparatively young Tertiary strata. This is all in accordance with the development of a geanticline, and the production of a fächer or fan structure, in which the axial plane of the central fold is vertical or nearly so, and the axial planes of the sharp flanking folds dip towards the central axis. As one recedes from the central axis of folding, the flexures gradually become less sharp and more symmetrical, till finally they may be represented by small gentle undulations or elevations which affect the dip of the strata so slightly that the pocket clinometer may not be sufficiently accurate and sensitive to prove a general dip in any one direction. In both Canada and Burma there are excellent examples of a series of flexures rapidly decreasing in sharpness as we recede from the central axis of folding.

Thus when a wide area is to be examined there is usually little difficulty in determining the direction of movement, and after a traverse across the main strike-lines of the country it should be possible to predict where gentle folds should be in evidence, where sharp or asymmetrical flexures, and where inversions of the steeper limbs of flexures may be expected.

The age and duration of the earth-movements is another matter of great importance. In some cases it will be found that movement has proceeded fairly steadily during the

Photo. by G. B. Reynolds

Scene in the Persian Oil-fields, near Kala Deribid.

deposition of a Tertiary series, causing older strata to be elevated on the crests of flexures, brought into the reach of denuding forces and actually denuded, while continuous deposition was proceeding in the synclines. The results produced are violent unconformities along certain lines, with the unconformability dying out laterally, while the older strata may be seen in localities sharply folded and overlaid conformably by successive younger strata in which the dips decrease steadily upwards, the uppermost beds perhaps being practically horizontal. The best instance of this that has come under the writer's observation is in Persia (cp. Plate VII), where the movement has been in operation since early Miocene times and is probably still continuing.

In other cases the movement may have been long-continued, but not continuous, so that at several distinct epochs, separated by intervals of quiescence, it has been rapid. The results will be the production of local unconformabilities at different stages, but these unconformabilities may die out laterally within a comparatively short distance, and must not be treated as if they were universal. Great lateral variations in the strata will be caused under such conditions. Sind and Baluchistan afford a good instance of this. In the records of the Geological Survey of India dealing with this province it will be seen that a great number of types of sediment are represented, and very frequently they are separated by unconformabilities. The unconformabilities in this case are almost entirely of local importance only; there is great lateral variation, but there has been little denudation of previously formed beds throughout the series from early Eocene up to perhaps middle Miocene.

In other cases definite periods of folding movement may be made out, and the relative ages of each can be determined by the effects upon series of different ages. This is the case in Burma, where one movement has been detected that effects the Pegu Series and earlier strata, while another and much greater movement in a different direction affects not only the Pegu Series but the younger Irrawaddy Series lying unconformably upon it.

In studying earth-movement it must be remembered that faults are part of the movement just as much as flexures.

A fault is merely a special case of folding, where the elasticity of the strata or the amount of "load" is not sufficient to prevent dislocation. Theoretically a fault may always be replaced by a sharp monoclinal bend, and the passage from one into the other may often be seen. It has too often been the custom to think of a fault as something quite apart, and to map a fault—to use a metaphor from whist—as one would play a trump, not following suit. The author has known faults to be recklessly strewn about a geological map in this manner, when the presence of one could not be justified without the mapping of two or three more which were entirely theoretical, for which no evidence could be obtained, and of which the amounts and directions of throw were purely conjectural. From such methods it soon arrives that when any structure has not been elucidated properly, the remark will be made " there must be a fault," and the puzzle is deemed to be explained. A fault would thus become a sort of makeshift to get faulty observers out of trouble. But the effect is just the opposite : such methods soon effect their own cure by involving the geological surveyor in a network of physical impossibilities, from which the only escape is to begin the mapping all over again.

Faults are really very simple matters, and they obey physical laws just as folds do. They must, therefore, only be mapped when justified on physical grounds, and no fault must be recorded of which at least the direction of throw, if not some estimate of the actual amount of throw, can be given.

Where the sedimentary series in which petroleum occurs is comparatively thin, or only thick very locally, it may not lend itself to extensive folding. A very good example of this is to be found in Egypt. The foundation of that country is a great plateau of granite and schistose rocks with a very irregular surface in some localities. Upon this plateau Carboniferous, Cretaceous and Eocene strata have been deposited without any powerful earth-movements taking place. But in Mid-Tertiary times earth-movement began, and continued for a long period, accompanied in places by igneous action. The fundamental plateau was too solid and firm to be thrown into great folds, but it had to give way under the stress of tangential movement, and the result is a series of great faults and faulted folds. There are two distinct movements, one producing folds running north-west to south-east, and one causing north and south structures. The former affects the Egyptian side chiefly; the latter is more dominant in Sinai and northward into Palestine. But many places are affected by both movements. Which movement is the earlier has not yet been determined; possibly they overlapped to some extent, but the evidence obtained so far points to the movement producing north-west strikes being the earlier.

The Gulf of Suez and the Red Sea are great troughs let down by fault movements, and the main structural features on land are sharp faulted folds bringing up the underlying granite and schist. These dislocated structures only occur where the covering of sediment was thin, for instance where the Eocene formation has either never been deposited or has been denuded in Miocene times.

During the Mio-Pliocene period active movement continued, and basins were cut off from the sea to the north; in them great deposits of gypsum and salt have been formed, but are confined to a fairly narrow belt, while rapid denudation of the older strata was in progress on both flanks of the trough.

It is only in the minor structures that oil has been obtained in commercial quantity. These minor structures occur between the major faults and faulted folds, and have been formed where the sedimentary capping is fairly thick and therefore capable of folding with more regularity into domes and anticlines.

Signs of oil are visible in many localities, seepages, impregnations, outcrops of bituminous strata, etc., but it is only where there are folding structures of fair size and regularity that good productions can be expected. There has been much unsuccessful drilling, which has afforded a mass of very interesting and valuable evidence, so it is possible with the help of well-records and the admirable publications of the Geological Survey to piece together a fairly conclusive geological history of the country. The writer, in his investigations in Egypt and Sinai, could have done little without the help thus available.

Whether new oilfields of importance remain to be discovered in Egypt it is too soon to say: there are but few localities where it is possible for favourable structures to have been formed, and some courageous speculative drilling will have to be undertaken to test the obvious chances that remain unexploited. The point to be observed is that only by a study of the earth-movements, their effects and their limitations, can the subject of petroleum development in Egypt be approached with any reasonable hope of success.

Structures favourable to Concentration of Petroleum.—With these preliminary remarks we may pass to a consideration of the structures most favourable to the underground concentration of petroleum. It is usual in books upon the subject to give a list of the various structures which have been tested and proved productive, and a great number of different classes of structure can be described. But any one can be assigned to one of a few main types. Anticlinal structure and petroleum are associated in the minds of all who have studied or worked in oilfields, aud though petroleum can be proved to occur in almost every known structure, in the vast majority of cases some form of anticline is present in a successful field.

Dome Structure.—It will be admitted generally that the most favourable structure of all is a dome or quaquaversal, with gentle dips near the summit and steeper dips upon the flanks, which again pass gradually and steadily into a position of horizontality, so that a large area can be included as properly belonging to the dome. This is merely a special case of anticlinal structure, an anticline with pitches of the axis away from a central point.

A broad round dome is very rare in nature, as it almost necessarily requires more than one earth-movement for its formation. Elongated domes, however, are fairly common and there are few anticlines that have not in one or more localities some trace of dome-structure. Spindle-top is probably an isolated dome of breadth approximating closely to its length, though the evidence does not seem ever to have been recorded very clearly. The famous Yenangyoung field in Burma is an elongated dome of great extent, nearly symmetrical, and only slightly affected by purely local faults. It is isolated from any other flexure by miles of approximately horizontal strata, and thus drains a large area, while steep dips occur on either flank, ensuring a high concentration of the petroleum. About two square miles of available drilling area is provided on its crest. It is obvious that under such conditions hydrostatic pressure of water in the strata is enabled to concentrate the petroleum from all sides towards the summit. In such ideal structures, whatever be the quality of the oil, and however small the porosity of the oil-bearing strata, such a concentration is bound to take place, and large productions may be expected whenever the oilsands attain to a reasonable thickness.

It is usual to distinguish several kinds of dome-structure; there is, as has been seen, that formed by simple earth-movement or a combination of two earth-movements. Then there are dome structures apparently formed by vertical movement. Of these possibly the most important are due to igneous intrusions of laccolitic type. In the Mexican oil-fields structures of this nature have been recorded, plugs of igneous rock being found with seepages of petroleum round them. Though the sections that have been drawn to explain these structures appear to be largely theoretical, there seems to be no doubt that the sedimentary strata have been heaved into something like a dome by these intrusions, which are probably of normal laccolitic type and not of the core or wedge shape that has been figured.

The igneous intrusions themselves are of little importance; the fact that the strata have been heaved is the significant feature. This has enabled a concentration of petroleum to take place, so that productive wells can be drilled near the margin of the igneous mass. Possibly thermal waters associated with the intrusion may have dissolved the limestone to some extent, making it cavernous and capable of containing large quantities of oil. It is probable, however, that such structures are neither so common nor so important as has been suggested.

Somewhat similar structures formed by vertical movement occur near the Persian Gulf, and in some islands in the Gulf, where volcanic action has been in operation during Tertiary times. In most of these cases, however, explosion craters have been formed with discharge of ashes and volcanic bombs, followed by remarkable cauldron subsidences almost circular in shape. A solfataric stage has in some instances served to obscure the evidence and rendered it difficult to unravel the history of these remarkable phenomena. Where no explosion crater has been formed an unbroken dome may be found, and any petroleum present in the upper strata will naturally be concentrated towards the crest, but deep drilling will probably reveal the cause of the dome in a concealed intrusion. On the whole, such laccolitic domes cannot be expected to be of great importance as oilfields, though it may be possible to obtain a certain production from them, if there be a sufficiently thick petroliferous series above the intrusive core.

Then there are what are called "salt-domes." In the plains of the Texas-Louisiana oilfield concealed dome-structures have proved very productive of oil, and in some at least of these deposits of rock-salt and gypsum have been found, as well as dolomitized limestone, which is usually the oil-bearing rock. The salt beds are said not to be found beyond the margins of the domes, and it has been suggested that the dome-structures have been formed by crystallization of the salt, by formation of gypsum by hydration of anhydrite, or by both. The evidence for this theory appears to be somewhat scanty and theoretical, and such explanatory sections as have been published are not drawn to scale, and are obviously diagrammatic, if not even to be stigmatized as fanciful.

In Transylvania also dome-structures containing what appear to be salt plugs are recorded, and it has been suggested that here also the salt is the cause of the dome, though how such heaving of sedimentary beds could take place is still somewhat vague. The writer, having no personal experience of such structures, is unable to offer any explanation at present, but would suggest that much additional evidence is required before any such theory can be accepted. If it can be proved, however, that a segregation of salt takes place towards any locality, or that deposits formerly of anhydrite in any particular small basin have been reached by water and converted into gypsum, it may well be that the surrounding sedimentary strata might be heaved into a dome shape. Even if it can be proved that an extensive bed of rock-salt has been dissolved over a large area, and only protected from solution in one or two localities, the formation of domes would be explicable by the gradual collapse of the strata surrounding the protected area. But further proof of the possibility of such action is necessary.

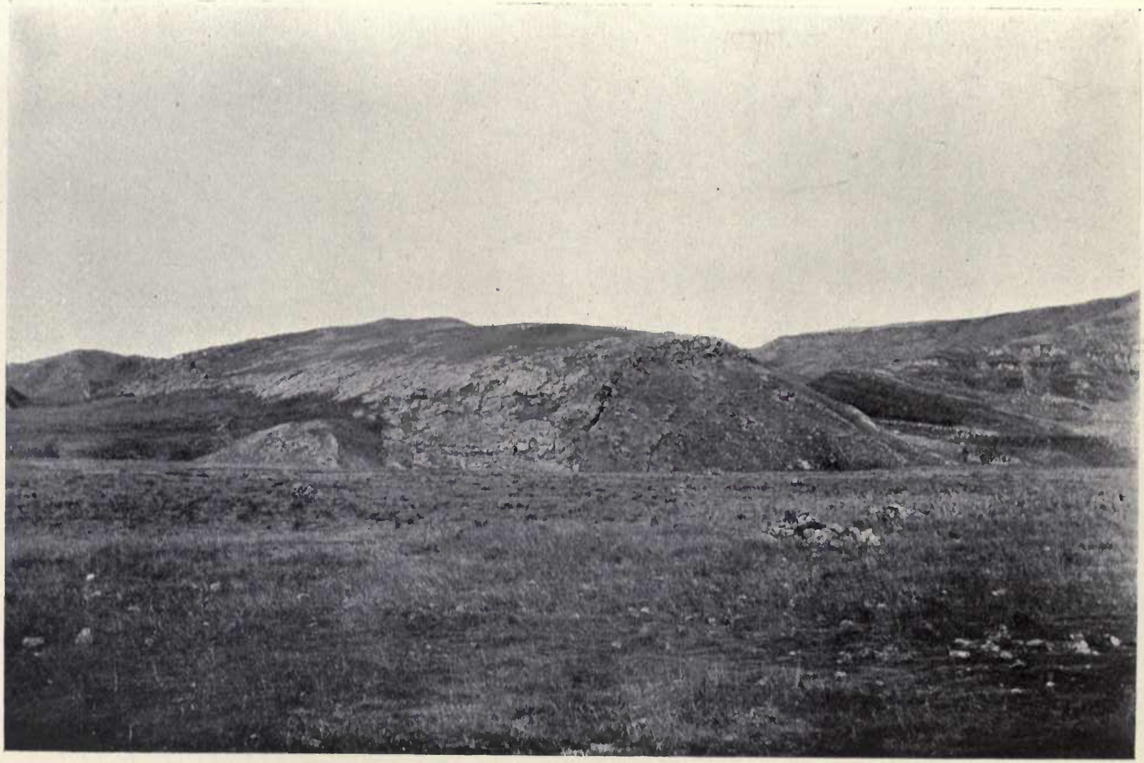


Photo. by J. Holland

AN ANTICLINE IN THE MAIDAN-I-NAPHTUN FIELD, PERSIA.

Oil is frequently associated with dolomitized limestone, gypsum, or anhydrite and salt, but it does not follow that there is any essential connection. It is the dome that is the important matter, and the reservoir rock, such as a dolomitized limestone. Once a dome-structure is formed, the concentration of petroleum in it takes place naturally, if there be any petroleum within the neighbourhood affected, but the association of these chemical or chemically-altered deposits may take place without any petroleum being involved.

Therefore such domes, however formed, may be of great importance, and evidence regarding their occurrence and mode of formation will be very valuable, since once we have a complete knowledge of the conditions under which they are formed and the process of formation, it will not be a matter of great difficulty to discover more of these structures, however well concealed, and thus possibly find new oilfields.

Symmetrical Anticlines.—Next in importance comes the simple symmetrical anticline (cp. Plate VIII), either without pitches of the axial line, or with pitches too low to have affected the structure favourably or unfavourably. Many of the eastern fields in the United States have structures of this nature, the anticlines, though extensive, being often so low and flat as to be only distinguishable by very careful levelling or by evidence from actual bores. It is obvious that the greater the extent of the flexure, the greater should be the concentration of oil towards the crest, given sufficient hydrostatic pressure. The effects of pitches and gentle dips will depend to a great extent on the nature of the oil and the porosity of the oil-bearing strata; the greater the specific gravity of the oil and the smaller the porosity, the slower and less complete will be the migratory movement. Thus structures that have proved remarkably favourable for the production of a light oil of paraffin base, may not cause any great concentration of a heavier grade of petroleum. In the United States the fields of New York, Ohio, Pennsylvania and Virginia, where as a rule the oil is light and mobile, show many instances of very flat structures, anticlines with slopes of twelve feet in a mile, for instance. It was in these fields that drilling for oil was first attempted and learnt, and they were taken as the type of what oilfields should be. This idea still survives to some extent in spite of the discovery of so many great fields with totally different structures. The advantages of these eastern fields in the States are many; horizontal or low dips make the easiest drilling, and the strata being palæozoic are mostly fairly hard and not very liable to "caving," so that drillers trained in these fields were acquainted with few of the difficulties attendant on drilling in soft Tertiary strata. When oil began to be discovered in other provinces under entirely different conditions, many a field that has since proved very profitable was condemned at first because it did not conform to the structural peculiarities deemed essential in the fields of the Eastern States, and many a practical operative, with only experience of the eastern fields, proved a failure when confronted with the task of drilling through soft and steeply dipping Tertiary strata.

Asymmetrical Anticlines.—Another form of structure that has provided many excellent fields is the asymmetrical anticline. This is an anticline with one flank gently and the other steeply inclined; the latter in some cases may be vertical or even inverted. Such flexures usually occur nearer to the central axis of folding than symmetrical flexures. The "terrace structure," well known and much sought after in the eastern fields of the United States, may be regarded as a special case of this form of structure, an anticline so flat and gentle that the gently dipping flank is for all practical purposes horizontal. In sharp asymmetrical anticlines such as those at Kasr-i-Cherin in Persia, and Yenankyat and Singu in Burma, it is evident that drilling on the actual line of crest is useless; the drill soon enters steeply dipping beds where great difficulties may be encountered in the drilling, while there may be no possibility of penetrating to a sufficiently low horizon. Mr. G. B. Reynolds pointed this out in the Persian fields, and Mr. Pascoe, in the Records of the Geological Survey of India, has since explained the effect of such a structure in the case of the Yenankyat field in Burma. This point will be referred to later in the chapter on "Location of Wells."

Compound Anticlines.—Compound anticlines may next be considered. These are only observed where the flexuring movement has been severe, and has produced a series of sharp folds, possibly with very steep flanks. The most striking instance that has come under the writer's observation is at Maidan-i-Naphtun, in Persia, where a group of no less than seven sharp local flexures is included in an area approximately one mile in breadth. Some of the flexures are so sharp that when a band of hard limestone is exposed on the crest it is possible to sit astride on the anticline. Highly inclined strata are the rule throughout this field, and vertical or inverted limbs of folds are common. These seven flexures converge towards and pass into one broader fold, which, being formed of strata less amenable to distortion, is somewhat gentler, and which really gives the key to the structure of the neighbourhood. The whole area is broadly anticlinal, and the sharp folds are merely puckers upon a well-defined flexure on a larger scale. Every well drilled in the area, whether upon one of the minor anticlines or in one of the synclines, has struck oil in paying quantity, but the surface indications of oil are nearly all upon or close to the crests of the minor flexures. These minor folds, though very striking and impressive, can therefore be disregarded and the compound anticline considered as a whole.

In Persia the writer discovered and mapped folding of practically isoclinal intensity among the older Miocene strata. Messrs. H. G. Busk and H. T. Mayo have since studied the region systematically, and in a paper before the Institution of Petroleum Technologists have explained the tectonics of the country and shown the relation of isoclinal areas to the great reversed faults, the underlying solid masses of Asmari limestone and the overlying masses of Bakhtiari conglomerate. It is only when the softer strata of clay, thin limestones, gypsum, etc., are unsupported and unprotected that they are folded in this manner against the massive resisting but simple flexures of the underlying limestone. After the folds have become packed as tightly as possible, further movement can only take place by the development of thrust movements, which on a smaller scale recall the phenomena of the sole-planes seen in the North-western Highlands of Scotland. Messrs. Busk and Mayo attribute considerable importance to the overlying masses of Bakhtiari conglomerate, but suggest that denudation must have proceeded to a considerable extent before thrust movements were possible to establish a new equilibrium. Such folding movements in Tertiary strata are very remarkable, but are probably only possible where such strata containing gypsum, which practically flows under severe pressure, are sandwiched between thick masses of more highly resistant rock.

Synclines.—Mr. W. T. Griswold has pointed out that under certain conditions synclines may be exploited for oil successfully. The necessary conditions are that the strata are not waterlogged, and are so covered or sealed that water cannot enter the oil-bearing bands at outcrop. In such circumstances any petroleum in a porous rock will tend to collect at the bottom of the syncline under the force of gravity. It is very doubtful whether many such cases exist, though, in rainless regions or where the bulk of the strata are practically impervious to water, such conditions are possible.

With an oil of approximately the same specific gravity as water, displacement by the water might be very slow and never quite complete: so a certain quantity of the petroleum might remain in synclines, especially if deposits of asphalt were formed upon the outcrops by inspissation of the exuding petroleum and the downward percolation of water checked if not entirely prevented. Thus, although with a light oil it may very seldom be worth while to drill in a syncline, with heavy asphaltic oils and in regions where rainfall is very small, shallow synclines might be worthy of being tested, and might prove highly productive. Even in Trinidad where the rainfall is high there is some evidence in favour of making a test of one of the shallow synclines, where extensive asphalt deposits cover most of the outcrops of oil-bearing sand. Where oils are very heavy and sluggish, a certain proportion of water in the oilrocks is rather a benefit than otherwise, assisting the flow of oil.

In cases where there is no water or only a limited supply of water in a sedimentary formation, any petroleum that is present may gravitate towards the centre of synclines if it is not in sufficient quantity to fill the whole porous reservoir, and may give good productions in wells drilled to tap it. Such cases are almost the only ones in which gas occurs above and separated from oil in the same rock.

The only other cases are those where the oil has been adsorbed to such an extent that only *light* residues remain in insufficient quantity to dissolve or occlude the lightest (gaseous) compounds: such occurrences are not infrequent among the older formations (see Chapter VII).

Where oil is heavy and asphaltic and the outcrop of the oilsand sealed by asphalt deposits, synclines may be protected from invasion by water and may yield oil in large quantities. It was a consideration of these conditions that led the writer to suggest that some of the synclinal areas in Trinidad might be well worth testing. This has since been proved conclusively by many successful wells drilled in the syncline between the La Brea and northern anticlines near the west coast. Some of these wells yielded thousands of barrels a day from a depth of about 1600 feet; one was credited with flowing as much as 22,000 barrels, but the yield fell off rapidly and was only 2000 barrels when the writer visited it some weeks later. Production from that locality seems to have fallen off considerably in the last few years, probably owing to water having found its way in as the oil was extracted. This must always be a danger with synclinal fields, so that the life of oilwells drilled in a syncline is not likely to be as great as that of wells in anticlinal structures, where the oil, though encroached upon by water up the flanks, retreats always towards the crest. In a syncline it is obvious that the retreat of the oil as water enters may be in any direction and so concentration is continually lost instead of preserved.

In California the pumping of water out of synclines has had the effect of bringing petroleum down the dip and making once again productive wells that had ceased to yield anything but water. Artificially produced migrations of this nature are said to have taken place over a distance of two or three miles in regularly dipping strata.

Monoclines.—Finally, oil may be obtained from monoclines, often in great quantity. In such cases the more gentle the dip, the better, but even quite steeply inclined strata may yield good productions. Many of the great oilwells in Russia are drilled into strata which crop out at the surface at no great distance: the new and much boomed field of Maikop is shown by the published geological maps to be in an outcropping series. In Peru, Trinidad, and some parts of California and Mexico, good productions have been obtained from beds that crop out in monoclines. It is to be noted that in these cases the oil is asphaltic and of fairly high specific gravity, the latter quality being due, partially at least, to inspissation.

In Burma, where a light oil of paraffin base is the characteristic petroleum, no adequate production has ever been obtained by drilling in a monocline to strike an outcropping oilsand. Native hand-dug wells have occasionally been worked at a profit for a short time in such structures, and many trial bores have been made at great expense, but all have been abandoned finally as unprofitable propositions. Except where the strata are for the most part impervious, and there is a probability of striking some isolated lenticular bed of oilrock, there is little hope of obtaining paying productions of light mobile oil by drilling in a monocline where all the horizons crop out. Thus, the class of oil to be obtained must be considered in relation to the structure; conditions favourable for an asphaltic oil may be quite unfavourable for a light paraffin oil.

It must not be forgotten in dealing with a monocline that it is really part of a great curve, on the flank of either some great anticline or syncline. Dips do not continue far at the same angle when traced downwards, as the geologist will discover at once in plotting sections. Any sudden change in angle of dip may have great effect on production. Thus, though a well may begin in strata dipping at 45 degrees or more, by the time the oil-bearing rocks are reached the dip may have decreased to 20 degrees or less, or may have increased and even become vertical. Each case must be worked out from the geological map of the area, for it is generally quite absurd to calculate on a dip remaining constant for any considerable distance. Before any wells had been commenced in an area now being exploited by a company in Trinidad, the writer (then Government Geologist in that colony) worked out the vertical and lateral changes of dip, where direct evidence of the inclination of the beds was very scanty and often unreliable, and furnished those responsible for the exploitation of the ground with particulars of the depth to the observed oil-bearing bands in different places and the angles of dip at which each would be struck, particulars which in the end were proved to come within a very small fractional error of the actual results obtained. In this case projection of the observed dips from the nearest reliable section would have given an entirely erroneous result, and would have made the area appear very unfavourable for development work. Every bit of evidence bearing upon change of dip must therefore be noted, and when outcrops can be traced, even though no actual observation of dip can be made, it is often possible to estimate change of dip by measuring the distances between two known outcrops. The writer has often found this method of great service in obscure ground.

Where the dip in a monocline suddenly becomes shallower, or where a sudden change of strike occurs, especially where a bend in the strike concave to the direction of dip in the monocline is observed, there is nearly always some favourable effect upon the concentration of petroleum. The oil nearly always is found to have migrated towards such structures. This can be readily understood in the case of a bay or bend in the strike which is frequently accompanied by a lowering of the dip; it is in fact an abortive anticline, since a tilting back of the monocline to a position of horizontality would make an anticline or dome of such a structure. Instances of this may be studied in Trinidad, perhaps the most remarkable being at Pala Seco near the southern coast on the northern flank of the great southern anticline. Structures such as this may be due to movements earlier than that responsible for the monocline, and the concentration of petroleum may have taken place prior to the great movement which caused the main flexures of the country. However this may be, such structures, bays in the strike concave to the direction of dip, always favour migration and concentration of oil.

Perhaps the best known monoclinal field that has attracted attention, not to mention capital, in recent years, is Maikop. The geological map of that field is well known, though on account of local difficulties and lack of evidence the mapping does not appear to have been done in great detail, and lateral variations do not seem to have been determined with any certainty. The field is a monocline with certain local irregularities, and possibly a lenticular development of oil-impregnated strata. There have been excellent but not long continued productions from individual wells, and a certain small but steady production continues, while there is always the hope of striking a big flow of oil in one or two localities which are now fairly well defined. But there is no structure in the whole field sufficiently favourable to have justified the enthusiasm with which during the oil-boom of 1910 British capital was poured forth for Maikop flotations. A consideration of the geological structure should have warned every one with a smattering of geological knowledge that astonishingly successful results over a wide area were on the face of it impossible. It is to be feared also that some of the experts upon that famous field hesitated to give the warning that their experience should have told them was called for.

As it is, Maikop will continne to produce oil in small or moderate quantity for many years, with perhaps an occasional sensation in the form of a richly productive but short-lived well. But the bulk of the capital subscribed has been lost, and doubtless many shareholders have become prejudiced against petroleum companies as very speculative ventures. Possibly much of the development work was undertaken before the geological structure was definitely recognized, but if so, the development companies were largely to blame. To begin drilling without a geological map is to court disaster. When the map is completed it may be seen that it is hardly worth while to drill even a first test well. Had geological structure been studied first of all, Maikop would not be a dark page in the history of the development of oilfields by British companies. A monocline, save under exceptional conditions, can never rival an anticline or dome as a petroliferous structure.

Every structure produced by folding can be classed under one or other of the heads detailed above.

Faulting.—Faulted areas are not to be regarded as a special class of structure, but faults may be of great importance structurally, so that it is necessary to give some account of how they occur in oilfields and what effects may be attributed to them.

The flank of any fold may be replaced by a fault, partially or wholly; in this case it is a strike dislocation having the same effect as a very sharp unbroken fold would have, and obviously due to the same movement that flexured the strata. In many cases what is mapped as a fault at the surface may become a sharp flexure at some distance beneath, where the load must have been greater during the period of movement, and consequently a higher coefficient of elasticity of the strata can be postulated. This applies both to "normal" and "reversed" faults, the former being in evidence on the flanks of symmetrical or gentle flexures, while the latter are frequent on the steeper side of asymmetrical folds, especially where vertical or inverted strata are observed.

In areas under insufficient load the cohesion of the strata may be overcome under flexuring stresses, and faults may be developed in many directions, all, however, having some relation to the flexure that the stresses are tending to form. Indeed, it is only under such conditions that what is called, rather unfortunately, a "normal" fault can be produced at all. The "normal fault" of the textbooks, a dislocation with a vertical or nearly vertical displacement, the downthrow being in the direction of hade, is by no means a common phenomenon in nature; it is only under simple conditions that such dislocations are physically possible.

A dislocation must begin somewhere and must die out somewhere, so it can be regarded as a sag or tilt, and strike faults, whether normal or reversed, whether thrusts, "slides," or the doubtfully possible "lags" of some authors, are direct and inevitable special phases of flexuring movements. Dip faults on the other hand may be simple tilts or sags, or may have a greater or less horizontal component. Many dip faults which map as normal faults, and are considered as such, can be proved to be largely horizontal displacements, thus approximating to the nature of "wrench faults." Every fault must be considered in relation to the flexuring movement, and thus the observation of a fault should be a help rather than a hindrance to the elucidation of structure, since, when once the direction of throw has been determined, it shows at a glance what tendencies of movement were induced in the strata in that particular locality by the stresses to which they were subjected. A *map* may be complicated by faults, but the *structure* should be explained by them rather than rendered more difficult to understand. The geologist who, after describing the structure of an area, concludes by saying that "there seems to be a good deal of faulting," or who tries to safeguard his views of a structure by saying "there may be a fault," which, if present, will put a different construction on the evidence, admits by so doing that he has not mapped the area, and has only the vaguest general idea of its geological structure.

Of course in strata of Palæozoic or Mesozoic age faults may be very numerous and of many different ages, but we are dealing principally with Tertiary rocks, where the flexuring and faulting are usually simple and the stresses that caused them easily understood. Petroleum is very seldom, if ever, found in highly faulted and contorted strata of Palæozoic age.

Since faults and folds are parts of the same earth-movement, the effects of faults upon an oilfield need not necessarily be prejudicial; strike faults may indeed help to ensure a greater

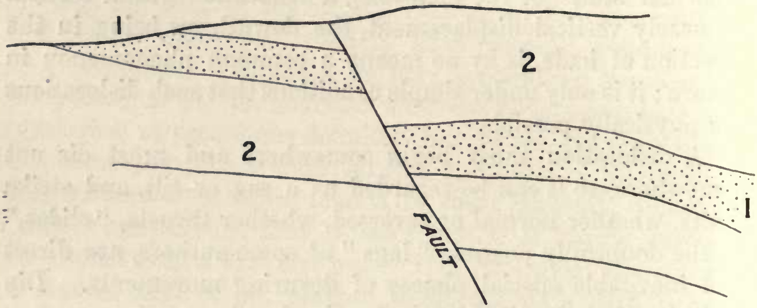


Fig. 3.—Fault sealing up an oilrock. 1. Oilrock; 2. Impervious strata.

concentration of the petroleum towards the crest of a flexure, and dip faults in a series where there are many oilsands may bring about communication between different sands, and so have a notable local effect upon production. Where the bulk of the strata are impervious, an oilsand which would otherwise crop out at the surface may be cut off by a fault and sealed beneath impervious beds (Fig. 3), and thus yield oil under much higher pressure when pierced by the drill than if it cropped out in the vicinity.

To illustrate the interdependence of folding and faulting, and at the same time the effects of two folding movements in different directions, we may take the Yedwet inlier in the Magwe district of Upper Burma. This was the first area examined by the writer in Burma, and it proved a very fortunate one on account of the importance of the evidence obtained.

The area consists of an inlier of the Pegu Series, surrounded by, and in places capped by outliers of, the unconformable fluviatile Irrawaddy Series. The inlier has an oval outline, and dips are gentle throughout, seldom rising to more than 20 degrees, and that only towards the margins. Presumably, then, the structure was dome-like. Careful examination proved that there was evidence of two flexuring movements, both very gentle, one tending to produce flexures running E. 20 degrees N. to W. 20 degrees S., of which two were recognized in the area, and another tending to produce flexures running almost north and south. The general form of the inlier is due to this latter movement, which was easily identified with the main flexuring movement of Burma. The presumption was that the former movement was an earlier one, which had not been recognized previously in Burma.

The flexures are so gentle that a very simple case of the dynamic conditions produced by one movement on the results of an earlier one is presented. The strata had evidently not been under great load at the time of the last movement, as a number of small faults were detected in various parts of the area. These faults are of the same age, they run into each other, and no fault displaces another. They have therefore evidently been caused by the same movement. There are two main directions for the faults, and though there are local modifications and variations, the lines along which dislocation has taken place are wonderfully constant throughout the area, viz. E. 20 degrees N. to W. 20 degrees S. and roughly north and south. That is to say, the systems of faults are parallel to the strike-lines produced by the two movements.

The process which caused these faults can be expressed very simply by a diagram (Fig. 4). Assuming that the movement producing the two flexures running E. 20 degrees N. to W. 20 degrees S. is the earlier, we have a force AB impinging obliquely upon a flexure EF. The force will be resolved into two components AC and AD, one tending to increase the height of the fold and the other tending to compress it and to raise a flexure in the direction BD. It is a simple parallelogram of forces. Let us consider how different parts of the area will be affected. A point upon the crest of one of the cross flexures will tend to rise, especially where the effects of both movements coincide. On the other hand a point in the syncline between the two cross flexures will be affected differently according to its position with regard to the second movement. Towards the margins of the area a point in these synclines will tend to sink, towards the centre of the area one component will tend to make

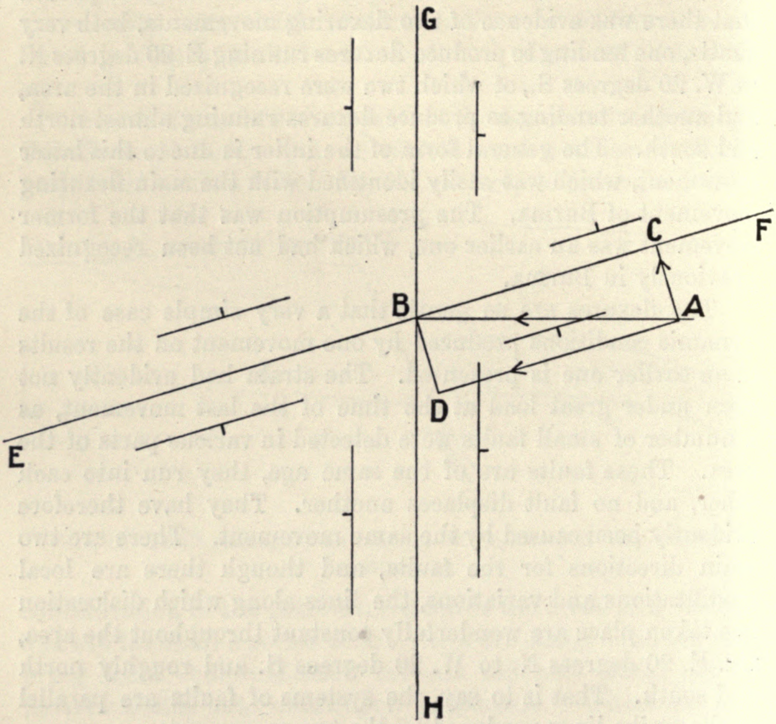


FIG. 4.—EF = crest of earlier flexure; GH = crest of later flexture; ⊢ = faults showing downthrow.

it rise and another to make it sink. The strata in such localities will be under a peculiar condition of stress, and adjustment will be arrived at by the development of small faults. Thus we get, so to speak, strike faults of both movements, though produced simultaneously and the directions of throw will be as shown in the diagram. All these faults were noted and mapped before any theoretical ideas as to their origin were conceived.

Replacing the faults by folds the action is quite easily intelligible, and can be reproduced experimentally.

The evidence obtained from this area was applied to other fields in Burma, and served to explain the presence of faults in many localities where physical reasons for their origin had not been ascertained. One of the first results was the proof of the relative ages of the two movements; that responsible for the cross flexures was found not to affect the younger Irrawaddy Series, while the other movement throws it into great folds. The cross movement is therefore the earlier.

The formation of dome structures, which are common in inliers of the Pegu Series, was also accounted for. It is almost entirely due to elevation by the earlier movement which, though always gentle, has had the effect of raising parts of the series locally before the commencement of the great movement which has produced the main strike-lines of the country.

Another interesting point is that petroleum has never been obtained in paying quantity in any field that does not show some traces of the earlier movement, even though these traces are often almost obliterated by the much more powerful later movement. It would seem that there has been a preliminary concentration of the petroleum contents of the strata towards the earlier flexures, which concentration has been greatly increased afterwards by the later and greater flexuring.

It is, of course, only in simple cases that such conclusive results can be obtained with certainty, but the Yedwet inlier will serve as an example of how the evidence from one area may assist in elucidating the more complex structures of other areas, and of the necessity for considering flexures and faults together and not separately.

Unconformabilities.—The only other phenomena of importance that must be considered when dealing with the geological structure of a country are those associated with unconformabilities. Unconformable junctions of different series, or of different parts of the same series, may often be the cause of considerable difficulty in the working out of the structure of an oil-bearing territory. Among Palæozoic or Mesozoic rocks there may be no difficulty in recognizing an unconformity, but in soft or lightly compacted Tertiary strata the discordance may never be seen in actual section, while the rocks both above and below may have very similar lithological characters, and fossil evidence may be wanting or too scanty and too little known to be conclusive. In such cases there is a danger of an unconformability being unnoticed, with disastrous results when estimates of thickness of strata and depth to oil-bearing horizons are being calculated.

When proved, however, by careful mapping, an unconformability may be of very great assistance to the field student in giving evidence as to the age and nature of the earth-movements in the country that is being examined. A case has just been quoted from Burma, where the proof of the relative ages of two movements depended on the evidence from strata of two different series, separated by an unconformability. Had the unconformability between the Pegu and Irrawaddy Series not been ascertained, this valuable evidence would have been lost. The discordance between these two series, moreover, is sometimes not easily recognized, the junction has several times been described as a passage, and at one time the Geological Survey of India were actually mapping one of the local basal beds of the Irrawaddy Series as the topmost bed of the Pegu Series.

The recognition, therefore, of an unconformity becomes matter of very great importance, and it must be distinguished from a plane of merely local or contemporaneous erosion. Local erosion is very frequent among rapidly accumulated Tertiary strata, such as are characteristic of areas where deltaic conditions occurred on a large scale. At the base of every thick or coarse-grained arenaceous group, where it rests upon finer argillaceous sediment, there are nearly always some signs of erosion of the underlying strata, and the divergence in strike and dip of the arenaceous group if current-bedded may be considerable, so that in a small section the appearance of a well-marked unconformity may be presented. On the other hand a great unconformability, representing a gap in the geological record, may appear in small sections to be a perfectly conformable sequence.

Careful mapping on a large scale will always make certain of any unconformability of importance by disclosing the overlap of one series on the other, but where evidence is very scanty, or where there is not sufficient time available for detailed work, other methods must be relied upon.

The presence of some mineral or minerals or fragments of rock in one series and not in the other is a bit of evidence to be noted at once, as it points to the strata having been formed from the denudation of different rocks, so that if any such sudden change in mineralogical composition is detected and proved to hold good over any considerable distance and through thick masses of strata, a *primâ facie* case for the presence of an unconformability has been made out.

Differences in the state of mineralization of the strata are also to be noted, the bedding, lamination and jointing may be of different characters in two apparently conformable series; and finally, and most important of all, the lower series may show evidence of small folding or faulting movements that do not affect the upper series.

In the case of the unconformability between the Pegu and Irrawaddy Series in Upper Burma, the point was established beyond doubt by evidence obtained from an area far to the northward of where the question had first arisen and become of importance. The Irrawaddy Series was found some seventy miles to the northward to contain evidence of volcanic action several hundred feet above its base. This evidence included outflows of lava, and formation of explosion-craters with beds of ash and agglomerate. The ashes contained many blocks and fragments of metamorphic rocks, abundance of acid lava bombs and fragments including beautifully silicified rhyolites. The strata of the Irrawaddy Series above the volcanic beds were found to contain pebbles of metamorphic rocks and agate, and occasionally much decomposed felspar and kaolin.

The basal beds of the Irrawaddy Series in the Magwe District to the southward, where the unconformability was in question, contain well-rolled pebbles of metamorphic rock and agate (from the silicified rhyolites), while kaolin was found in some of the sands. None of these appear in the underlying Pegu Series, and it was the occurrence of kaolin in a bed, then considered to belong to the Pegu Series, that first turned the attention of the writer to the possibility of there being an unconformability. Examination of intervening, but discontinuous, areas gave confirmatory evidence, and it became clear that the basal beds of the Irrawaddy Series, in the Magwe District are post-volcanic, and that the pre-volcanic beds of the Irrawaddy Series, some hundreds of feet thick in the Pakokku District, have either never been deposited in the Magwe District or have been removed by denudation. Thus a considerable gap in the succession was proved, and the detection of pre-Irrawaddy movements, as explained above, completed the chain of evidence. The identification of fossil horizons in the Pegu Series has since made clear that this unconformability is often of very great extent, and that great thicknesses of the upper beds of the Pegu Series have been removed by denudation in many localities before the deposition of the basal beds of the Irrawaddy Series.

Another instance of unconformability, for long a matter of doubt, may be given from Burma, namely, the unconformability between the basal beds of the Pegu Series and the underlying Bassein Series, probably of Eocene-Cretaceous age. This line of discordance had been crossed and recrossed by several geologists without its being detected, and presumably they classed the underlying Bassein Series with the petroliferous Pegu Series above. The first evidence that called attention to the possibility of there being an unconformity was afforded by the fact that the great littoral arenaceous group of the Yaw sandstones, which forms a very strong feature in the foothills of the Arakan Yomas, is underlaid by softer strata with a rather different aspect as regards lamination, bedding, jointing and state of mineralization. Subsequently evidence of movement, folds, and small faults were noted in the underlying series and proved not to affect the Yaw sandstones, and finally the mapping on the six-inch scale of a few square miles, where excellent sections can be seen, proved that the Yaw sandstones transgress over hundreds of feet of the Bassein Series. In many small sections, notwithstanding, the two series differ so slightly in strike and dip as to appear perfectly conformable.

In Persia the detection of an unconformability proved of the greatest importance from the practical point of view of oilfield development. During the detailed mapping of the oilfield at Maidan-i-Naphtun the possibility of there being such an unconformability had been suggested by the discovery of the detrital limestones, and the occurrence of great conglomerates at various horizons in the Tertiary series full of well-rounded pebbles of limestone. It was known from the work of previous observers that a great mass of limestone (the Asmari limestone) lay at a lower horizon, and it had been suggested that drilling in anticlines of this limestone might be profitable. When the Asmari limestone was first encountered by the writer on the north-west pitching end of the Asmari anticline, evidence of unconformity was at once searched for, but beyond thin beds of detrital limestone resting here and there on a somewhat irregular surface of the calcareous rock, the occurrence of one small patch of breccia, and a slight discordance in dip and strike between overlying beds of gypsum and the Asmari limestone, possibly due to movement, no evidence was forthcoming. The various kinds of limestone preserved in pebbles and fragments in the conglomerates near Maidan-i-Naphtun were, however, matched from the solid outcrop of Asmari.

A few days later, in the next great anticline to the north-eastward, where the Asmari limestone again appears, demonstrative evidence at once came to light. A great transgression of beds high up in the oil-bearing series, chiefly conglomerates full of limestone pebbles, was observed cutting right across the anticline of limestone, which in places is entirely removed by denudation, some 2000 feet of thickness having been denuded. On the flanks of the limestone outcrop bed after bed of the oil-bearing series makes its appearance between the calcareous rock and the great conglomerates which lie across the denuded anticline.

Recent work by members of the Anglo-Persian Oil Co.'s geological staff has shown that great overthrust faults account for some of the structures formerly believed to be due to unconformability, and that the unconformable Bakhtiari conglomerates are of later date than the oil-bearing series and belong to a different group. This, however, does not affect the evidence of a great change in conditions accompanied by local unconformability between the Asmari limestone and the oil-bearing (Fars) series.

It appeared probable that these anticlines were denuded as they rose under the flexuring movement, and that the succession may be entirely conformable in the synclines; consequently at the north-west end of Asmari Hill, where the fold of limestone pitches sharply downwards, no striking evidence of unconformity could be expected.

The point of importance from the oil-development point of view is that the oil-bearing strata belong to a different series, and are of later age than the Asmari limestone, and to attempt drilling in the latter would be entirely speculative and unjustifiable. But for the detection of this unconformability we should be, as far as that region in Persia is concerned, still in the dark as regards the conditions under which these Tertiary strata were deposited, and as to what districts are most favourable for exploitation.

In Southern Ohio probable unconformities that do not crop out at the surface have been detected in strata either horizontal or very gently dipping, and the transgression is sometimes exceedingly regular. Mr. Frederick G. Clapp has explained this matter very clearly in one district, showing that the Clifton sand (a well-known oil-bearing horizon) increases in depth eastward at a rate of from 30 to 100 feet per mile more than is indicated by the datum line given by a characteristic bed exposed on the surface. In such a case the evidence from wells becomes more important than a detailed study of the surface. But such remarkable regularity must be exceedingly rare, and there is always the possibility that the effect may be due to lateral variation, the thinning or thickening of the oilsands and the beds intervening between them and the surface, rather than to unconformability and overlap. Variations in thickness as great as this when a series is traced far in the same direction may be observed in the Sabe and Yenankyat fields in Burma, where a series of deep valleys across the strike makes it possible to measure the thicknesses of groups in actual sections. In cases such as that of Southern Ohio, the evidence from wells is essential, and it is a matter more for the consideration of the oil-engineer than for the geologist, whose examination of the evidence at the surface should be complete before wells are drilled in a new field.

Unconformabilities, the extent and directions of increase of which have not yet been worked out, are already causing difficulties to those entrusted with the exploitation of some areas in Trinidad, and have perhaps done something to confirm the popular idea that petroleum is a very capricious mineral, and that, as the driller is fond of reiterating, "the only way to find oil is to drill a hole for it."

But of all oilfields, the successful development of which depends on a study of unconformability and overlap and the directions in which erosion of the denuded surfaces beneath unconformable junctions increase or decrease, the most remarkable perhaps is the island of Barbados.

The writer had the pleasure of making for the Colonial Government a complete oilfield survey of that charming island on the scale of six inches to the mile, and found that many interesting problems have to be faced in advising as to the exploitation of the petroleum, of which the indications are plentiful and good. Here we have evidence of folding movements of considerable severity acting in different directions and at different times. There are two great unconformities. The oil-bearing series, much folded and not a little faulted, is overlaid unconformably by a series of oceanic deposits, which in their turn have been thrown into flexures, raised within the zone of denudation, and overlaid unconformably by a thick mass of coral limestone of comparatively recent date, which rises in terrace after terrace lying horizontally and covers by far the greater part of the island. The surface of the oil-bearing series is irregular, and there is an overlap of the upper beds of the Oceanic Series over the lower, while there is another overlap of the coral limestone over the Oceanic Series, which has doubtless been removed by denudation in many places, so that the coral limestone rests directly on the petroliferous series (the Scotland Beds) in several districts.

The petroliferous series is folded on E.N.E. and W.S.W. axes as a general rule, but the folding strikes more N.E. and S.W. towards the centre of the island. A distinct post-Oceanic folding also has taken place, striking N.E.–S.W. to N.N.E.–S.S.W. This second folding, though not very intense, is probably the more important from the petroleum point of view. During the formation of the coral terraces the movement seems to have been a simple one of elevation with intervals of quiescence.

In these circumstances some very complicated structures have been produced, and it is only by paying special attention to the unconformabilities that areas can be discovered where conditions favourable for the concentration and storage of petroleum exist; for it is evident that if the petroliferous series be too deeply denuded and overlaid by coral limestone, the intervening Oceanic beds having been removed by denudation, there will be little prospect of finding oil in quantity. Again, where the pre-Oceanic denudation has been great the Scotland Series of petroliferous rocks may be insufficiently sealed. But in localities where the Oceanic Series is found in large and well-defined folds and in considerable thickness the petroliferous rocks may be well sealed and, though complicated in structure, generally speaking, in an anticlinal position. Belts of country where such conditions exist have been recognized, mapped and described, and only await testing with the drill, a test which has hitherto been denied them, but which in the national and Imperial interest should not be long delayed. Yet in spite of sharp folding, faulting and unconformabilities, oil has been produced in small quantities for several years, and though the work has not been a great commercial success up to date, there are prospects of valuable oilfields being proved. Success will depend upon the working out of the effects of the different movements and consequent unconformabilities, and the determination by such methods of where the petroliferous strata, whether deeply buried beneath younger deposits or not, will be found under conditions most favourable for good productions of oil.

Sufficient has been written to show that unconformabilities are common phenomena in Tertiary oilfields, and that they must be studied carefully if the structure of a country is to be ascertained beyond the possibility of doubt. They are of great practical importance to any company undertaking development work.

Thus folds, faults, and unconformabilities must be considered together and in detail before any connected history of a country or district can be presented, and it may often be necessary to visit areas far beyond the confines of a district before some of the problems in structure that it exhibits can be solved. There must be no such thing as *opinion* about geological structure; only the facts will suffice, and the geologist must make absolutely sure of structure if the drilling programme is to be directed with the least possible number of failures and the greatest number of successful results, since in the area selected through knowledge of the oil-bearing series and its lateral variations it is the geological structure and nothing else that determines the extent of each field.

An oilfield with several producing wells, but with no geological map, may be part of a great potential producing area, or may be the merest fringe in which oil production is possible. The area between two producing wells is *not* developed or proved, unless the geological structure of the intervening ground is known, and known to be favourable. But a very few wells, carefully located, will enable the geologist to determine within reasonable limits the probable productive area of a field.

Hence every detail of dip, strike, change in dip or strike, hade of axes of flexures, and pitch of axial lines must be noted, and if the area be undulating the height of each locality where observations have been made about a datum line should be ascertained. Then and only then can absolute certainty as to structure be achieved.

CHAPTER VI

INDICATIONS OF PETROLEUM

"OUR Manager cables as follows:—'Borehole No. 3 has reached a depth of 792 feet, and the indications are favourable.'" To how many meetings of anxious shareholders have such or similar comforting words been read, and how often do we see a message of this nature dealing with a new field under exploitation quoted in the public Press? And it would be a very bold and even impudent shareholder who would rise in his place and ask pointedly: "What are the indications, and why are they considered favourable?"

Such queries would no doubt receive answers, but in all probability they would be vague and carefully guarded statements, for the Chairman or Managing Director of a company may very naturally consider that it is not his duty to study geological data; he depends upon the Manager or Field-Superintendent, who has cabled; or the log of the well has been submitted to an expert at home, who has pronounced the indications "favourable." And the shareholders may go away satisfied, though it may be that neither Field-Manager nor expert has any certain knowledge of what would be "favourable" indications *in the locality and at the depth stated.*

This at once raises the question of what are favourable indications of petroleum, *i.e.* indications that point to the probability of good productions being obtained.

The subject naturally divides itself into (1) Surface indications, and (2) Indications in a borehole.

(1) **Surface Indications.**—It is to indications at the surface that attention has always been attracted. The expert who visits a new district goes first to the localities where "shows," as they are called, are to be seen, and it is largely by the

presence of "shows" in any piece of land that it is judged by persons without technical knowledge. The field-student will do well to make himself acquainted as soon as possible with the nature of the "shows" which he may expect to find in the country that he is examining. He has, let us say, made his preliminary traverses, gained some idea of the lateral variation, and discovered that favourable structures produced by the earth-movements he has been studying are to be found. The time now comes for him to study the indications at the surface as a guide to what thicknesses of strata and what horizons may be expected to prove petroliferous, and what variety of oil is present.

Let it be admitted at once that the actual shows of oil are of great importance; much is to be learnt from them, but the study of structure must take first place. It is a surface show that always attracts the lay mind. During the writer's first examination of an oilfield he inadvertently grieved an enterprising pioneer who had pointed out a small seepage with the remark "there is what would make glad the heart of a Rockefeller," by bluntly answering that he himself took little interest in such indications so long as the geological structure was still unsolved. As a matter of fact, it is very frequently where surface shows of oil are seen that drilling would be entirely unsuccessful, and many of the greatest oilfields known to-day have not a single surface indication within their length and breadth.

Surface indications are of various kinds according to the class of oil, the nature of the strata, and the geological structure. They comprise:—

(*a*) Seepages of oil.
(*b*) Asphalt deposits.
(*c*) Evolution of gas from gas-pools, mud-volcanoes or dry ground.
(*d*) Outcrops of bituminous strata,
and
(*e*) Veins of manjak or ozokerite.

In addition to these the evolution of hydrogen sulphide may be in some cases a favourable indication, and crystals of sulphur in cavities in a rock, or the presence of minute traces of sulphur in flecks and patches may also be important. Belts of stunted or sickly vegetation may give a valuable indication where no solid evidence is available. Finally a faint odour of petroleum may sometimes be detected where no actual seepage can be discovered.

(*a*) *Seepages of Oil.*—Where an oilrock reaches the surface there is generally some sign of petroleum. It should be looked for in low ground, in the beds of streams, or at the foot of hills, and, if the strata be bent into anticlinal form, at or near the crest of the anticline. In many cases where the upper part of an outcrop has lost all signs of petroleum through weathering, a seepage will be noticed where the outcrop crosses the valley of some small stream or gully. In such localities films of oil with a beautiful iridescence may be seen on the surface of the water. The odour will at once distinguish these films from decomposing bicarbonate of iron which also gives an iridescent film (of hydroxide), and which has often been mistaken for evidence of petroleum. The films in these two cases, however, are by no means identical, and when seen side by side could never be mistaken.

If the seepage be more copious, brown or greenish or black drops of oil may be seen, and these may collect into patches on the water near their source or in eddies and still pools down stream. Gas is frequently seen bubbling up through the water. In some cases actual trickles of oil out of the rock may be observed. But the greater part of the outcrop of an oilrock will probably give no indication of being petroliferous until dug into for a few inches or perhaps feet.

The cavernous detrital limestones of Maidan-i-Naphtun exude oil rapidly in the valleys of streams, and where the water is clear small spherical drops of the oil may be seen emerging from cavities and rising to the surface. But the greater part of the outcrop is barren of indications. The greatest natural show of liquid petroleum which the writer has seen occurs in this field; as much as 20 barrels a day of oil flow to waste in one stream. Three or four brisk seepages combine to make up this quantity, and from time immemorial the Shusteris have collected the petroleum and burnt off the light oils to obtain bitumen.

Another remarkably large seepage occurs in the Trinity Hills Forest Reserve in Trinidad. At the time of the author's visit to this spot a stream some three yards in breadth was covered entirely with a dark brown oil with green fluorescence for a distance of nearly a hundred yards, while gas bubbled up briskly both through the water and from several places on the banks. This show is on an outcrop of the Galeota Oil-bearing Group.

Oils with a paraffin base usually make smaller and less striking seepages than asphaltic oils, as the results of inspissation are more readily washed away by rains, and the rock from which the oil exudes is more easily and quickly robbed of its petroleum contents under weathering processes. Many of the outcrop shows in Burma, where the oil is generally light and full of solid paraffin, consist, even on the outcrops of thick oil-sands, of very small pools not more than a foot or two in diameter in the courses of small ravines and stream valleys.

Oil obtained from seepages is always more or less inspissated, and does not give a fair sample of what may be obtained by drilling, the light fractions having evaporated.

An asphaltic oil can usually be distinguished from a paraffin-base oil by the manner in which it inspissates; the former generally remains liquid or semi-liquid for a longer time but dries finally to black asphalt; the latter soon coagulates into little flakes often of a reddish-brown colour, and when present in quantity and containing much solid paraffin dries into a soft mass like vaseline, which does not adhere to exterior objects with the same tenacity exhibited by asphaltic oil, and is consequently more easily washed away.

The most remarkable seepages of oil are those that have been naturally filtered, and partly or entirely decolorized. In such cases the petroleum, though it has probably lost its most volatile constituents by inspissation, has also been deprived of the bulk of its heavier fractions by filtration. The "white oil" of Kaleh-i-Deribid in Persia has already been mentioned; it is a limpid mobile liquid that the writer could hardly believe to be oil till he had dipped his hand in it.

Another interesting example of a filtered oil, this time of asphaltic base, may be observed exuding from an outcrop of sandy clays in a small tributary of the Lizard River in the south-eastern corner of Trinidad. The locality has been called "Lizard Spring." The oil is dark brown with a green fluorescence, and it collects on the surface of the water in the stream bed. When the writer was encamped in the forests near this spot a sample of the oil was skimmed by means of a leaf from the surface of the water, bottled, and taken into camp, where it was burnt that night in a small open lamp, hardly clogging the wick at all. An analysis of the oil collected in this manner at Lizard Spring was made some years ago by Professor Carmody, Government Analyst of Trinidad, who found it distilled like a refined oil, and gave:—

Petroleum spirit	0
Illuminating oil	73
Lubricating oil	25
Residual bitumen	2
	100

The specific gravity was ·867, and the flash point was above 145 degrees (Abel's test). This oil is sufficiently inspissated to make it a perfectly safe burning oil, and to contain a fair percentage of heavy oil and residue. A year or two later a small excavation was made in the outcrop, at the author's suggestion, to obtain a further sample of the oil. Professor Carmody's analysis showed this second sample to contain:—

Petroleum spirit	12
Illuminating oil	81·25
Lubricating oil	6
Residual bitumen	0·75
	100

The specific gravity was considerably lower. This is obviously a dangerous oil on account of its percentage of petroleum spirit, and could not be burnt with safety in a lamp. The two analyses are interesting as showing the effects of inspissation. The oils are both well filtered by passage through the argillaceous strata, and it is hardly necessary to say that were a borehole drilled at this spot an oil of this class would not be obtained in any quantity, though heavier unfiltered oils from the same source would probably be struck.

Evolution of oil is not unfrequently observed in the sea, where an oil-bearing stratum is exposed beneath the water. In the Caspian Sea such shows were well known for many years before any active drilling was undertaken at Baku.

Off the coast of Trinidad there are many places where oil is occasionally to be seen. Perhaps the best known is just west of the famous Pitch Lake, where a brisk evolution of gas with drops of brown oil may be observed about a quarter of a mile off shore. The activity of this show varies considerably, but on a breezy day the locality can usually be detected by the presence of a patch of smooth water, the film of oil covering it being sufficient to prevent waves from breaking.

At the mouth of the Vance River, and again at Point Ligoure, where outcrops of the Rio Blanco Oil-bearing Group run out to sea, the water is sometimes covered with a film of oil for a considerable distance. Other submarine shows near the eastern and south-eastern coasts are sporadic and occasionally of explosive violence; after an outburst sticky oil and soft asphalt are washed up on the shore in considerable quantity.

Off the south-western corner of Tobago there is apparently a submarine outcrop of oilrock, for sticky inspissated petroleum is washed up on the beach and the coral limestone in great quantity at some periods of the year.

It may occasionally happen that there is some doubt about an oil-seepage being genuine. Not that the geologist is ever likely to encounter "salted" ground, since it is almost impossible to give a genuine appearance to any manufactured oil-show at the surface, and any crude attempts that may be made to deceive a scientific observer have little chance of success. But there are cases of genuine mistake where oil is found in the ground and its source is not immediately recognizable. Often such occurrences are merely ludicrous, but they may deceive many people without scientific knowledge and may cause quite unnecessary excitement and even speculation.

When the search for petroleum in Britain was initiated many amusing cases were brought to the attention of the writer. There was, for instance, the drainage of a lubricant made of oil and soap from a munition works into a bed of porous alluvium and so into a well at some distance away

This "seepage" was easily recognized by the colour and the presence of soap. There were several similar "shows" reported from different places, and some without even such meagre justification which the writer had to visit and report upon.

But the most amusing of all was the case of Ramsey, in Huntingdonshire. It is worthy of being staged as a comedy—or tragedy, but the facts are simple and instructive and so may be recorded. The country is almost absolutely flat, and the town of Ramsey lies just on the margin of the fens. There is about sixteen feet of sandy alluvium and then clays of Jurassic age and great thickness. They have been drilled through to a depth of over 300 feet in the near neighbourhood, without giving any sign of petroleum. Now in the main street of Ramsey there is an ironmonger's shop where kerosene and other oils are kept, and have been kept for thirty-four years. There was once one large tank for kerosene sunk in the ground (said to have contained one thousand gallons), but it had been removed. Next to the ironmonger on the one side is a butcher's shop and yard, with a well and pump, while at a slightly greater distance on the other side is a hair-dressing establishment, also with a yard, well and pump.

These wells are about twenty feet deep: they are not used much, as the surface water is not fit for drinking purposes.

There had been no rain to speak of in the neighbourhood for three months, water-level in the alluvium had sunk low, and the accumulated leakages of many years of kerosene storage collected in the wells. At this time, so the story goes, the butcher had a new boy, who being ordered to get water from a horse-trough some distance up the village street to put in the pigs' food, thought it better to use the pump that was at hand. He pumped a gallon or two of refined kerosene into the pigs' food, and that started the "Ramsey Oilfield." Next day the barber tried his pump, and not only found kerosene—after pumping out a little water—but also soapsuds, which were promptly called "petroleum jelly."

It is quite unnecessary to recount the excitement that followed, the newspaper correspondence, the exaggerations as to the quantity of oil actually obtained, the talk of forming an exploitation company, etc. Many people visited the locality, studied the evidence, and took it seriously or as a tragi-comedy according to their knowledge and experience. But as one shrewd Canadian who visited Ramsey remarked to some of the farmers of that district, "when you can show me broad-cloth growing on the back of a sheep, I'll believe in refined kerosene coming out of the ground."

It is to be feared that that point could not appear unanswerable to those who have never seen crude petroleum, nor know the differences between it and its refined products, but on those differences the distinction between leakages and genuine seepages is drawn without possibility of error. A renewal of drought at Ramsey has lately caused the kerosene to appear once more in the wells, but the short-lived oil-boom can hardly be expected to recur.

(*b*) *Asphalt Deposits.*—Oils of asphaltic base nearly always make their presence obvious, when the conditions are favourable, by more or less extensive deposits of asphalt along the outcrops of the petroliferous strata. There is, of course, no hard-and-fast line between a seepage of crude oil and a deposit of asphalt; every gradation of sticky and inspissating oil between the two may be observed on the same outcrop. In Trinidad, where most, though not all, of the oils are asphaltic, the phenomena of asphalt deposits can be studied on a remarkable scale. Foremost of all comes the famous Pitch Lake, the best known, though not the most extensive, asphalt deposit in the world. Much has been written about it, and many theories have been propounded to account for the origin of this lake. Without going in detail through the theories of various authors and pointing out where each has advanced the knowledge of the day, it may be as well to give a brief description of the field evidence and the last published, and so far accepted, theory; the author may be pardoned for inserting a lengthy quotation from his official account from the Council Papers of Trinidad, No. 60 of 1907, more particularly as this account has been drawn upon extensively by others, and large portions of it published verbatim and without acknowledgment.

"A brief account of the evidence obtained in the field, and from other sources, must be given. The Pitch Lake lies upon a well-defined plateau 138 feet above sea-level. The area has recently been affected by gradual upheaval, as proved by raised beaches in the neighbourhood, and it is probable that the plateau at no distant date, geologically speaking, stood at or below sea-level, and is in fact a raised beach or coastal bench itself.

"The geological structure is a gentle anticline which runs roughly east and west, the lake being upon the crest. The vicinity of the lake is almost entirely covered with surface deposits concealing the solid evidence. The underlying rocks are lightly compacted and are often disintegrated to a great depth, and the surface wash of disintegrated material covers almost all the ground. The 'brown shales' mentioned by Messrs. Louis and Gordon, though often giving an appearance of stratification, are not Tertiary sediments, but recent surface deposits. The brown colour is due to the presence of finely divided bitumen or asphalt dust.

"The La Brea oilsand, a deposit of variable thickness, is the source of all the pitch. It crops out to westward of the lake in the coast section, to eastward of the plateau, and also to the southward near the Vessiny River, and in inliers in hollows. Its outcrop has been mapped for several miles. This oilrock is covered by a fine bluish clay, which, when impregnated sufficiently with bituminous material, has occasionally become ignited and burnt to porcellanite, *e.g.* south and south-west of the lake. The clay in its turn is covered by a soft yellow sand, the disintegrated outcrop of which covers much of the area north of the lake.

"Whenever the capping of clay is thin, or the oilrock is merely covered by superficial deposit, or is actually exposed, soft asphalt exudes, forming small cones, examples of which may be seen beside the road between the Asphalt Company's works and the lake, and at several places north and west of the lake.

"The oilrock, where it is exposed on the shore west of the lake, is a fine dark sand, so full of bitumen that the superficial layers actually flow slowly, the semi-liquid asphalt as it exudes carrying the inorganic material of the rock with it. Pieces of this rock may be twisted off in the fingers and rolled into pellets. An analysis of a specimen by the Government Analyst gives the following results:—

Water, etc., volatile at 100° C. . .	5·24
Bitumen	15·1
Non-bituminous organic matter . .	29·70
Ash	49·96
	100·00

Soluble in petroleum ether . . . 8 per cent.

"This specimen was taken from a weathered tide-washed outcrop. The quantity of non-bituminous organic matter is remarkable, but, as will be seen later, recent work by Mr. Clifford Richardson has thrown much light upon this point.

"A shallow boring (about 60 feet) was made in the outcrop of oilrock west of the lake, many years ago. It is situated 200 feet from the sea and yields a small quantity of rather heavy oil. A sample taken from the surface gave the following results on analysis by the Government Analyst:—

Specific gravity	0·950
Mineral matter	0·02 per cent.
On distillation—	
Water	1·2
Petroleum spirit	12·8
Illuminating oil (150°–300° C.) . .	36·0
Lubricating oil (above 300° C.) . .	32·0
Residual bitumen	12·3
Loss	5·7
	100·0

"In the sea at a distance of about 200 yards west-south-west of the last-mentioned locality, there is an oilspring. A smooth patch on the water is often conspicuous, and in it drops of brown oil may be seen floating, while gas bubbles up all round, and a film of oil sufficient to prevent waves from breaking sometimes covers the surface for a considerable distance.

"In the hollow east of the plateau on which the lake is situated, the oilrock crops out again, and large flattened cones of semi-liquid asphalt may be seen with slight evolution of gas. In these cones or rather pools of soft pitch the material can be seen exuding, and it is streaky with the quantity of inorganic matter brought up with the bitumen, indicating that either the cohesion of the oilrock breaks down when it is exposed, or that superincumbent material is carried up by the flow of asphalt and gradually absorbed in it.

"Borings made by the Asphalt Company in 1893 have furnished additional evidence of the underlying oilrock. In the centre of the lake a depth of 135 feet was reached without touching bottom, but at 1000 feet from the centre on the north side fine sand was struck at 80 feet, then more asphalt, and at 90 feet asphaltic sand, *i.e.* the more or less disintegrated oilrock. A boring south of the lake also struck a hard asphaltic sand, obviously the same which crops out to the east-south-east, the course of which can be traced by lines of asphalt cones. The oilrock cannot be identified in the coast section in Guapo Bay, but porcellanite and lignitic shales covered by sands and sandy clays probably represent it, and indicate that the oilrock is thinning out and the oil-producing conditions at this horizon ceasing in this direction.

"The next evidence to be considered is the composition of the lake pitch. This is treated of so fully in Mr. Clifford Richardson's book, 'The Modern Asphalt Pavement,' that a few brief quotations will suffice. The average composition of the lake pitch is given as:—

Water and gas	29 per cent.
Organic matter, not bitumen	7
Mineral matter	25
Bitumen	39
	100

"The asphalt is an 'emulsion' of these constituents. The inorganic matter consists of fine sand and clay with a small quantity of iron oxide and soluble salts. Mr. Clifford Richardson gives an analysis of the mineral matter as follows:—

SiO_2	70·64
Al_2O_3	17·04
Fe_2O_3	7·62
CaO	0·70
MgO	0·90
Na_2O	1·56
K_2O	0·35
SO_3	0·97
Cl	0·22
	100·0

"This corresponds with the composition of a normal sandstone, with slight admixture of argillaceous material. The microphotograph of the mineral matter which Mr. Clifford Richardson published ('The Modern Asphalt Pavement,' p. 34) shows all the characteristics of the debris from an ordinary fine waterborne sandstone, the grains not being greatly abraded as in windblown sands, nor having any of the characteristics of silica deposited from solution. The finest material is a fairly pure clay. The percentage of 'Organic matter not bitumen' presents a point of great interest: as recorded above, the percentage of this in the La Brea oilsand was as much as 29, while in the Rio Blanco oilsand it was only 0·46, a difference great enough to enable these different types of oilrock to be distinguished easily. Recent work by Mr. Clifford Richardson upon the absorptive properties of fine clays for bitumen explains the occurrence of this percentage of this hitherto little-understood constituent in asphalts, oilrocks and manjaks. In a paper read before the American Society for Testing Materials, and afterwards published in the 'Engineering Record,' he describes experiments made with Trinidad lake-asphalt and tests of the absorptive and 'adsorptive' properties of various fine clays upon solutions of bitumen. The results arrived at are briefly that fine clays have the power of decolorizing bituminous solutions by absorbing or 'adsorbing' a proportion of the bitumen in such a manner that it cannot again be removed by the action of solvents. Thus the greater part of the 'organic matter not bitumen' can be proved to be bitumen which cannot be removed in solution. The presence of water may also have some effect in favouring this absorption, but the proportion of fine clay present seems to be the more important factor. Applying these results to lake-pitch and the oilrock from which it is derived, we have at once an explanation of the presence of argillaceous material in the asphalt, and we must increase the percentage of bitumen in lake-pitch by almost, if not quite, 7 per cent. and the percentage in the oilrock probably by a much greater amount. This makes the breaking down of the cohesion of the oilrock on exposure much more intelligible.

"The lake itself is, by the latest survey made under the supervision of the Inspector of Mines, 137 acres in extent, the margins being covered in places by superficial deposits washed down from the surrounding ground. In the centre the surface of the asphalt is about six inches higher than near the sides, and for some distance from the centre there are no water-channels. Then comes a broad zone characterized by water-channels dividing the surface into roughly circular areas with rounded edges. Near the shore the pitch is harder as a rule, and less cut up by water-channels. Near the centre there is an area of very soft asphalt, where a little gas issues slowly, while there are similar but much smaller patches near the western margin and between it and the centre. The distribution of these areas of very soft pitch indicates the proximity to the parent oilrock, whence continuous but minute exudation of pitch is still taking place. Lest there should be any misunderstanding upon this point, it must be repeated that Messrs. Louis and Gordon have proved conclusively that the lake is exhaustible, and is being depleted at a very rapid rate, but the presence of the patches of soft asphalt and the difference in level between the centre and sides make it clear that additions of asphalt, probably amounting to only a few tons in the year, are still being made, just as the same material is exuding in the ground to the eastward and south-eastward of the lake.

The gas given off from the lake is chiefly sulphuretted hydrogen formed by the action of water on sulphur compounds in the asphalt. It is seen bubbling up in the water-channels. A small quantity of oil-gas, however, may be detected issuing from the soft patches.

"The 'pitch-lands' of La Brea village are undoubtedly, as pointed out by Messrs. Louis and Gordon, an overflow from the lake. This overflow has taken and occupied the valley of a small stream, known as the 'pitch-lake ravine,' and has in effect pushed the stream westward, where it now flows at a higher level than its original course. There is no evidence of any exudation of asphalt in the village lots, though gas has been detected issuing from the ground on one or two occasions. Weathered surface deposits underlie as well as overlie much of the land asphalt, proving that the overflow, which ceased some years ago, took place under subaerial conditions.

"From the evidence detailed in the preceding pages the origin of the Pitch Lake can be explained as follows:—

"In the first stage the La Brea oilsand, covered by its cover-clay and succeeding sediments, lay below sea-level. Under a flexuring movement acting in a north and south direction, the area was subjected to elevation, a gentle east and west anticline being gradually formed, and the strata above the oilrock were raised within the zone of denudation, though probably still below sea-level. Denudation of the crest of the anticline took

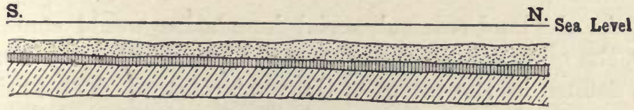


Fig. 5.—Stage I.

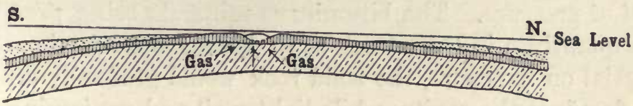


Fig. 6.—Stage II. Submarine mud-volcano.

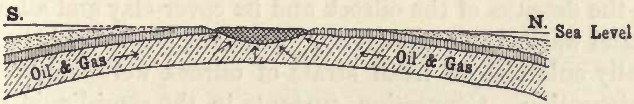


Fig. 7.—Stage III. Formation of plateau.

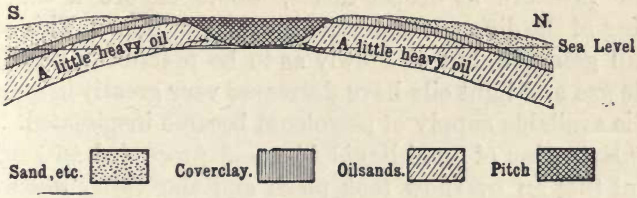


Fig. 8.—Stage IV. Present day.

Figs. 5–8.—Diagrams to illustrate formation of Pitch Lake, Trinidad.

place till the reduced thickness of the puddled cover-clay was not sufficiently tenacious to resist the upward pressure of gas from the oilrock. A mud-volcano would be the result, and, as denudation and elevation both continued, would increase in size. All this probably took place beneath the water. As the covering was gradually removed, oil began to exude and to dry up to a sticky asphalt.

"About this time the anticline was probably becoming more clearly defined, and the site of the pitch-lake began to emerge from beneath the sea as a hollow in which discharge of gas and oil was continually taking place, while mingling with inorganic minerals would be favoured by tides and wave action. This stage is marked by the formation of the plateau, suggesting that the surface remained at or near sea-level for a considerable time.

"As the land rose sub-aerial denudation would come into play, the oilrock itself being exposed over a roughly circular area defined by the extent of the mud-volcano. The anticline being now well marked, gas and oil would be forced from all sides towards the crest, where the exposed oilrock would afford relief of pressure. The bituminous minerals being present in such quantities in the oilrock as to destroy the cohesion of the material on exposure, the solid rock would gradually crumble and flow into the cavity, while lighter oil and gas issuing from below assisted in the incorporation of the inspissating petroleum with the detritus of the oilrock and its cover-clay and all other material washed into the cavity. Thus the basin would be continually enlarged as fresh strata of oilrock were laid open to disintegration. Convection currents in the semi-liquid mass and discharge of gas, while there were still quantities of gas under pressure at deeper levels, would ensure a thorough mixing of the different materials into an emulsion. This action is still going on, but so slowly as to be practically negligible, while gas and light oils have decreased very greatly in quantity as the available supply of petroleum became inspissated.

"Extrusion of semi-liquid bitumen proceeded to such an extent that an overflow took place and the valley northward towards the sea was completely filled with asphalt, which is still flowing slowly downward, though there has not been any escape of asphalt from the lake for some years. That this overflow took place under sub-aerial conditions is proved by the weathered state of the superficial deposits beneath the land-pitch, and by the form of the valley floor. This shows also that the site of the lake had by this time reached a considerable height above sea-level, and sub-aerial denudation must have meanwhile been affecting the surrounding country, leaving a remnant of the plateau, but trenching it so deeply on the east-

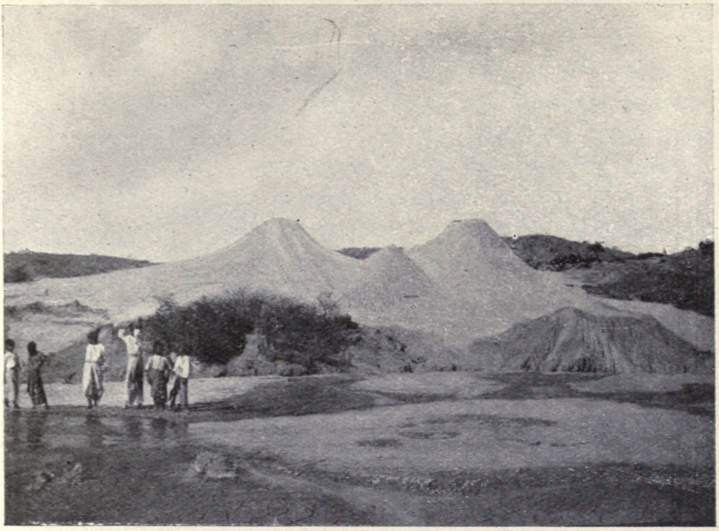


Photo. by S. L. James

i. GROUP OF MUD VOLCANOES AT MINBU, UPPER BURMA.

Photo. by S. L. James

ii. THE LARGEST MUD-VOLCANO AT MINBU.

ward and south-eastward as to expose the oilrock, but not under such conditions as regards gas-pressure, etc., as to give rise to mud-volcanoes. The flow and exudation may at one time have been fairly rapid, but it is now, naturally, very sluggish owing to gradual inspissation. In its latest stage, soil has actually been washed down from the surrounding country over the margins of the asphalt in several places."

The lake is exceeded in size by similar asphalt deposits in Venezuela, where, however, the bituminous material is purer, softer, and more difficult to work commercially. The depths of these Venezuelan lakes have never been ascertained.

Though the evidence of the extrusion of asphaltic petroleum as afforded by pitch-lakes is very striking on account of the concentration of the material in one locality, it is no more significant than the asphaltic deposits that mark the outcrops of oil-bearing strata in many parts of Trinidad. The deposits are usually in the form of flattened and rounded cones strung out in lines along the outcrop, and where no actual exposure of the strata is seen it is often possible to map the outcrop simply by these exudations. They vary in size from a diameter of a few inches up to as much as seven or eight yards, and in height from an inch up to six or eight feet. Where the exudation is rapid and copious the cones often coalesce, and an area of an acre or more may be completely covered with the material. Similarly a flow of asphalt down a gully may be seen occasionally, though it is seldom that such streams exceed one hundred yards in length and eight or ten feet in depth.

The consistency of the material also varies from soft sticky oil to hard compact asphalt that can be broken by the hammer, the softer varieties being the most recently extruded. The skeletons and remains of birds and small animals are not unfrequently found in such soft asphalt deposits, showing where they became mired, and being unable to extricate themselves, perished. The writer on one occasion found a live "morocoi" or land-turtle firmly embedded in a soft exudation.

There is nearly always some evolution of gas with the soft asphalt, but as a rule it is discharged very slowly. In some of the cones there is a deep crater in which a bubble of semi-liquid asphalt rises under pressure of gas from below periodically, perhaps once in two minutes. The bubble ascends to the lip of the crater where it breaks by the formation of a small orifice, allowing the gas to escape with a gentle sibilant sound, while the enclosing film sinks down again. In some parts of the forest where the extrusion of asphalt has been so copious that a thick outcrop of richly petroliferous sandstone has been almost completely sealed, a weird effect is produced when the asphalt cones are heard sighing around one; the imaginative geologist may weave romances upon this slender basis, and picture the imprisoned oil sighing for the advent of an Exploiting Company by whose powers it will find release.

These asphalt deposits are always more or less mingled with inorganic and vegetable matter and all the debris lying on the surface of the ground, but in spite of this analysis usually shows a percentage of bitumen of 70 or 80.

In the forests of Trinidad the outcrop of an asphaltic oilsand is usually marked by a belt of stunted vegetation, creepers, and vines taking the place of the larger trees to a greater or less extent.

As an outcrop becomes clogged by the exudation, the sticky oil or liquid asphalt breaks out again and again in the direction of dip, so that we find the escarpment side frequently marked by hard asphalt, while the fresh exudations are towards the dip-slope. Such evidence has more than once proved of value in giving an indication of the direction of dip in a locality where no exposures of solid rock were to be observed.

It has often been suggested that such asphalt deposits are not a favourable sign, that exudation on a large scale must have depleted the oil-bearing strata beneath the surface, and that the oil will necessarily be greatly inspissated and too heavy and viscous. There is a modicum of truth in such suggestions, but in actual practice the geologist need not fear such hypothetical depletion; where he finds an outcrop steadily exuding sticky oil and asphalt, he may be assured that rich sources of oil lie beneath the surface, and that inspissation, though it has doubtless had a considerable effect upon the grade of the petroleum, will not have made it by any means valueless. In California, Mexico, Trinidad, and many other countries this has been proved again and again. In fact, we may consider that such asphalt deposits are among the most favourable indications that an oilfield can furnish.

In Trinidad it is possible to walk for miles in the forests without ever being out of sight of asphalt, and near Fyzabad and Oropuche, and on Morne L'Enfer are localities where more asphalt than soil is to be seen. Such deposits are sometimes worked commercially, but the difficulty in regard to them is that the material is subject to many local variations, owing to greater or less admixture with inorganic matter, and to higher or lower degrees of inspissation. Consequently the asphalt requires some refining to standardize it before a commercial sample of constant composition can be assured. For this reason an asphalt like the lake-pitch of Trinidad with its practically invariable composition is much more valuable as a commercial product, though its percentage of bitumen may he much less than that of some other asphalt deposits.

(*c*) *Evolution of Gas.*—Almost every seepage of oil or exudation of asphalt is accompanied by a distinct evolution of gas in greater or less volume, but similar discharges of gas may take place with little or no sign of liquid petroleum, and it is to these that the term "gas-shows" is given.

The most striking are mud-volcanoes (Plate IX), which must not be confused with the solfataric mud-volcanoes due to true volcanic action. The mud-volcanoes with which we are dealing occur where oil-bearing rocks come near the surface but are covered by argillaceous strata. The crest of an anticline is the most usual position as regards structure, but favourable conditions for the formation of mud-volcanoes can be brought about in various ways. Thus, where an oilrock crops out amidst a great thickness of clays, and the clay has been washed down over the outcrop thus sealing it to some extent, a mud-volcano may be formed. Again, argillaceous alluvium lying upon an outcropping oilsand may furnish a sufficiently impervious cover. Mud-volcanoes may also be formed along lines of fault which permit gas from underlying oilrocks to reach the surface, but this is a rarer phenomenon than is generally supposed. Argillaceous outcrops of an older series unconformably overlaid by petroliferous strata, may have absorbed sufficient gas and petroleum to form small mud-volcanoes. Lastly the sealing up of the outcrop of an oilsand by copious extrusion of asphalt may be so complete that the gas and oil try to force their way through the outcrop of over-clay and form small mud-volcanoes. Instances of the two latter cases may be seen in Trinidad near Piparo and La Lune respectively.

It is, however, on the crest of an anticline, where the surface is formed of a stiff and thick clay, that the ideal conditions for the formation of a large mud-volcano are afforded. Here the gas-pressure is concentrated continually till during dry weather the surface of the clay cracks, and the cracks gradually extend downwards sufficiently far to allow a little gas to escape. Once a channel of exit is formed it will probably never be permitted to be closed entirely again. The gas issuing under pressure puddles the clay with the help of any surface water available, and through the mud thus formed the gas reaches the surface steadily or spasmodically, carrying a certain quantity of the mud and saline or oily water with it, and thus in the course of time forming a cone. From the evidence afforded by wells drilled near large mud-volcanoes it appears probable that where these phenomena attain to any considerable size, there is either a certain quantity of water in the oilrock or there is a water-bearing band in close proximity above the oilrock. In the case of small cones the water and mud are probably confined to the zone nearest the surface; most clays contain sufficient moisture to allow of mud being formed when the strata are disturbed by discharge of gas, and surface water must enter by the cracks in the surface. The water is usually slightly saline, but not a strong brine.

Professor Carmody has analyzed the water from the crater of a small mud-volcano near La Lune, Trinidad, with the following result:—

Total solids	2·506 per cent.
Loss at 180 degrees C. (water of hydration and ammoniacal salts) . . .	0·0149
Sodium chloride	2·04
Alkalinity as Na_2CO_3	0·38
,, ,, K_2CO_3	0·40

and traces of iron, alumina, lime, and potash.

The water also contained a small quantity of petroleum.

This volcano occurs beside the outcrop of the Galeota oilsand, where cones of asphalt cover nearly all the surface; the discharge takes place through the outcrop of the cover-clay above the oil-bearing rock. The cone is a small one with a crater four feet in diameter and full of water. Two or three other small cones are to be observed in the neighbourhood.

It is after a long drought that mud-volcanoes are generally most active; this is no doubt due to the parching and cracking of the clay that occupies the surface, an action that extends downwards for a considerable distance.

Mud-volcanoes are of all sizes. Of the number which the writer has observed (nearly one hundred), the smallest has a crater 5 inches in diameter, and the largest a crater of 150 yards diameter. There is usually a surrounding belt of dried mud; this has flowed or been washed down from the crater, which is often raised considerably above the level of the surrounding ground. Sharp cones are more characteristic of the smaller volcanoes, and are formed when there is not a superabundance of water present, while the larger volcanoes are often almost flat with larger craters often containing much water and soft mud. The smaller volcanoes are usually the most steadily active; the larger are liable to sudden and violent eruptions at intervals perhaps of several years.

All the phenomena characteristic of true volcanic cones are simulated; the flows of mud are exactly like lava streams; and when a cone has reached a certain height it frequently becomes inactive and another orifice opens on the side of the cone or near it. Thus lines of cones, extinct and active, are seen, reproducing on a small scale the well-known manifestations of true vulcanicity along a fissure.

Strewn about the larger volcanoes, blocks and fragments of rock, possibly brought up from a considerable depth, are frequently seen. A little oil may usually be detected in the water or liquid mud of the craters, and a faint odour of petroleum pervades the whole locality, and is especially noticeable when any fragment of porous rock lying about the crater is broken for examination.

The best known and perhaps the largest mud-volcano in Trinidad is in Columbia Estate in the Ward of Cedros. The usual appearance of the crater is a flat circular area of dried mud strewn with many fragments of ironstone nodules, sandstone, pyrites, etc. A great number of small cones from a few inches up to 2 feet in height are distributed over the expanse of mud, and these occasionally show signs of activity. The writer once had the good fortune to see this crater in eruption, but only a part of the crater, which is 150 yards in diameter, was explosively active. A circular orifice of 8 yards in diameter filled with liquid mud had opened towards the north-western side of the crater, and was surrounded by a belt of half-dried mud some 30 yards in diameter, and raised above the surrounding level. At intervals of about a minute the liquid mud rose in a huge bubble and burst, hurling about a ton of mud 6 or 8 feet into the air, while small fragments torn off the mass were thrown 20 to 30 feet upwards. Every minute cone in the barren mud area was streaming gas and burnt steadily when set fire to. The next day all signs of activity were at an end.

Sometimes the outbursts of a mud-volcano are very violent, especially when its periods of activity are separated by long intervals of quiescence. The "Devil's Woodyard," near Princestown in the Ward of Savana Grande, is a good instance. It received its name on account of the uprooting and killing of trees during an eruption that took place in the first half of last century. When the writer visited the locality first, the crater was almost entirely overgrown with vines and bush, and a few small mud-pools, in which a few bubbles of gas could be detected, were the only signs of activity. In May, 1906, there was a very violent eruption, which was said by eye-witnesses to have thrown mud over the treetops of the surrounding forest. After the outburst the volcano presented a very different appearance; the crater is now 100 yards in diameter and has been raised 5 or 6 feet, all traces of vegetation have been buried or blown away, and blocks of a thin band of fossiliferous limestone are to be found here and there on the surface of the dried mud. A few very minute cones distributed near the centre of the crater are still active.

Another volcano close to the southern coast of Trinidad is remarkable for the fact that a flow of mud nearly 250 yards in length stretches from it to the beach (Plate X); from this the name "Chemin du Diable," or its equivalent in the local

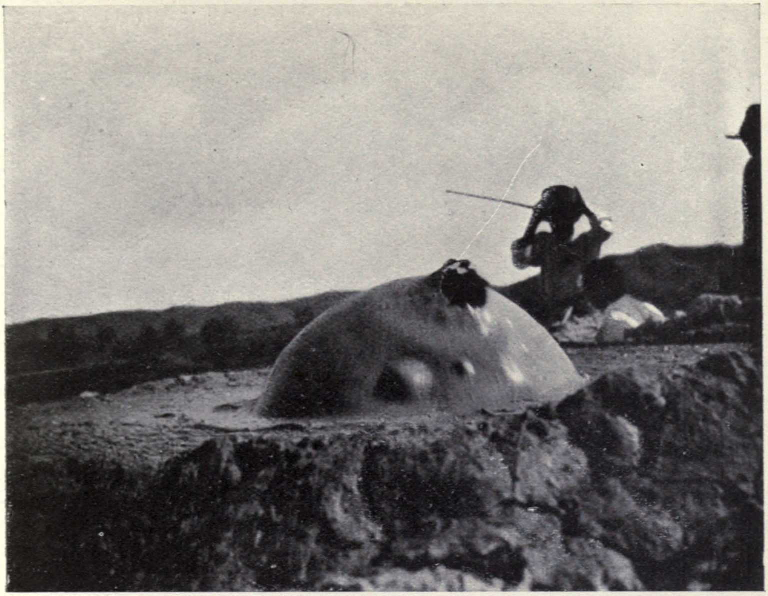


Photo. by S. L. James

i. BUBBLE BURSTING IN THE CRATER OF THE LARGEST MUD-VOLCANO AT MINBU, UPPER BURMA.

Photo. by C. S. Rogers

ii. PART OF THE CRATER OF A LARGE MUD-VOLCANO ("CHEMIN DU DIABLE") IN TRINIDAD, SHOWING TWO MINOR CONES.

patois, has been given to this oilshow. Every ten or twelve years there is an outburst, which is evidently very violent (cp. Plate X), as blocks of rock up to one foot in diameter have been blown out from underlying strata, and trees of more than a foot in diameter have been broken off and the upper part hurled away from the centre of disturbance. For the last few years this vent has been practically quiescent, and only a few very minute cones show any signs of activity, and the forest is beginning to encroach upon the area of barren mud.

Lagon Bouff in the Trinity Hills Forest Reserve is another well-known and very active vent. It lies in low ground near the foot of the hills, and consists of a lake of liquid mud 100 yards in length by 60 in breadth. It is in constant activity from two or three centres, and there are occasional violent discharges that can be heard some miles away in the forest.

Beside these well-known mud-volcanoes there are many others of almost equal importance in various parts of the island. Of the smaller cones those of L'Islet Point and those at Galfa Point are perhaps the best formed and most typical.

In Burma in the Districts of Minbu, Thayetmyo, Prome, and Henzada, there are mud-volcanoes, most occurring on the crests of anticlines, though some small ones are apparently formed on lines of fault. Those at Minbu (Plate X) are the largest and best known; they are well-formed cones and are characterized by steady activity rather than by paroxysmal outbursts, owing probably to the oil-bearing strata lying nearer to the surface than in the cases of the large mud-volcanoes described above.

Though it is seldom that much actual oil is discharged from mud-volcanoes, and it may not even be observed at all except where large pools of liquid mud and water fill the craters, there is no doubt as to the presence of oil beneath the surface. The only instances that the author has seen of oil-wells drilled near such gas-vents have nearly all been successful in striking oil.

The conditions under which mud-volcanoes are formed still require some elucidation. Wells drilled in the vicinity of mud-volcanoes, even when on the crests of well-marked anticlines have not infrequently encountered soft mud or clay accompanied by high gas-pressure, with the result that the mud entered the well almost as quickly as it was drilled. This difficulty has in some cases proved insuperable, causing wells to be abandoned. It seems not improbable that for the formation of mud-volcanoes there must be either water in the oilsand as well as oil, or that a water-bearing rock exists close above the oilrock. Such a water-logged stratum might easily became impregnated with gas from below and the overlying clay might be puddled and the flow of oil sealed off, while endless mechanical difficulties in drilling might be caused.

If such be the case, mud-volcanoes cannot be considered such favourable indications as has often been supposed.

About one point there is no doubt; mud-volcanoes may occur where no good production of oil is possible, though gas may be present in considerable quantity and under high pressure. Both in Trinidad and in some parts of Baluchistan there are instances of such conditions, even where the mud-volcanoes occur on the crests of large flexures. It is therefore necessary to obtain as much evidence as possible as to the local conditions that determine the formation of mud-volcanoes before assuming that they are indications of the presence of oil in commercial quantity at lower depths.

Mud-volcanoes are undoubtedly sometimes formed along lines of fissure or fault in argillaceous strata, and in some cases they are formed in strata older than the oil-bearing series which have been impregnated by downward or lateral migration; in such cases the impregnated beds are apt to yield their petroliferous contents, liquid or gaseous, very slowly.

But when all is said and done and every reservation made, the fact remains that many of the world's great oilfields contain mud-volcanoes among their indications of petroleum.

Evolution of gas often occurs without the formation of a mud-volcano, especially where the strata are hard or sandy, but it may also take place from a clay outcrop. One interesting example of this may be seen in the Ward of Oropuche, Trinidad, where gas issues steadily from the clay soil over an area of about a square yard. This show is situated about the crest of the Central (Western) Anticline. The land has been cleared for cultivation recently, and something in the nature of a regular vent is forming. In the course of time it will probably become a small mud-volcano.

Gas-wells, small pools of water disturbed by steady evolution of gas, are not unfrequent occurrences in oilfields, and the volume of gas is sometimes sufficient to be used continuously as a source of light and heat. The "Boiling Spring" in Barbados (Scotland District), is well known; it is kept in a constant ebullition by the gas from an oilsand bubbling through the water. Near Guayaguayare, in Trinidad, there are similar bubbling springs, the gas from which burns steadily when ignited.

All these gas-shows, whether in the form of a great mud-volcano or little gas-pools, are very important evidence, as without sufficient gas-pressure an oilfield may be very expensive to work and the wells may not have a long life.

The nature of the gas is always an important point to note in the case of such evolutions or shows, *i.e.* whether it is "wet" or "dry" gas. By wet gas is meant a gas containing appreciable quantities of hydrocarbons higher in the series than methane, while a "dry" gas is almost entirely methane, with perhaps a proportion of hydrogen, nitrogen, or carbon dioxide. A rough practical test of a gas is to smell it; any really wet gas will have a distinct odour resembling that of petrol, while a dry gas is odourless: analysis, however, is required to detect the presence of small proportions of ethane, propane, butane, and even pentane. A compressor plant is, of course, the best means of testing a gas, since by its means the heavier hydrocarbons are easily liquefied at ordinary temperatures, while the methane remains in the gaseous state, but it is but seldom that such a plant for testing gases can be available.

It is obvious that the heavier and wetter a gas the more favourable the evidence of the presence of oil in the neighbourhood. Though there may be steady and brisk flows of gas or gas-wells at a locality, it does not necessarily prove that oil can be obtained by drilling there, but should the gas be heavy with a fair percentage and a strong odour of hydrocarbons higher in the series than methane, the prospector will be justified in concluding that a body of liquid hydrocarbon is somewhere in the neighbourhood.

It must be remembered, however, that gases are filtered just as oil is on the way to the surface, and so the heavier constituents may become practically eliminated before the gas mingles with air. Very interesting and important evidence on this point has been obtained in the foothills of the Rocky Mountains in Alberta. In these foothills in longitudinal valleys coinciding more or less with anticlinal structures somewhat complicated by faulting, gas springs have been known for many years, and were well known to the Indians long before white men settled in the country. Some of these consist of brisk and steady evolutions of gas from pools near a river-bed, others are evolutions of gas near the base of hills; some of the gases have a distinct odour of petroleum and others are odourless, but all are inflammable, and burn fiercely with an almost colourless flame.

In some cases the gas seems to have arrived at the surface *viâ* a fault plane. One of the best-known of these gas seepages was situated in alluvium beside the southern fork of the Sheep River, where the famous Dingwan Well now stands. When the writer first visited this locality, long before any drilling for oil had been attempted, a pool of water in the alluvium some 8 feet in length by 3 feet broad was violently agitated by the issuing gas. The day being windy, there was some difficulty in lighting the gas, but once it had been lighted it was equally difficult to extinguish it, as the flame flickered about all over the surface of the pool. The gas had no appreciable odour, but after it was extinguished a slight film reminiscent at least of oil was left upon the surface of the water. When the Dingwan well was drilled strong gas was struck at a depth of some 300 feet, and the evolution of gas in the pool ceased. The gas struck in the well still had little or no odour of petroleum. At greater depth stronger gas with a very distinct odour was encountered, and at intervals as the drilling proceeded stronger and wetter gas was met with in strata almost impervious. The gas flow became very strong and signs of light oil were noticed, till at 1562 feet a very light oil was struck in small quantity and accompanied by very heavy wet gas. At 2718 feet an intermittent flow of very light oil containing 72 per cent. of petrol was encountered, gas being still very strong, and with a somewhat unpleasant smell due to small quantities of sulphur compounds. The gas put through a Bessemer compressor is credited with giving a minimum of one and a half gallons of condensed petrol per 1000 cubic feet. This was a case in which the odourless gas-show combined with favourable anti-clinal structure was sufficient evidence to induce the prospectors to drill for oil.

Drilling in the same belt of country near other shows of gas with more distinct odour has not yet been completed.

Other cases have come within the writer's observation where flows of dry gas either from the ground or in wells occur where there is no hope of obtaining more than a trace of oil, so the evidence of a gas-show must be considered along with other facts, such as the geological structure, if its value as an indication is to be appreciated correctly. The great gaswells of Bow Island and Medicine Hat in Alberta have tempted more than one company to test shallow flat domes for oil in territory where, though the presence of gas is to be expected, the finding of oil is so problematical, and indeed so improbable, that it would never have been undertaken except as a forlorn hope.

Another form of gas-show which is sometimes a very helpful sign is the evolution of sulphuretted hydrogen. This may not be connected with petroleum at all, but in many oilfields this gas, only too readily detected by its odour and its action upon metallic silver, is formed by the action of water upon sulphur compounds in the petroleum and its inspissated residues. Where the oil-bearing rock is a limestone, as in some of the "sour" oilfields of Ohio and Indiana, discharge of hydrogen sulphide is not uncommon from the oil-bearing series. The evolution of this gas may be so copious as to be dangerous to life. At Marmatain in Persia, where a sulphurous oil in the limestone bands forms this gas under weathering processes, two Persians lost their lives by going to bathe in a pool in a small gully where the gas had collected on a still day to such an extent that it overcame them; the bodies were not discovered till next day. In the prolific field of Maidan-i-Naphtun also, one of the wells gave a gas with a large proportion of sulphuretted hydrogen, and birds and jackals were found after a still night dead near the derrick.

(d) Outcrops of Bituminous Strata.—Even when no seepage of oil, exudation of asphalt, or evolution of gas is to be observed, it is generally possible to recognize an oilrock by its outcrop. With an oil of asphaltic base this is a simpler matter than when paraffin oils are dealt with. In the former case there is usually at least a slight bituminous impregnation or discoloration, and the odour of petroleum may be detected even when there is very little coloration. Oilsands are often so highly impregnated that even when the oil is dried up by inspissation at the surface the bituminous content is so high that the rock can hardly be broken by the hammer, but can be dented or cut, and small projections can be twisted off in the fingers and rolled into pellets in the hand. There are large areas in Trinidad covered by outcrops of this kind, and the material has been quarried for use on roads; the rock crushed under traffic forms a smooth surface that does not wash away easily during rains, nor become hard and slippery in cold and wet weather as does an asphalt surface. The "tar-sands" of Barbados are precisely similar, though not always so highly impregnated.

But when an outcrop has been subjected to weathering for long periods without fresh access of oil or bitumen, it may show very little trace of a former impregnation. In such cases the mode of weathering or the traces of sulphur compounds may be sufficient to prove that we are dealing with an oilrock. Any sand may be an oilrock, but if in examining a section one finds certain bands softer and less coherent, darker in colour, and with rounded contours as compared with otherwise similar sandstones in the same section, it may be presumed that if any of the strata have been, or are beneath the surface, oil-bearing, it is these, and if followed up in the field and studied under different conditions as regards structure and exposure, clear and unmistakable evidence may be forthcoming.

Faint yellow stains or flecks due to traces of sulphur from decomposed sulphur compounds often afford additional evidence, and may be the last remaining traces of a former impregnation.

The coloration due to metallic oxides or sulphides, iron or manganese compounds, may in some cases simulate a coloration due to bitumen, but when the rock is crushed and washed or vanned, or treated with a solvent such as benzine, there can be no mistake as to the nature of the colouring material.

With oils of a paraffin base there may be no such evidence, and when a weathered outcrop is suspected of having been impregnated, it is necessary to break open any nodules or hard and compact bed that the strata may contain to search for traces of petroleum. The more compact and fine-grained the material, the less easily will any impregnation be removed by weathering, so a survival of an impregnation may be discovered in a hard nodular band, when the surrounding more porous and once more highly-impregnated strata have lost all trace of the former presence of oil. A faint odour of vaseline is often the only evidence that can be obtained. In Trinidad the oils of paraffin base occurring in thin sands among thick masses of stiff clay frequently betray their presence by the residues of an impregnation and the unmistakable odour of vaseline in nodules of iron and lime carbonates found in the clay. In Burma also, where paraffin oils are the rule, the oilrocks at outcrop frequently show no trace of petroleum, and compact or nodular bands have to be examined.

Where the oilrock is a limestone there may be no signs of petroleum at outcrop, but, as pointed out already, crystals of sulphur or evolution of sulphuretted hydrogen may be sufficient to point to the former presence of an oil containing sulphur compounds. The staining of pebbles in a stream by the deposition of sulphides, and the presence of finely divided sulphur in the water, giving it a milky appearance, are pieces of evidence that very frequently characterize outcrops of limestones or shale that contain or have contained an oil with a percentage of sulphur.

(*e*) *Manjak and Ozokerite Veins.*—No account of indications of petroleum would be complete without some mention of the veins of solid petroleum residues, known by various names in different countries, and according to differences in their composition. The solid bitumens, though all closely allied in composition, differ greatly in physical characters such as lustre and jointing, while in such practical matters as melting point, purity and efficiency as insulating material in electrical work, there are also many differences. In the United States Gilsonite and Uintaite are the prevalent names, while a hard and much altered form is known as Grahamite. In Canada Albertite is the designation of a very hard variety. But every gradation between the hardest and most mineralized form and a viscous pure bitumen can be discovered. The author prefers to use the old name Manjak or Munjac as a generic term for all these bituminous minerals; the term has been in use in Barbados since early in the seventeenth century.

These minerals are classified according to their percentages of fixed carbon, and their behaviour under the action of certain solvents. The following table gives the characteristics of a number of these minerals:—

Mineral.	Specific gravity.	Bitumen, Percentage soluble in CS_2.	Malthenes, Percentage soluble in petrol.	Fixed carbon.
Gilsonite	1·04	93·4 to 99·5	35 to 72	3·3 to 26·2
Barbados manjak	1·08	97·4 to 99·2	15 to 36	25
Egyptian glance pitch	1·09	99·7	23·5	15
Trinidad manjak	1·09 to 1·1	84 to 96·2	6·3 to 56	24 to 33
Grahamite	1·16	94·1 to 98·2	0·4 to 3·3	41 to 53
Wurtzilite	1·05	6·7 to 12·8	—	5·2 to 8·8
Albertite	1·07 to 1·2	1·6 to 11·9	Trace to 3·2	29·8 to 54·2

It is seen that some, such as Barbados manjak, are almost pure bitumen, while others, such as albertite, may have less than two per cent. of that material.

These minerals are truly intrusive, and simulate nearly all the phenomena of igneous intrusion.

Ozokerite is to an oil of paraffin base what manjak is to an oil of asphaltic base, but though there are many varieties of ozokerite the mineral is less common than the solid bituminous minerals, and the term is applied to all grades of mineral wax. The origin of these minerals is the same; they are the solid residues from the inspissation of petroleum *beneath the surface*, and may be looked upon as intrusive petroleum.

Though it may not be possible in all cases to prove that manjak veins are essentially phenomena of an oilfield or the margin of an oilfield, their association with petroleum has been established so frequently, and they afford in many instances such valuable indications as to where the search for oil is likely to be successful, that we must regard the study of the manjak group of minerals as part of the necessary knowledge with which the geologist who has to specialize in oilfield work must make himself familiar.

The important points to be noted are the conditions under which veins of manjak are found. Briefly put, manjak veins occur where a thick series of strata, partly or wholly of impervious material, overlies a source of asphaltic oil, and where, either due to the softness of the superincumbent rock, to contraction owing to partial drying, or to earth-movement, planes of weakness have been developed enabling intrusion of petroleum from below to take place. Manjak veins are invariably highly inclined or even vertical, except where small local offshoots from a larger vein may take gentler inclinations. Bedding-planes, fault-planes, joints or minor slip-planes in an argillaceous mass afford opportunities for this intrusive action. The occurrence along bedding planes has more than once led to the belief that manjak is of the nature of coal, and a mode of formation by the sinking of heavy tropical timber to form a deposit in water of not more than one hundred fathoms in depth has actually been suggested and published. Quite apart from its inherent improbability, such a theory fails at once when the facts are studied in the field. The occurrence of manjak among foraminiferal clays, *e.g.* in the San Fernando Manjak-field, is hardly compatible with a drift-origin theory, while the fact that the veins cross the bedding in all directions, and only occasionally run along it for short distances, proves that the mineral is not a deposit and must have reached its present position in some other manner. In the United States Mr. Eldridge has described vertical veins of gilsonite which have been traced for great distances through horizontal or nearly horizontal strata, which are trenched by great cañons; the orientation of these veins varies very little, and may be due either to earth-movement or to the drying of the strata caused by proximity to the cañons.

In Trinidad and Barbados the mineral occurs in thick masses of argillaceous strata, and slip-planes, joint-planes, and occasionally bedding-planes determine the directions of the veins, but irregular pockets are developed here and there. The veins vary in thickness, orientation, and dip, but, as stated before, are nearly always highly inclined. Perhaps the largest vein of manjak that has ever been described is the Vistabella

Vein in the San Fernando Manjak-field. It attains a thickness of thirty-three feet for part of its course.

Manjak varies considerably in purity and composition, according to the environment in which it is found. It is usual in testing a manjak to treat it with petroleum ether, which removes in solution a percentage which is called "petrolene," while the insoluble percentage is called "asphaltene." The most valuable types are jet black, bright and lustrous, with a beautiful conchoidal fracture and a high percentage of petrolene. Small percentages of water, volatile matter, and inorganic impurities, are always present. The quality of a sample is determined by its freedom from impurities and its percentage of petrolene, since a high proportion of the latter enables the solid bitumen to be fluxed more readily.

Columnar jointing is a frequent phenomenon in veins of manjak, and it may extend across the whole vein, the columns being at right angles to the sides. The columnar variety is usually poorer in petrolene than the variety with conchoidal fracture; it has also a duller lustre and a coaly fracture. The structure is due to the loss of volatile constituents. Every phenomenon of an intrusive dyke or vein of igneous rock is simulated by these intrusive bitumens, and veins may be seen with margins of columnar structure and a central portion of the lustrous conchoidal variety, which represents a later intrusion. The percentage of petrolene also increases towards the centre of every vein, and further increases in analogous parts of the same vein as it is traced to deeper levels, while a vein that does not crop out at the surface generally contains a greater proportion of petrolene than one that is exposed. These facts prove that there is a gradual loss of volatile constituents, and a gradual drying-up or inspissation of the mineral towards the sides of the vein and towards the surface. Thus a specimen from the 50-foot level in Marbella Mine can be compared with a specimen from the same vein at a depth of 125 feet, the analyses being by Professor Carmody:—

	From 50 feet level	From 125 feet level
Water	0·65	1·0
Organic matter	94·80	96·20
Mineral	4·55	2·80
Percentage of petrolene	8·80	9·6

Specimens from deeper levels in the Vistabella Mine gave percentages of petrolene up to 15·2.

In Barbados, where many of the veins do not crop out at the surface, even higher percentages of petrolene are recorded. One vein gave 18 per cent. from its columnar selvage and 35 per cent. from the central portion.

The clays surrounding manjak veins are often seen to contain sticky inspissated oil or liquid asphalt along joint faces and slip-planes, and nodules of clay-ironstone slightly more porous than the clay show abundant evidence of impregnation. From the centre of a vein with columnar jointing in Marbella Mine the writer has seen a semi-solid bitumen slowly extruding. This material was brittle enough to be broken up by a sharp tap, but could be bent and twisted without breaking if pressure was applied slowly. Its percentage of petrolene was 56; it is a later intrusion.

From this evidence it is obvious that the mineral has been introduced in a liquid or semi-liquid state, and has gradually dried and hardened *in situ*. A still more convincing piece of evidence is the fact that sometimes when a vein is followed to a considerable depth it is found to end in a sand or sandstone fully impregnated with sticky oil, "tar-sand," as it is called in Barbados. This makes the origin of the mineral quite clear, and its relations to petroleum on a larger scale can usually be established by field evidence. Thus in the San Fernando Manjak-field an oilsand, with several "shows" of heavy oil on its outcrop, dips steeply beneath the clay beds in which the manjak is worked (Fig. 9), and presumably underlies these strata throughout the syncline. The shaded part in the diagrammatic section shows the zone in which manjak veins have been proved by mining. It is natural to expect that the crest of an anticline would be the most likely place to find veins of manjak, and small veins have certainly been discovered on or near anticlinal crests where a considerable thickness of impervious argillaceous strata lies above the oilrocks, *e.g.* in the Poole District and near the "Devil's Woodyard," in Trinidad, but the centre of a sigmoidal flexure, between syncline and anticline seems to have some special advantages that make it eminently favourable to the intrusion of these bituminous minerals. Probably the strains developed during the earth-movement that caused the flexures have resulted in slip-planes in the argillaceous strata and so favoured the intrusive action. The pressure of gas occluded in or associated with the oil was probably the moving force.

On a minute scale intrusion from the upper surface of an oilrock may frequently be seen. Where the La Brea Oil-bearing Group is exposed in coast-section near the Pitch Lake, small veins of asphalt may be observed extending vertically upwards from the upper surface of the petroliferous sand, and hand specimens may even be obtained of such veins not more than an inch in thickness with portions of the country rock on each

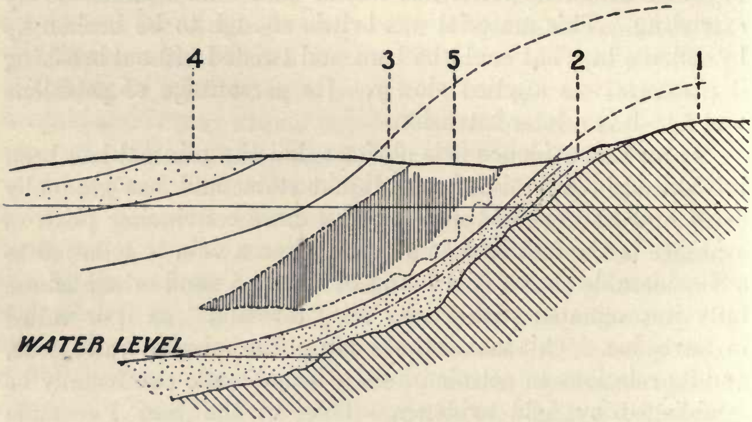


FIG. 9.—Diagram illustrating mode of occurrence of Manjak veins in Trinidad (San Fernando Field). 1. Cretaceous inlier; 2. Oil-bearing sand; 3. Clay; 4. Sandstone; 5. Zone containing Manjak veins.

side. This is sufficient to suggest the possibility of similar intrusions on a much larger scale, given the requisite conditions.

Ozokerite veins occur under much the same conditions, but seldom attain to the same size and thickness that manjak veins reach.

Paraffin oils being as a rule more mobile and lighter, and containing less material capable of forming solid residues than asphaltic oils, are liable to find their way further without solidifying as they gradually become inspissated, and are not likely to coagulate in such large masses. Consequently thin veins and networks of veins, and bands of porous inorganic material impregnated with the solid paraffin wax are more frequent than thick, well-defined intrusions. The colour of the ozokerite varies from yellowish-white to brown and black, but the latter colours are by far the most common. The mineral, being of considerable value, is frequently mined, but the mines do not always become great commercial successes owing to the lack of thick and solid veins.

There is a possibility that where the manjaks are strongly in evidence inspissation or polymerization may have proceeded to such an extent in the underlying oilrocks that at the best only small productions of heavy oil may be obtained by drilling. Evidence from manjak fields such as the Gilsonite fields of the Western states of America certainly point to the probability that it is now too late to drill for oil with success in such localities. It becomes necessary to consider the nature of the manjak, the thickness of the oil-bearing series and the history of the area. It is obvious that a highly inspissated asphaltite such as the Albertite of New Brunswick is a less hopeful indication than a fresh manjak such as that of Barbados, where the "Kerogen stage" has not been reached. Again, if the series containing signs of petroleum extends to much greater depths than those at which the manjak veins are found there is much greater probability of finding stores of petroleum that has not become highly inspissated in the lower beds.

The older the series also the more probable that inspissation or polymerization may have proceeded too far. All these points must be taken into account before drilling in any locality can be advised on the strength of the occurrence of manjak veins. But the occurrence of such veins in a series may be of the greatest value as indicating the petroliferous nature of the strata; in another locality, where conditions may be more favourable, inspissation may be less in evidence and a good production of petroleum possible.

The occurrence of rock-salt or brine-springs is not dealt with as evidence of petroleum, although the association of brine or salt with oil is frequent in many parts of the world. In a former chapter it was shown that this may not be an essential association, but another indirect effect of the same cause; consequently though the search for brine has often led to the finding of oil, and its occurrence may often give valuable evidence to the geologist, it is hardly justifiable to class rock-salt or brine with surface indications of petroleum.

As will be seen in a subsequent chapter, the writer's researches on oil-shales have led him to the conclusion that these deposits are intimately connected with oilfield phenomena, and are in fact the final relics of a former impregnation with petroleum. Oil-shales in the higher zones of a series may thus be an indication of free petroleum at greater depth where structures capable of concentrating and retaining oil have been developed.

All the phenomena described above must be noted by the geologist, and the significance of each learnt, so that he may be able to ascertain whether or no a series is or has been petroliferous; evidence may be very scanty in jungle-covered ground, and he may have to rely upon very meagre indications, which might easily be overlooked. It is, therefore, necessary that every variety of indication should be familiar to him. In argillaceous strata he must be especially on the alert; where exposures are few and dips unreliable, a minute gas-show, or the discovery of a few fragments of manjak, may be of great value in assisting him to determine where a test well should be located.

2. Indications in a Borehole.—Evidence that may be considered as "favourable," and as pointing to the prospect of striking oil in a drilled well, may be of almost any nature, and such evidence can only be interpreted by reference to what is known of the geological formation or series that is being tested. During the first tests of a new presumed oilfield, where perhaps little or nothing is known of the geology of the district, a state of things which even nowadays may be met with only too often, "shows" of gas and oil are really the only favourable indications that can be recorded. And even these may be entirely deceptive, for it may be that such shows are derived from horizons which in other districts are represented by thick and prolific oilrocks, but which have thinned out to insignificant streaks in the area being tested. And the driller may be tempted to drill deeper and deeper into strata that are not and never have been petroliferous. The well may even pass through an unconformability into some lower series, which, if exposed at the surface, would never be tested for petroleum even by that most hopeful of optimists, the driller of wild-cat wells. Yet, because light shows of oil and gas were encountered at some stage or stages, the well may be continued for months at ruinous expense.

On the other hand, when the geology of a district has been carefully worked out, when the strata to be drilled through are known, and the depth to be drilled estimated approximately, a "favourable indication" consists of any evidence that shows that the strata to be tested are being approached, and the fact that *no* shows of oil or gas are encountered may be a favourable indication, proving that the petroliferous contents of the strata beneath are securely sealed beneath an impervious cap and that migration upwards has been prevented.

The recognition of any known band of rock in the log of the well, or by fragments from the bailer, even if it be a prolific water-sand, which will enable the depth to the oil-bearing horizon to be re-estimated, is often of great importance, as, where lateral variation in rock groups is the rule, estimates of thickness made from some section at a distance can never be very accurate.

When one or two wells have been drilled, information from the boring journals should be sufficient to enable the geologist to judge whether the prospects of a third well are promising or not, and the depth can be calculated with a fair degree of accuracy if the area has been geologically mapped. But without a large-scale geological map the boring journals are of very little use unless the wells are close together. In the author's experience estimates of the depths to be drilled have come within 10 feet of the actual depth in the case of new wells two miles distant from any previous well, and for depths of nearly 2000 feet, in an area of great and sharp flexures. Such estimates were arrived at by careful six-inch mapping and making allowance for the thinning of rock groups owing to an ascertained lateral variation.

Oil is seldom struck without any warning; light gas "shows" or light shows of filtered oil and gas ofter occur at some distance above the actual oilrock. These are due to a gradual migration from below. Gas is not necessarily a hopeful indication, but when gas-pressure increases steadily as the drill penetrates deeper and deeper into a fairly impervious group of strata, it may be taken as a very favourable sign; the first porous band of any thickness met with will probably be oil-bearing. Even in such a case, however, the oilpool may be missed and the oilsand found to be full of water. An example of this occurred in Trinidad. A light show of oil was struck at shallow depth and cased off; the well was continued and struck strong gas in a sandy shale. The gas-pressure continued to increase as the boring proceeded, and caused much difficulty in the drilling. At greater depths, however, the gas-pressure began to decrease, and when the well reached a thick sand-bed it was found to contain salt water. The gas had reached the locality by lateral migration.

It is, of course, when the first tests of a new field are being drilled that indications become most important, and especially when unknown strata are being penetrated. Though a district may be mapped geologically with great care, and the series proved to be petroliferous, the first well may be drilled into strata that are not exposed for a distance of many miles from the locality. A study of the lateral variation may have made it appear highly probable that oil-bearing strata are beneath the surface, the geological structure may be eminently favourable, and the well carefully located, but, as the depth to be drilled is unknown or roughly estimated, there is necessarily some uncertainty. It is in such circumstances that the evidence from the log must be most carefully studied. Any light show of gas or oil, if in thin beds, will be a favourable sign. But if thick porous beds are pierced with light shows of gas or oil accompanied by water, the indication is most unfavourable. If the drill has passed through a great thickness of stiff argillaceous strata, when it first reaches a porous bed important evidence will be forthcoming; if oil appears in the bed the indication is most hopeful, but if water, the prospects of the well are gloomy. The nature of the argillaceous strata has also to be considered; if they are typically marine throughout, the prospects will not be quite so good as if estuarine conditions are indicated by the presence of gypsum or selenite at some horizons, and especially towards the base of the argillaceous group.

Alternating bands of clays and sandstones may be regarded as moderately favourable, even if the sands contain water.

Nodules of clay-ironstone, calcareous concretions in sandstones, glauconitic sands, and all the characteristics of estuarine and deltaic beds may be regarded as favourable.

Beds of coal or lignite, if pierced at comparatively shallow depths where comparatively thick clays underlie them, are hopeful indications if the geological structure be good; if struck at great depths, the field will probably have to be abandoned.

Beds of gypsum or rock-salt are indifferent evidence; oil-bearing strata are not infrequently found below them, but just as frequently above them, while in many cases they are not associated in the same series with petroleum.

The occurrence of marine limestone is, generally speaking, a bad sign, though many prolific fields have a limestone as their reservoir rock. An entirely marine series, without intercalations with littoral or estuarine beds, is to be avoided.

Fresh arkoses or grits containing fresh felspars, micas or volcanic material, are usually unfavourable as indicating the proximity of crystalline rocks or volcanic strata which were being denuded while the series was being deposited. The approach to an uncomformability, however, which may be indicated by the presence of conglomerates formed of pebbles derived from an older series is often worth noting, as the basal arenaceous groups of a series are frequently oil-bearing under favourable conditions. The reason of this is obvious when we consider the landward margins of a delta, and the probability of the formation of swamps between the main mouths of a river and the higher ground that may bound the delta on one or both sides. Pebbles or fragments of pebbles may frequently be brought up in the bailer, and a bed consisting chiefly of pebbles can be recognized by any competent driller, so there should be no difficulty in ascertaining the presence of conglomerates.

If a thick arenaceous series, whether conglomeratic or not, is being drilled, and salt water is found in it, there is little hope of an oilwell till some underlying impervious rock group is reached and drilled through.

But when all is said and done, every case must be considered on its merits by reference to what is known of (1) the geology of the district or country; (2) the stratigraphy of the series that is being tested; and (3) the geological structure in the particular locality. An indication may be exceedingly favourable where the structure is not very attractive, while in a field with ideal geological structure it might give by no means a hopeful prediction as to the results likely to be obtained.

It is therefore almost impossible to tabulate what are, or are not, hopeful indications, and the table on p. 181 must be regarded only as a rough guide to the geologist who has to study well records in a new field. It is presumed that the well has been located *where the geological structure is favourable*, since what might be a very poor indication under favourable conditions of structure might be a very good indication where structural conditions are not so favourable. This is quite obvious if we take as an instance the comparison between two wells, one drilled into the heart of an anticline and one into a monocline. Water-sands occurring beneath thick impervious strata in the first case could not be regarded as a favourable indication if unaccompanied by any signs of oil or gas, whereas in the latter case such evidence would be merely indifferent, neither good nor bad. The occurrence of sulphurous water in the former case would be somewhat unfavourable evidence, but in the latter case distinctly favourable.

It must not be supposed, also, that even after indications classed as "always unfavourable" it is impossible to achieve success finally in a borehole. A well may pass from one formation into another and encounter totally different conditions of strata and geological structure. Thus the unfavourable indications may be passed through, left behind and succeeded by much more favourable indications. However, in any case where the geology of the district has been carefully worked out and the approximate depth to be drilled known, it should be possible to predict what indications are to be expected so that the driller may be on the look-out for them. When indications are obtained at the approximate depth expected and under the expected conditions as regards strata it cannot fail to give confidence in the eventual success of a well, and all such indications, whatever they may be, may be considered favourable, seeing that they prove that those responsible for the selection of the location have not failed to

Favourable.			Unfavourable.	
Always.	Usually.	Sometimes.	Usually	Always.
Shows of oil with strong gas in thin porous beds among impervious strata.	Shows of filtered oil with gas.	Shows of oil with very little gas.		Light shows of oil in thick porous beds with water or brine.
	Evidence of estuarine or deltaic conditions.		Evidence of entirely marine conditions.	
		Beds of gypsum or rock-salt.		
			Brine.	
	Shows of gas below or in a thick argillaceous series.			
	Shows of partially inspissated oil near the surface.		Shows of partially inspissated oil deep down.	
				Water - sands below a thick argillaceous series.
		Lignites or coals, fossil resin, sulphur or sulphuretted hydrogen.	Sulphuretted hydrogen accompanied by hot water.	Hot water with neither oil nor gas.
	Gas in slightly porous strata, with pressure increasing downwards.		Gas-shows accompanied by water in porous beds among impervious beds.	
	Ozokerite or manjak veins.			
"Wet" gas.	"Dry" gas.	Dry gas in porous beds below impervious beds.		
		Oil-shales at top of thick series.	Oil-shales deep in series.	
		Torbanites high in series.		

diagnose the case correctly. As it cannot have been without good reasons that a well is being drilled under geological advice the fulfilment of expectations as to the indications that are met with as the boring proceeds must undoubtedly make the prospects of a successful result look brighter. For this reason the geologist will do well to give to the drilling staff all the information possible as to the indications that may be expected at different depths. This will ensure that such indications are not overlooked, and may even incline the drillers to what very few are likely to be endowed with, a belief in the value of geological work.

This point must be kept firmly in mind, lest misunderstanding should arise as to the reading of evidence from a boring journal.

No hard and fast rules can be laid down, and it must not be supposed that the striking of oil is impossible even after symptoms classed as invariably unfavourable have been encountered. The boring may pass, for instance, through a series full of the most unfavourable indications and may enter another, perhaps unconformable, in which conditions and geological structure are very different. It may be very difficult to recognize the unconformable junction, and it may not even be guessed that the drill is operating in another formation till months afterwards, during which time unfavourable indications may have been so gradually replaced by more favourable evidence that the drillers have noticed little change. Possibly overhead water, from the younger series, may not have been completely shut off, and the drillers may report flows of water after every pause in the drilling under the impression that the water is coming from the bottom of the well. Such cases are very frequent in the exploitation of unknown ground, and a comparatively small head of water from above may obscure evidence of the greatest value from the strata at the bottom of the well. It is not unlikely also that the driller in charge may resent and repudiate the idea that water has not been completely shut off as reflecting upon the efficiency of his work, and the expert may thus be led into the belief that water is entering from an entirely different horizon. This is only one of many instances of how unreliable evidence may be disseminated. It shows how necessary it is that a geological expert should be almost constantly on the spot while an important test is being made in new territory. He will determine what are favourable indications and what are unfavourable, and, if he has sufficient knowledge of the series being tested, it should be impossible for him to make any serious mistake, by becoming unduly optimistic or the reverse.

CHAPTER VII

NATURAL GAS OR GASEOUS PETROLEUM

The term "natural gas" is used extensively in the United States and Canada to denote the supplies of inflammable gas that are obtained by drilling and are distributed by pipe lines and marketed for power purposes and domestic use.

The term is, of course, a misnomer, but it is a useful one, serving to distinguish the gas delivered from its rock-bound reservoir by nature from the gas made in gas-works, which presumably should be labelled "artificial gas."

Yet there are many gaseous emanations in nature which are demonstrably as "natural" yet are of very different chemical composition from the commercially utilized flows which have given the term "natural gas" its industrial significance. For instance, there are in colliery workings outbursts of gas which, though containing methane, are also rich in carbon monoxide and dioxide and even in hydrogen and nitrogen; there are emanations of carbon dioxide such as that of the Grotto del Cane; there are effusions of hydrogen sulphide in such quantity as to be dangerous to life. All these can fairly be called "natural gas."

The natural gas which is of importance commercially, and which is the subject of this chapter requires, therefore, more precise definition; it is admittedly intimately connected with phenomena relating to petroleum, it is even, we may say, generically connected with liquid hydrocarbons, and the term "gaseous petroleum" proposed by the late Sir Boverton Redwood, though possibly open to criticism on the grounds of strict scientific definition, is certainly the best term that has been suggested, and serves to explain itself and to fill the want of a suitable name under which the origin, occurrence, and utilization of this valuable product can be discussed.

It is true that in using the term "gaseous petroleum" it may be held that a great question has been begged, but the evidence, as will be seen, is so conclusive that there is a connection between liquid petroleum and the more important supplies of inflammable gas that an apology is hardly necessary.

Seeing that it is only in North America that gaseous petroleum is deliberately drilled for, distributed, and marketed on a large scale, it may not be recognized by every one what a very valuable product this gas is, and what a very large part it plays in industrial life. The continent of North America furnishes more than two-thirds of the world's supply of liquid petroleum, yet the value of the gaseous petroleum won and utilized in a year is far in excess of that of the oil. The utilization of gaseous petroleum has increased by leaps and bounds in recent years, prevention of waste has been recognized as a national necessity, and the search for new gasfields has become as important and as keenly prosecuted as the search for new oil-bearing territory.

Hence it becomes as vitally important to study the origin and occurrence of gaseous petroleum as those of its liquid congener. Yet strange to say there has been apparently very little research work done upon the subject; oil and gas are treated of together, their occurrences accepted as facts without critical and scientific inquiry, and the reasons why a gasfield is found in one locality and an oilfield in another have never received the intimate attention to which they are entitled. It is with a view to directing scientific inquiry to these points that the subject is approached here, in the hope that by a collection and marshalling of the known facts it may be possible to arrive at conclusions which will lead to a more complete understanding of the problems involved and may even point the way to the discovery of new gasfields.

Chemical Composition.—The principal constituent of gaseous petroleum is methane, CH_4, the first hydrocarbon of the paraffin series. Some analyses are recorded showing a percentage of as much as 98 of this gas, but such occurrences are rare, 90 per cent. being nearer the average.

There is, unfortunately, a lack of complete analyses of these natural gases, and even when analyses are available other important data may be omitted. Messrs. Bacon and Hamor in their book upon the Petroleum Industry of the United States give partial or complete analyses of twenty-two different gases from various countries, twelve being from the United States, but it is not stated whether the gases are from gasfields or from oilwells, and no information is given as to where the samples of gas were taken, at the well-mouth or from a town's supply mains. One gas from Staffordshire is from a colliery and can hardly be classed as gaseous petroleum. However, from this table and from many other sources some very interesting facts are to be obtained. The percentage of methane recorded from different gases ranges from 53·35 to 97·7. Heavier hydrocarbons do not appear to have been estimated always, but the percentage of these occasionally ranges as high as 20. These hydrocarbons consist of ethane, propane, butane, and vapours of pentane, hexane, and heptane among the paraffin series; the three last are liquids at ordinary temperatures but are carried over as vapours by the other gases. Olefines are also to be detected among the higher hydrocarbons, ethylene, propylene, and butylene, as well as vapours of amylene, hexylene, and heptylene, have been recorded. In gas from Russian fields, where the oil is of asphaltic base and consists largely of unsaturated and polycyclic hydrocarbons, olefines to the extent of from 3 to 5 per cent. have been separated.

The presence of these higher hydrocarbons can be detected in a gas by the odour, methane being odourless. When they are present in quantity the gas is known as a "wet" gas, since during cold weather, for instance when the temperature drops below zero Fahrenheit, a condensation of the less volatile hydrocarbons may take place and the gas mains may even be choked by the liquid formed. "Dry" gas, on the other hand, is gas composed almost entirely of methane and other gas equally or more difficult of condensation which do not cause such mechanical difficulties during "cold snaps" or under high pressure.

The other gases most frequently found in natural gas or gaseous petroleum are carbon dioxide and nitrogen. The former has been recorded up to as much as 15·5 per cent. from the Santa Maria oilfield in California, while the latter, though usually present in mere traces, reaches as high a percentage as 40 in some cases. Where nitrogen is present in quantity it is usually accompanied by oxygen and indicates that air has been allowed to mix with the gaseous hydrocarbons, but the ratio of nitrogen to oxygen is frequently greater than that in air, suggesting that some oxidation of oxidizable products has taken place. Other gases that have been identified are hydrogen (up to 1 per cent.), carbon monoxide (up to 3·5 per cent.), indicating rapid oxidation, and hydrogen sulphide. The last is generally admitted to be due to the action of water upon sulphur compounds in gaseous or liquid petroleum. Helium and argon have been identified in small quantities in several natural gases, and the former may be eventually of great value for airships if it can be separated in sufficient volume.

As a general rule it may be said that the higher hydrocarbons are most conspicuous in gases from recognized oilfields, especially in what is called "casing-head gas," the gaseous emanations from wells that produce oil.

Carbon dioxide occurs in greatest percentage in gases from the Tertiary fields as compared with the fields in older strata, and the same may be said of nitrogen and oxygen. The gases from Palæozoic fields are as a rule "drier" than those from younger fields. Much, however, depends upon where the samples of gas are taken: if sampled at the well-mouth appreciable percentages of the higher hydrocarbons may be detected, while in the gas-mains of a town possibly many miles distant from the source of supply little or no trace of the more easily condensible hydrocarbons may be present.

All these facts are of significance, which will be seen later.

Stratigraphical Evidence.—The next point of importance which has been established with regard to gasfields is stated very clearly by Messrs. Johnson and Huntley: they point out that the geological formations which contribute the bulk of the supplies of liquid petroleum are not those which supply the greatest quantities of inflammable gas. This is a practical and very significant point. It is true that over large areas in North America—it has been stated that only in North America are gas supplies seriously exploited on a commercial scale—the older formations are naturally less easy to tap by drilling than the younger, but taking the practical question of the supplies of oil and gas as separate matters, those formations that give the greatest total yields of gaseous petroleum are not the formations that give the highest total yields of liquid petroleum. To put this point more succinctly, Messrs. Johnson and Huntley have arranged the different formations in North America from which gas and oil are obtained in commercial quantities as follows in order of decreasing supply :—

Yield of Oil.	Yield of Gas.
(1) Tertiary	Devonian
(2) Carboniferous	Carboniferous
(3) Cretaceous	Cretaceous
(4) Devonian	Silurian
(5) Ordovician	Ordovician
(6) Silurian	Tertiary

This method of stating practical results is not, of course, entirely satisfactory, but some facts at once spring forward to meet the eye. For instance, the Tertiary formations, the most prolific producers of oil, are the lowest producers of gas in commercial quantities. The Cretaceous, a Secondary formation, occupies a middle position as both an oil and a gas producer, and the Devonian, foremost as a gas producer, takes fourth place as a producer of oil. Though much of the Tertiary and Cretaceous gas is "wet" gas, from which gasoline (petrol) is extracted by either the compression or the absorption, process, and thus may be said to yield oil, the relation of gas-production to age is made clear. Messrs. Johnson and Huntley in commenting upon these facts give the following conclusions : "(*a*) the older the formation the greater the ratio of gas to oil in the underground reservoirs, and (*b*) the younger the formation the more water in the total contents of the reservoirs."

The reasons for these facts and the determining factors that lead to these conclusions are not stated, but the facts themselves will be found of great assistance in arriving at a comprehensive theory to account for gasfields as apart from oilfields.

Structural Conditions and Field Evidence.—Still keeping strictly to the admitted facts, we are next led to consider the structural conditions under which gasfields occur. It has been seen already that gas extends often to a considerable distance beyond the confines of an oilfield, that is to say, wells drilled beyond the productive area of an oilpool may yet strike gas in quantity sufficient to be utilized for commercial purposes, though not necessarily at the same geological horizons that yield the oil. Instances of this will be familiar to every geologist who has worked in oilfields, and so need not be cited here. The occurrence of such gas-producing margins is easily understood when it is realized that every body of petroleum tends to give off gas, and must give off gas, unless sealed in so completely and under such great pressure that the evolution of the lightest hydrocarbons is prevented or reduced to negligible proportions. Even the water-sands round an oilfield, or water-bearing areas in a sand which is oil-bearing in the neighbourhood, are often found to be heavily charged with gas when struck in a well located outside the oilpool: in some cases this gas brings the water foaming to the surface in such a manner as to cause the drillers to dub the well a "soda-fountain."

It can well be understood, then, that gasfields may exist which are continuations or extensions of oilfields. The gas migrates with greater facility than liquid petroleum and may even pass beyond what has been called the "spilling-point" of the structure.

But a study of the gasfields of America shows that we can distinguish between two classes of gas-producing territory, those that are obviously continuations of oilfields or connecting links between separate oilpools on one general line of structure, and those that are apart from oilfields and that do not yield oil at all. The former class is more likely to yield wet gases, while the latter may be characterized by a production of dry gas.

The great gasfields of America run frequently parallel to the oilfields, and are often situated on well-defined anticlinal structures, sometimes better defined than the structures that determine the oilpools. In the Appalachian region most of the gasfields lie to eastward or south-eastward of the oilfields, that is, nearer to the disturbed and sharply folded area of the Appalachian chain.

The same general conditions necessary in the case of liquid petroleum seem to govern the concentration and preservation of gas underground, an anticlinal or dome structure, an impervious cover and a porous reservoir, but it is to be noted that the reservoir rock need not be nearly so porous as an oil-rock to give very good results: from quite a fine-grained, hard sandstone that would only yield oil slowly and grudgingly a very good outflow of gas may be obtained.

Another interesting point, and one that does not seem to have been taken note of sufficiently, is that the productive areas of the great gasfields are as a rule far larger and broader than productive areas for liquid petroleum. Vast and very gentle anticlinal structures, where the dips are so low that it is only by examining a great breadth of country that the inclination of the beds can be ascertained, may be gasfields, yielding their hydrocarbon contents over many square miles or tens and even hundreds of square miles, whereas a great oilfield may be confined to two or three square miles at the most or may even be more appropriately measured in acres. As an instance we may take the gasfield in Ohio between Knox County and Hocking County; it is a somewhat irregular field with a length of sixty-four miles and a maximum breadth of sixteen. Needless to say, no oilfield of comparable dimensions has ever been discovered.

Perhaps even better instances are afforded by the great gasfields of Western Canada. Through the prairies of Alberta at a varying distance—averaging roughly about fifty miles—from the first foothills of the Rocky Mountains runs a very broad and exceedingly gentle anticlinal structure in a great curve from the latitude of Edmonton to the international boundary with the United States. The flexure is so broad and gentle that it can only be shown by plotting the results of geological examinations upon a small-scale map. It brings up the group of Cretaceous strata known as the Belly River formation from beneath the Bearpaw Shales and the Edmonton Series. From the foothills eastward the Cretaceous formation thins out steadily, becoming at the same time much more argillaceous in character, so that towards the centre of this great anticline there may be only some 2000 feet of the formation to drill through to reach the base. The Kootanie and Dakota Groups, which measure some thousands of feet in the

Rocky Mountains, can be pierced on this anticline with little more than 2000 feet of drilling, and the strata above them are chiefly argillaceous. The Kootanie Group has been proved to be oil-bearing in the great "tar-sand" outcrops of the Athabasca and Peace rivers to the north, and also in some localities in the foothills to the westward, *e.g.* near Okotoks, and in the great prairie anticline this horizon still retains to some extent its porous character, though greatly thinned. Thus all the structural conditions for the preservation of petroleum are fulfilled.

This great anticline is an enormous gasfield, the capacity of which has hardly been fully recognized as yet. Two localities have been producing gas in large quantity for a number of years. At Medicine Hat, slightly down the eastern flank of the flexure, the production is from sandy beds of an upper horizon, doubtless sealed to the eastward by the increasingly argillaceous nature of the strata, and at Bow Island wells are drilled in the centre of the structure down to or near to the very base of the Cretaceous formation. North of the main line of the Canadian Pacific Railway the anticline gradually becomes appreciably narrower, though still very broad and gentle, and in this northern part drilling for gas has been very successful in recent years, especially in the neighbourhood of Viking.

The Bow Island field has a very large production; individual wells have been credited with yielding as much as 29 million cubic feet per day. This field supplies Calgary by pipe-line, at a distance of 180 miles, as well as many intermediate townships.

The area of gas-producing territory on this great structure can already be measured in tens of square miles, and its full extent can at present only be guessed at.

The gas is remarkably dry, but not without identifiable traces of ethane and higher hydrocarbons. The Medicine Hat gas is somewhat drier than that from Bow Island.

This we may consider as a typical gasfield; it has an area vastly greater than any known oilfield, the strata are horizontal, or so gently inclined that the dip is negligible, over a huge area, but it resembles an oilfield in having a porous reservoir rock covered by hundreds of feet of impervious argillaceous strata.

And the association with the phenomena characteristic of oil-fields does not end here. It is the general impression that no oil is found in these gas wells, but in more than one of them, drilled right down to the base of the Cretaceous formation and into Devonian limestone beneath, a little heavy oil has been found in the last few feet drilled. In the Viking field, where the anticlinal structure is narrower and consequently more pronounced, oil has been struck, though not in great quantity. This discovery has only been made comparatively recently and has caused some excitement; numbers of leases have been taken up and some are being tested, but the probability is that oil will not be found in great quantity, and that the supply of liquid hydrocarbons entering the wells will be neither prolific nor rapid. The oil is said to be heavy, more resembling a residue than a normal free petroleum.

Somewhat similar evidence of the occurrence of gas can be adduced from many parts of the world. For instance, in Queensland deep drilling for artesian water supplies has encountered gas in great quantity and under high pressure near Roma. Over a great extent of country in this province there is a thick sedimentary series of Cretaceous age with no appreciable inclination, though the underlying rocks do crop out at a distance of fifty or sixty miles from Roma. The structure, in fact, is more what would be called an "acline" in the United States rather than a monocline or "homocline." Further drilling to test the gas and utilize it is proceeding under the guidance of the Geological Survey, a depth of 4000 feet being aimed at. Interesting and informative little brochures by Mr. W. E. Cameron, Deputy Chief Geologist of the Queensland Geological Survey, have been issued giving an account of the borings, stating all the relevant evidence and discussing the possibility of striking oil.

Full analyses of the gas obtained at Roma are not available, but a sample from No. 3 Bore, tested at the Government Chemical Laboratory, showed the presence of ethane, and possibly other heavier hydrocarbons.

Other deep bores have been made in the same state at intervals over an area of 200 miles by 60, and the writer is indebted to Mr. W. E. Cameron for some details concerning them. All are in the same formation.

At Springleigh, in a deep bore, a flow of hot water from a depth of over 3000 feet brought up in liquid form a very interesting variety of bituminous mineral. On cooling the material solidified to a black and slightly glossy mass. Tested by the method of solution it gave:—

	Per cent.
Soluble in petroleum ether .	65·5, *i.e.* "petrolene."
Soluble in turpentine and then chloroform . .	16·5 (?) "malthene."
Other organic matter . .	5·2
Inorganic residue (containing metallic iron) . . .	12·8
	100·0

This shows the material to be of the nature of a very highly inspissated petroleum, but not so highly inspissated as manjak or gilsonite. The "other organic matter" may be the percentage that has reached the "Kerogen stage" (see Chapter VIII) or may be chiefly malthenes.

The inorganic residue consists, no doubt, of debris from the walls of the boring, with metallic iron from the drill.

Some sixty miles west of the Springleigh boring, another deep well at Ruthven yielded small quantities of a semi-solid bituminous matter, which on analysis by solvents yielded:—

	Per cent.
Soluble in petroleum ether . . .	90·0
„ in turpentine and then chloroform	4·0
Other organic matter	0·7
Ash (chiefly metallic iron)	5·3
	100·0

This material, as Mr. Cameron points out, is obviously less highly inspissated than that from the Springleigh boring; it is in effect a petroleum residue.

It is unfortunate that no recognized method of testing such minerals and residues has yet been devised and adopted universally, so that evidence from all parts of the world could be brought into line, but it is hoped that this is a matter that will soon be remedied.

Within the area of twelve thousand square miles, including these borings and the Roma borings, several other wells have been drilled; from one other solid or semi-solid bituminous matter is recorded, and from two "drops of petroleum." The points to be noted in this evidence from Queensland are of great significance; they may be stated in the briefest manner thus: (1) the geological structure so far as is known is not adapted to the concentration of petroleum, liquid or gaseous, towards any definite or restricted localities; (2) in this thick sedimentary series, disposed in a very gentle monocline or "acline," there are not only strong flows of gas to be tapped, but small quantities of very highly inspissated petroleum are present also.

One other gasfield may be considered before the field evidence may be said to be complete, and for this purpose the gasfield of New Brunswick is selected, since it may be regarded as a type of many other fields, and definite and accurate information is available concerning it. In New Brunswick, upon an irregular surface of Archæan strata a series of Devonian-Carboniferous age has been laid down, and is now deeply denuded and largely masked and overspread by glacial deposits. A considerable thickness of the series, however, has been proved in several localities, while boring and mining have added greatly to the knowledge obtained from examination of outcrops. The series, about the exact age of which there has been some discussion, contains hydrocarbons in considerable quantity. In Albert County the famous vein of Albertite is now exhausted, but it was worked to a depth of 1300 feet, while deeper explorations showed that it originated from sandy beds, still bituminous, 200 feet beneath. The overlying argillaceous strata are so highly impregnated with "Kerogen," or adsorbed petroleum, as to be among the richest of true oil-shales known, and many other localities over a wide area have also been proved to contain thick and workable seams of rich oil-shale.

Drilling for oil has been undertaken in several places, but has never been really successful, though small quantities of heavy petroleum and occasionally a little lighter filtered oil have been obtained.

But there is a gasfield of fair dimensions which is now being operated with considerable success; it supplies the town of Monckton and other places in the vicinity. The geological structure of the gasfield is a gentle anticline, but not nearly so gentle nor so large as the Alberta fields. A little oil is got from some of the gaswells, but not in such quantity as to be of any real importance to the operating company. In fact, unless other and new oilfields be discovered in the Province, all the evidence may be said to point to New Brunswick as a "has-been" from the point of view of free petroleum. There is much evidence of the former presence of oil, but apparently only the dregs are left. Still, gas of excellent quality remains to be obtained in supplies of commercial importance where geological structures favourable to its preservation occur.

The significance of these facts is obvious; they add another link to the chain of evidence which has been followed through the preceding pages. It appears that the association of gas in commercial quantity with highly inspissated oil or the residues of oil is of fairly frequent occurrence, not only in areas that have never been oilfields, but in territory that gives abundant signs of having been highly petroliferous in a past age.

Inspissation and Adsorption.—This brings us naturally to a consideration of what is meant by the process of inspissation. This point has been dealt with before, but it may be as well to recapitulate, and it must be understood that the word inspissation is here considered in its widest possible sense, as the action or actions that result finally in a solid residual mass, largely or even entirely insoluble in carbon disulphide, being produced from what was liquid petroleum. Strictly speaking, and on the face of it, the term means a "drying up," such as takes place where a seepage of oil reaches the surface. The oil loses its lighter fractions by evaporation, and thereby the heavier hydrocarbons become concentrated. Hydrocarbons of the paraffin group, especially those of low molecular weight, are dissipated most easily, but unsaturated hydrocarbons may be preserved in various ways, *e.g.* by chemical action. For instance, a certain amount of oxidation must take place during inspissation at the surface, since asphalts formed on the outcrop of asphaltic oil rocks all contain oxygen. What are known as oils of asphaltic base contain or have contained large percentages of unsaturated hydrocarbons, and these are naturally more liable to form new compounds with oxygen, sulphur or any other available element, if brought into contact with them in suitable combination. So while the saturated hydrocarbons, the paraffins, may be largely dissipated during weathering, the unsaturated hydrocarbons, or compounds derived from them, tend to become concentrated. Thus the weathered outcrops of oilrocks may be traced for miles, when the oil is of asphaltic base, by cones, flows and deposits of asphalt, while the outcrop of a rock containing oil of paraffin base may give little or no sign of the presence of hydrocarbons except under the most careful and detailed examination.

So far merely weathering of the hydrocarbons has been considered as part of the process of inspissation; it takes place not only at the surface, but down to considerable depths, as may be proved by analyses of manjak veins, the margins of a vein always showing a higher stage of inspissation than the centre at the same level, and an increase in the degree of inspissation towards the surface being invariably noticeable. It is evident, however, that besides this weathering there must be some other action, for weathering can hardly be believed to account for the alteration of liquid petroleum at a depth of two or three thousand feet beneath the surface and probably well sealed under water-logged strata. It is suggested that this other action is a polymerization of the less complex hydrocarbon compounds. This no doubt may be operative in the zone of weathering and at the surface, but with time and high pressure it is probably by far the more important action *relatively* at the greater depths. That some action that slowly turns liquid petroleum into solid minerals does take place at great depths is proved by the occurrence of manjaks or asphaltites. The albertite of New Brunswick, for instance, has reached such a high state of inspissation that it contains ten per cent. or less of material soluble in carbon disulphide, *i.e.* bitumen, and perhaps only two or three per cent. soluble in petroleum spirit (petrolene). Yet, like all manjaks, it is obviously derived from liquid petroleum, and has reached its present position in a liquid or semi-liquid state. In a manjak vein in Trinidad part of the central portion has been found to be still plastic.

Once again it is noticeable that petroleum of asphaltic base is more prone to undergo polymeric change than petroleum of paraffin base. Ozokerite, the final product of the underground inspissation of a paraffin oil rich in paraffin wax, occurs in thin veins and strings and networks of veinlets through strata that have formerly been impregnated with oil, but never in the great veins and intrusions characteristic of the manjaks. The reason for this is not far to seek. Asphalt consists of polycyclical hydrocarbons formed by the building up of simple unsaturated hydrocarbons into complex molecules, chains and rings, which enable the full valency of the carbon atoms to be satisfied. There is, therefore, a natural tendency for the formation of such compounds with high molecular weight causing in an oil a gradual passage from liquid to solid hydrocarbons. Fully saturated hydrocarbons such as form the bulk of oils of paraffin base do not and cannot have the same tendency. To put the matter briefly, the solid paraffins found in nature are more of residues; the asphalts and asphaltites, though they must be regarded to some extent as residual, are formed also by direct chemical action of the nature of polymerization.

This explains why paraffin oils may be dissipated in the course of time, which is an important factor in these processes, as volatile liquids and gases, while asphaltic oils tend more to concentrate and coagulate into solid residues.

Oils of mixed paraffin and asphalt base naturally possess intermediate characters.

The process of adsorption treated of in Chapter III has also to be considered here. It has been seen that it is the unsaturated hydrocarbons, and especially the inspissated products built up from them, the asphaltic material, that is fixed by adsorption, while it is the lighter fractions, the saturated compounds, the hydrocarbons of smaller molecular size and weight that filter through. An oil containing both solid paraffin and asphalt may filter through thousands of feet of strata, bringing with it in solution its solid paraffin content practically unaffected, but its asphaltic content may be almost entirely eliminated in the process. Excellent evidence on this point is to be obtained in Egypt, where the Jemsah field yields a fairly light paraffin oil with little or no asphalt, while the Hurghada field, much lower in the series and representing the main source of oil in the country, yields an oil containing a large percentage of asphalt and a fair percentage of solid paraffin. Compared with the Jemsah oil the Hurghada oil contains naturally a lower percentage of solid paraffin in proportion to the amount of asphaltic material. The Jemsah oil appears from all the evidence available to have reached its present position in the cavernous Miocene limestones by migration from a much deeper source.

Thus, given strata with sufficient colloidal contents to act as adsorbent media—and few strata are without some colloidal properties—an oil of asphaltic base sufficiently inspissated or polymerized may be adsorbed *in situ*, or in the near neighbourhood of its origin or place of concentration, while a paraffin oil may be gradually dissipated as light oil and gas without leaving any conspicuous traces of its former presence save a few veinlets of ozokerite. Adsorption of the heavy paraffins, however, does take place also, when the oil has reached such a stage of inspissation that the solid paraffin begins to separate out. This adsorption cannot affect the lightest hydrocarbons that are gaseous at ordinary temperatures or at the earth-temperature at any particular depth beneath the surface.

Now summing up the evidence detailed above, it is possible to obtain a fairly clear and comprehensive idea of how gasfields have originated, of their connection with oilfields, and the reasons why we find a gasfield in one locality and an oilfield in another.

All oil contains gas in greater or less quantity, chiefly methane, but also ethane, the gaseous olefines, etc. This gas may be considered to be combined with, dissolved in or occluded in, the oil; it is really *potential* gas, and does not exist as gas till release of pressure allows it to expand and disengage itself from the liquid prison. As has been shown, it is probably the release of pressure that has caused such a readjustment among the mixed hydrocarbons as to allow of methane and other gaseous compounds being evolved. Everywhere round a body of oil where egress is not prevented gas will be found filling all porous strata and often exerting great pressure.

Now take the case of a great gasfield such as that of Alberta. Petroleum was doubtless formed throughout the vast gentle anticline wherever the raw material to form it was present. But there was not, and there is not yet, a sufficiently pronounced geological structure to have caused a migration of the petroleum formed, against friction, towards definite localities where it could be concentrated in such quantity as to constitute a commercial oilfield. In consequence there was never sufficient oil in one locality to fill the porous reservoir available, and the lighter hydrocarbons naturally permeated the porous strata as gas. As the oil was formed, whether in argillaceous strata or in direct association with the reservoir rock, it would find its way to the most porous stratum, and the gas would be diffused over a great area, only checked in its migration by the impervious covering strata and water-logged beds on the flanks of the great flexure. Had there been any well-marked or pronounced anticline the liquid petroleum would have steadily if slowly migrated towards it, driven by hydrostatic pressure, and filled the porous reservoir completely, thus forming a body of oil that would long have resisted the action of inspissation. But in the absence of such a concentration the oil would be continually drained of its lighter elements to supply the porous reservoir with gas, and inspissation of the liquid residue would be favoured and might take place fairly rapidly. Adsorption of the heavier asphaltic compounds would then be naturally encouraged, and the body of oil, small enough in any locality, would decrease by adsorption. As the mass of liquid petroleum decreased thus under adsorption any dissolved or occluded gases would be gradually released, and these actions would proceed steadily till at the present day we find only the residues of an oil impregnation in such localities as either favoured a slight concentration or supplied originally the greatest quantity of raw material, while the bulk of the porous stratum is filled with the lighter or gaseous hydrocarbons that could neither polymerize into heavier molecules nor be adsorbed by the colloidal material in the beds.

Theoretically the gas pressure should be constant throughout the porous gas-impregnated rock, so long as the porosity does not vary, but practically there is always apt to be higher pressure towards the crest of the flexure or the localties where the porous reservoir is thickest. This is due largely to friction, which, however slight, must affect the migration of gas. Differences of porosity also cause higher or lower pressures in different localities. But these differences may be comparatively small; gas under a fairly constant pressure can be obtained by drilling over a wide area, while oil may be only in evidence here and there, where the porous rock is completely pierced by the drill and the lowest layers of the reservoir reached.

All the greatest and broadest gasfields conform generally to these conditions, but there is another point to be considered: time is an important factor. It is obvious that in the oldest oilfields there has been more opportunity for polymerization and adsorption and consequent reduction of the body of liquid petroleum, and more complete resolution of the liquid into its lighter elements in the gaseous form and its heavier elements or residues produced by long-continued inspissation. Thus even in a well-marked anticline that has once been a potentially prolific oilfield the lapse of ages may have left little but a residue of heavy oils and a great body of gas filling the porous strata that were once more or less fully impregnated with liquid petroleum. The New Brunswick field is a good example of this, and the same actions account for the greater production of gas in comparison with oil from the older formations in the United States and Eastern Canada. In these cases, also, it is to be noted that the oil, which has survived from Palæozoic times, is of paraffin base and light gravity: it may have lost some asphaltic products through time and adsorption, but the probability is that the oil being largely composed of fully saturated hydrocarbons has been unable to polymerize and form heavy inspissated residues and so has been preserved.

Of course the gas given off by such bodies of oil in its migration through the porous strata carries vapours of the lighter liquid hydrocarbons with it, especially if the depth temperature be sufficiently high to favour evaporation, but these hydrocarbons will be gradually eliminated in a lengthy migration, and the farthest confines of the gasfield will yield the driest gas. Similarly the oldest formations, except perhaps actually on the crests of flexures once highly petroliferous, yield, as a rule, drier gas than the younger. This is substantiated by such analyses as are available for study.

Except those gasfields which are continuations of productive oilfields and indissolubly connected with them, where, in fact, the gas has passed beyond what has been called in the United States the "spilling point," all gasfields will be found to come under one of the two types generally indicated above.

The case of Queensland is specially interesting in this connection. That the strata have at one time contained oil cannot be doubted on the evidence collected; that the oil was never concentrated seems equally certain; that the oil has been inspissated and probably adsorbed at great depth is evident, and that the gas is still present to be tapped in great quantity beneath the water-bearing strata in favourable localities has been proved by boring.

In the younger formations time has naturally had less effect in separating petroleum into heavy and polymerized residues and gases uncondensible at normal temperatures and pressures. In consequence the oil and gas are found together, and the latter if utilized otherwise than as fuel can be collected from the casing of oil wells in specially designed plant. It is then known as casing-head gas, and it is almost invariably "wet" gas. By compression and cooling it may be made to yield large quantities of the most volatile petrol, the ethane, propane and butane, and their unsaturated homologues being condensed as well as vapours of pentane, hexane, and higher hydrocarbons. A yield of three gallons or more of casing-head gasoline or petrol from one thousand cubic feet of gas is quite frequent by these methods, and even half that quantity will pay for extraction if the flow of gas be sufficiently great. To utilize it as petrol the liquefied product has to be mixed with heavy naphtha.

A method by which even smaller quantities of these easily condensible hydrocarbons can be extracted with profit is to pass the gas through heavier oils, which dissolve the most easily condensible vapours and can be made to give them up again by slight heating. The process can be made continuous. The production of gasoline by these methods in the United States already amounts to hundreds of millions of gallons per annum.

The residual gas after passing through either the compressor or the absorptive oil is naturally a dry gas, and can be used for fuel for power without the disadvantages with which an admixture with the easily condensible gases and vapours would endow it.

A consideration of the above theory of gasfields naturally leads to the question as to whether new gasfields can be discovered by the application of the principles indicated : the answer, though it cannot be made strongly affirmative except perhaps in individual cases which it is not necessary to discuss here, is decidedly hopeful.

It must be remembered that gas existing at high pressure underground is much freer to migrate than oil. It is not affected by gravity but can diffuse in any direction, seeking naturally any locality where the pressure is lower and finding its way through all strata not completely waterlogged and impervious. Thus downward diffusion and lateral diffusion are as common as upward diffusion, and in most cases such downward or lateral movement is easier, since but for an impervious cover there could be no concentration of gaseous hydrocarbons. An oilfield may be a thing of the past, may have been so deeply denuded as to have lost its store of liquid petroleum by inspissation, adsorption, etc., or may have been exhausted by drilling, but a gasfield may yet be discovered beneath it, even if the gas has had to migrate into a different formation, and possibly into strata not markedly porous.

For a free flow of oil a fairly porous reservoir is necessary, but gas may be obtained in quantity from strata of very much lower porosity. Two instances illustrating these points may be given, one from surface observation and one from evidence obtained by boring.

In Trinidad the Cretaceous formation is not primarily petroliferous, but Cretaceous strata are found not infrequently impregnated to some extent with petroleum when overlaid by highly petroliferous Tertiary beds : even in localities where the Tertiaries have been long ago removed by denudation the impregnation may be conspicuous, *e.g.* San Fernando Hill. In one locality in an outcrop of Cretaceous shales small mud-volcanoes may be seen, showing that sufficient gas, if not oil also, has penetrated deep into the older series, and is still being evolved where some surface fissure or fault-plane favours the escape of the volatile hydrocarbons. It is to be feared that this occurrence may have led astray more than one prospector among the number of "petroleum geologists" who have visited the island.

The other instance which has come under the writer's personal observation is in Manitoba, where the CretaceousSeries of Western Canada rests in a very gentle monocline upon Devonian strata. The lowest member of the Cretaceous formation in the district is known as the Dakota Sand, a coarse quartzose grit well known south of the international boundary line. It is overlaid by a thick series of estuarine shales, which, however, contain a few thin bands of fine, hard, calcareous sandstone and some shaly beds of slightly greater porosity than the bulk of the strata. Much of the shale contains a slight impregnation with Kerogen, too slight to be easily recognizable in hand specimens: it yields some six or eight gallons of oil per ton when distilled, but there is no sign of free oil in any of the shale beds.

In this district there would probably have been an oilfield had there been any geological structure capable of concentrating and retaining oil: the Dakota Sandstone would have been the oil-bearing bed.

Drilling some miles to westward of the outcrop of that formation, where it lies at about 600 feet beneath the surface, gas was encountered in the shale and calcareous sandstone beds not far above the Dakota Sandstone. The latter when pierced by the drill was found to be full of salt water without a sign of oil or gas. The gas is dry and of good quality and under fairly high pressure, but as there is no thick porous reservoir rock the pressure decreases rapidly, and is only slowly regained when a well is shut in. Were there an extensive porous reservoir it would almost certainly have been invaded by water as was the Dakota Sandstone; the shales have proved sufficiently impervious to repel invasions by water, yet sufficiently porous to contain considerable quantities of gas in certain localities. The yield of gas has not proved so far to be sufficient to utilize except locally, but its occurrence and environment are very significant. Other wells drilled further to the westward and to much greater depths have also yielded gas in several localities.

These facts indicate that even under unpromising conditions a supply of gas may be obtainable long after true petroliferous characteristics have been lost.

The application of what has been learnt from these facts to the practical question of the search for new gasfields in North America is likely to meet with successful results in several territories, and according to Messrs. Johnson and Huntley the possibilities are not being overlooked.

But an even more interesting application can perhaps be made in the case of Great Britain.

The question of drilling for free petroleum in England and Scotland has been much before scientists, certain official departments, and the public in recent years: there has even been something in the nature of a controversy among scientific authorities as to the prospects of success.

The writer has for a number of years been in favour of certain test-wells being drilled in localities with which he is familiar, though never unduly hopeful as to results. Of the tests now being made some have fair chances of success, though results up to date are less favourable than has been represented. Still, even as these words are being written the striking of oil in Britain may be an event of the near future and may be an accomplished fact and a nine days' wonder long before this page sees the light of print. But what the writer wishes to emphasize is that though it is possible that oil may never be obtained in paying quantity by the enterprising Government agents, the striking of gas is quite probable in several different counties.

Seepages of oil are known in very many localities in coal and shale mines, and such oil in almost every case has been of paraffin base. Such oils, as has been seen, are apt to be dissipated in the course of geological ages, leaving little trace, but they frequently are the progenitors of prolific gasfields.

Suitable geological structures to contain and preserve the gas are known in many places: though unfortunately rather small, they are adequate and are sometimes little affected by faulting. Suitable porous strata with suitable impervious cover at suitable depth are also known to exist. The only danger to be feared is the presence of fault-planes, which though not unfavourable to the accumulation of quantities of liquid petroleum may have enabled gas, owing to its powers of diffusion, to have escaped during the geological periods that have elapsed since it was first concentrated. However, the drilling for gas is a proposition worth considering even in localities where the drill has already pierced the horizon most likely to give a yield of oil. On some anticlines in the Scottish shale field quite considerable outflows of gas have been recorded in a region which, as will be seen later, was once an oilfield and may yet prove partly petroliferous.

The gas at Heathfield in Sussex has been known for many years and has been utilized locally, but has never been tested thoroughly nor its origin explored. In this case the gas is apparently found in porous sandstones at the base of the Cretaceous formation, but its origin lies deeper. It emanates from an oil of asphaltic base which has probably not survived inspissation and adsorption, though traces of its former presence may be found in boreholes passing through the Purbeck and Portland beds, in outcrops of the Portland Sand and in the impregnated oil-shale beds of the Kimmeridge Clay. It was a sulphurous oil.

That gas may be obtained by drilling over a considerable area in the South of England is still an untested possibility, for the deep borings that have been made for water, coal, etc., have not been situated on favourable structures for the storage of gas, except at Heathfield.

Even the phenomena in the dug-out at Cheriton, where at a very shallow depth puffs of gas were encountered during the digging of a subterranean chamber, are suggestive, as the locality lies not far from the crest of the great anticline of the Weald. These phenomena caused a great sensation in the newspapers towards the end of 1917. It is true that eminent authorities attributed these occurrences to the mischievous activities of a poltergeist—whom the writer did his best to have interned as an alien enemy during the war,—but whether English spook, poltergeist or natural gas were responsible for the strange happenings, the mode of occurrence and the situation on a great gentle anticline were sufficient to interest those familiar with the many phases of petroleum, and to suggest that we have yet untested areas in this old country that might be profitably exploited.

When all is said and done, if a cheap and clean fuel can be obtained, if only for local consumption, it is of little moment under which misnomer it is known, "natural gas," "gaseous petroleum" or "poltergeist."

CHAPTER VIII

OIL-SHALES AND TORBANITES

THAT oil-shales and torbanites are connected, however remotely, with crude petroleum has only lately been recognized, and is not yet by any means generally accepted. However, much evidence has been collected on the question, and with each new contribution to the subject, chemical or geological, the phenomena of these deposits are becoming more clearly understood.

The reader is referred to the first two chapters of "A Treatise on British Mineral Oil," in which the writer has summarized the result of his researches, and the evidence upon which his conclusions are based; for further details papers before the Royal Society of Edinburgh and the Institution of Petroleum Technologists may be consulted.

Research, however, is never at a standstill, or at least never should be, and it will be found in comparing these publications that the author's views and theories have suffered some modification as the investigations proceeded, not, perhaps, in the essential issues but in details which as knowledge progressed became more completely explicable. It will be sufficient to recount briefly the main points, giving special attention to those details in which further progress towards complete understanding has been recently made.

It is as evidence of former oil-bearing conditions or the approach to oil-bearing conditions that oil-shales and torbanites are considered here, thus bringing them within what may be classed as indications of petroleum. This may be thought a bold assumption by many, but the reader is requested to study the evidence carefully before giving a verdict upon the conclusions, which, however distasteful they may be to some of the shale-oil experts, have not yet been seriously combated.

Oil-shales.—It is unnecessary to recount the various theories, all somewhat vague, that have been advanced to account for the occurrence of oil-shale; they will be found in many publications, official and otherwise. In most cases only one particular area or shalefield is dealt with, though notes upon or references to other fields and types of oil-shales may be included. Only too frequently torbanites and oil-shales, entirely different deposits of different origin, are treated together as if they were of the same nature. Oil-shales in different fields and different parts of the world present so many different characteristics that an explanation which appears plausible for one particular country or field may break down badly if applied to another. What is required is one simple theory that shall have regard to all essential facts, and that can be applied universally to all oil-shale phenomena. This the author claims to have formulated, however crudely: the theory is based on geological field evidence and microscopic evidence, and is confirmed by chemical analyses and the practical results of retorting experience.

Oil-shales are adsorption phenomena due to the so-called affinity of certain argillaceous deposits for petroleum. Oil-shale fields bridge the gap in a thick series of deposits between the true petroliferous phase below, and the carbonaceous phase above. Oil-shales are often the last relics of a former impregnation with petroleum; they are associated with phenomena—such as the intrusive asphaltites or manjaks—common to petroliferous regions, but in many cases the parent oilfields, the sources of the former impregnation, are things of the past, and it may be that no trace of free petroleum may be found even in the lowest zones of the series that contains oil-shale.

There is free petroleum in oil-shale, but it is frequently such a small percentage that its presence has been overlooked, especially as such petroleum is usually of the nature of solid bitumen only to be extracted by treatment with carbon disulphide or other solvents. In the Scottish shalefields only some 2 per cent. or even less can be extracted thus and classed as free oil or bitumen; in the Kimmeridge oil-shales of Dorsetshire the richest bands, yielding some forty gallons to the ton in the retorts, contain as much as thirteen gallons of "free" oil; in the Monterey shales of California most of the hydrocarbon content is free, as distinguished from what has been called "Kerogen," material that only yields oil by distillation.

The characteristic that determines that a bed or stratum should become an oil-shale is its absorptive and adsorptive capacity; the oil that impregnates it, or has at one time impregnated it, is adventitious. Searching more closely into this quality of absorptive and adsorptive capacity it is found to depend upon the presence of colloids. Alumina, silica, ferric hydroxide, and all fine argillaceous sediments are potential colloids; lime and magnesia, except in combination as silicates and in a very finely divided state, have very little colloidal property. Thus fine clays, chiefly composed of finely divided silica, alumina, and ferric oxide, and poor in lime and magnesia, *e.g.* clays of the nature of fuller's earth, make the best and richest oil-shales.

An oil-shale, then, is a combination between the disperse phase of the colloid solution or sol known as crude oil and the mineral colloids of a fine clay of suitable composition. Whether the sol be a suspensoid or an emulsoid sol is a matter of no importance. In an asphaltic oil the material adsorbed is chiefly the polycyclical hydrocarbons, in a paraffin oil the paraffin waxes; these, as has been seen, may be regarded as the disperse phase in the colloid solution known as crude oil.

But to enable adsorption to take place to a sufficient degree to form a rich oil-shale it is necessary either that a great volume of oil should migrate through the bed or that the sol should be concentrated, that is to say, should contain a large proportion of the disperse phase. Now migration of a large volume of oil through a fine argillaceous rock can hardly be considered possible on account of physical difficulties, so it follows that a concentrated sol is essential. The reason for this is obvious when we remember that the concentration varies as the square of the amount adsorbed. Thus even long-continued migration of a sol of constant composition could not make a richer oil-shale at any given temperature. But if the sol is becoming more concentrated by the loss of some of the lighter fractions forming the continuous phase, and if the temperature be decreasing, the amount of disperse phase adsorbed will be naturally increased. Such concen tration can only take place by inspissation and polymerization, and such reduction in temperature can only take place by the strata being brought nearer to the surface by elevation and denudation. Therefore it becomes evident that the formation of an oil-shale is favoured at a somewhat late stage in the petroliferous history of any series, when inspissation has affected the oil and denudation brought the strata nearer to the surface, thus reducing depth temperature.

An oil-shale may be looked upon for all practical purposes as a gel, varying in composition according to the constituents of the crude oil and the mineral matter. It is, moreover, a very stable gel, enabling it to remain for geological periods with very little change, and to resist successfully resolution into its two components by anything but a temperature high enough to initiate distillation.

But however stable, an oil-shale is still liable to show deterioration which may be looked upon as inspissation or resolution of the gel, and we have direct proof that during the countless ages of geological time the composition of an oil-shale is gradually changed by the loss of the lighter hydrocarbons, leaving only those of greatest molecular size and weight. It is conceivable in fact that the gel may be completely resolved ultimately, leaving a carbonaceous shale consisting of what was once bitumen scattered in minute particles throughout the fine argillaceous debris of the original deposit. Such gels have taken possibly a comparatively short time to form, but they require ages to break down; the action may be arrested or continuous according to the conditions to which the strata are subjected.

Extraction with solvents such as carbon disulphide is really a partial reversal of the gel to a sol again, a portion of the adsorbed material coming into solution again till a new equilibrium is established depending on the concentration. This reversal is naturally selective, the latest material to be adsorbed being the first to redissolve. Thus the younger and less inspissated or resolved oil-shales naturally give greater percentages of soluble material—"free oil" or bitumen—than the older, more inspissated and resolved oil-shales.

It matters little whether the original crude oil be formed within the shale beds or be forced into them from below or laterally by gas or hydrostatic pressure: given the colloid deposit and the colloid solution, sufficiently concentrated, in juxtaposition, the result will be an oil-shale. Oil-shales may be formed under any conditions of geological structure, in synclines, monoclines or anticlines, but the probability pointed out above of the formation of an oil-shale being at a somewhat late stage in the history of a formation makes it probable that earth-movement has taken place, and it is possible that the formation may be thrown into well-defined folds. In such a case the crude oil while still free will be concentrated towards the anticlines and there will be subject to inspissation and to reduction of depth temperature. The final result will be that the richest shales will usually be found in anticlinal structures, a fact which has been observed in many countries from Scotland to Peru. In the Scottish shale-fields much shale is worked in fairly deep synclines, but it is never so rich as that found in the anticlines or generally anticlinal areas. But the deeper shales, that is those worked in the synclines, is frequently richer in ammonium sulphate though poorer in oil, while the specific gravity is usually somewhat greater. The explanation is not far to seek. The depth temperature has been greater, thus reducing the adsorption, and the adsorption being selective only the heaviest hydrocarbons, in which the nitrogenous material is concentrated, have been adsorbed; the free or unadsorbed oil has migrated towards the anticlines, there encountering more favourable conditions for both inspissation and adsorption. Hence the 35 and 40-gallon shales of the Broxburn dome, and the 18-gallon shales of the synclines, the latter, however, yielding perhaps as much ammonium sulphate as the richer shales.

The fact that oil-shale fields and coalfields occasionally overlap to some extent in vertical section is another indication of the formation of the oil-shale being a late development, or a development that continued to a late stage: the shalefield may survive for periods after the oilfield stage beneath has become a thing of the past. But in many cases the lower zones of a series may still be in the petroliferous stage, and even profitably productive, while the upper zones are characterized by oil-shale beds with a mere two per cent. of bitumen.

It is for this reason that oil-shales may still be regarded to some extent as indications of petroleum, especially if they occur in the upper beds of a thick series, the deeper zones of which have not been explored with the drill. Truth to tell, up to the present no commercial oilfield has been discovered by drilling through an oil-shale field to reach the petroliferous phase that may be beneath, but it is possible that such a discovery may yet be made. The Green River Beds of Colorado, Utah, and Wyoming have a thick series of oil-shale beds surmounting a distinct petroliferous phase, but the geological structures are not favourable to a concentration of petroleum, the anticlines being deeply denuded, and the massifs of Green River Beds lying in great synclinal plateaux.

In New Brunswick oil has been found in small quantities, and gas in fairly large quantities, beneath oil-shale fields, but the lack of large well-defined anticlines and sufficient thicknesses of strata has militated against any large store of petroleum being preserved. It is possible, however, that more favourable structural conditions may yet be discovered in that Province.

In the Scottish shale-fields, where structures suitable for the conservation of liquid petroleum are well known, drilling is even now proceeding with the hope of striking oil in paying quantity. The structures are unfortunately small, with one exception—the Cousland-D'Arcy anticline,—and though indications of free petroleum are not wanting in some of the domes the striking of it in commercial quantity is problematical. This matter will be dealt with in a subsequent chapter; the point to be noted here is that it was the writer's researches on oil-shales that first led him to consider the possibility of free oil being still existent, and to make a special study of the geological conditions in the Scottish shale-fields to enable him to advise as to speculative drilling.

This matter is still *sub judice*, and only the drill can give a complete answer to the question, but in adding oil-shale to our list of indications of petroleum it is necessary to make the reservation that such deposits near the top of a thick series may be of value, while if they occur low in a series the oilfield searched for may prove a "has-been." In any case a thick series with well defined anticlinal or dome structures will be necessary if any petroleum is to be found that has been preserved from colloid combination, or in the parlance lately in vogue, "reached the Kerogen stage."

Torbanites.—The deposits known as torbanites or boghead coals take their name from the famous Torbane-hill Mineral of Bathgate. They have been the cause of much litigation and the subject of much research, to which it is not necessary to refer here. Suffice it to say that the litigation turned upon the question as to whether a torbanite is a coal or not. In another work * the writer has made a contribution to the literature of the subject.

It has been generally believed that torbanites are of rare occurrence, but this view requires some modification: good examples of torbanites are known in France, Kentucky, South Africa, and New South Wales, while investigations of the late Petroleum Research Department of the Admiralty and of the Committee on the Production of Oil from Cannel Coal have added a large number to the known torbanitic deposits of England, Scotland, Ireland, and Wales.

A torbanite is essentially a phenomenon of the carbonaceous as distinguished from the petroliferous phase, and thus, in a thick sedimentary series, should occupy a position above those of oil-shales or oil-bearing rocks, but yet it furnishes evidence of great importance and interest in connection with the formation of crude petroleum. This will be seen when we consider the conditions under which alone torbanites can be formed.

They are essentially beds of impure vegetable debris, and are usually classified as cannel coals of a somewhat special type. The inorganic matter is usually very fine and argillaceous: such analyses as are available show it to consist chiefly of silica, alumina, iron oxides, and alkalis, with little or no lime and magnesia, all in a very finely divided state and well distributed throughout the deposit, in fact colloidal material. This inorganic matter amounts to from less than ten to more than thirty per cent. of the deposit. The rest is fine vegetable debris with few vegetable fossils of any large size; such material is capable of forming coal, but if it has since deposition reached the coal stage completely no torbanitic development can ensue. It is the preservation of part at least of the

* "A Treatise on British Mineral Oil."

vegetable matter in an uncarbonized, or possibly a "jetonized," state that admits of the special development to which the term torbanitic is applied.

Briefly, then, a torbanite is a special form of cannel coal, though it may in some cases look like a black shale, and most cannels have some trace of torbanitic growth, though only where such structures are very conspicuous can the term torbanite be applied to the deposit.

As seen under the microscope a torbanite consists of a coal matrix, in which globules of yellow or red-brown matter, spherical or ovoid in shape, are scattered more or less thickly. These globules consist of hydrocarbons and inorganic matter so intimately combined that they cannot be resolved by ordinary microscopic means. They are *gels*, formed *in situ*, and are so stable that it may require vast ages or higher temperatures to resolve them.

It requires a combination of favourable circumstances before a torbanite can be formed: these are uncarbonized vegetable debris mixed with the finest argillaceous sediment, sufficient pressure and effective sealing; no high temperature is required, in fact, quite a low temperature would be favourable. Under these conditions the globules begin to form from centres and spread outwards; they usually show a faint and irregular radial arrangement. The size of the globules varies greatly in different deposits and in different laminæ of the same deposit. In beds in which the lamination is very strongly marked the globules are usually oval in cross-section with their larger axes parallel with the lamination. In very rich torbanites, where the globules form nearly the whole of the deposit, the globules impinge upon one another but do not anastomose as a rule.

These globules are simply incipient drops of petroleum, which have formed gels with the inorganic colloid material as they came into being, and we have thus preserved for us one of the stages in the formation of petroleum, the action being arrested almost as soon as it has commenced.

These gels do resolve into their constituents in the course of time, the action being for all practical purposes an inspissation, or perhaps it would express the action better to say that by inspissation to which these gels are liable they gradually become resolved. Four stages in this resolution can be recognized, and have been described by the writer (*op. cit.*). The final stage shows a complete breaking down of the gels.

In the case of very rich torbanites in which eighty or ninety per cent. of the rock is formed of globules, there is usually a slight flattening of the spheroids along the planes of bedding. The Joadja Creek torbanite, the richest and perhaps the least deteriorated ever discovered, shows this flattening distinctly, and one of the Transvaal torbanites gives similar evidence. It would at first seem astonishing that in such cases these petroleum gels could have sufficient rigidity to withstand crushing pressure at all. The explanation lies in the fact that each globule is a gel. The resistance of a gel to deformation is enormous—a point, it may be noted, upon which the whole problem of viscosity turns. It is possible to form an emulsoid gel from oil with one per cent. of soap solution, a gel so rigid that it can be cut into blocks with a knife. Thus the fine mesh of a suspensoid gel formed of fine inorganic material and petroleum may be enabled to resist great pressure with very little deformation. In torbanites of less richness, where there is a coaly matrix forming from forty to eighty per cent. of the deposit, the gels may easily escape any flattening or distortion by pressure.

By an unfortunate generalization the globules of a torbanite have been confused with the gel-like masses of oil-shales, both being grouped together under the useful name of "Kerogen." But they are really different, as can be proved chemically and by practical retorting tests. The gel-like masses of oil-shales are formed from inspissated oils in which nitrogenous compounds, and possibly sulphur compounds, have been concentrated through the loss of light oils, while selective adsorption has accentuated this concentration. This means that polycyclical hydrocarbons, solid paraffin and generally the compounds of greatest molecular weight in a crude petroleum, are more prominent in an oil-shale than in the gel globules of a torbanite. In consequence the crude oils recovered by distillation of oil-shale and torbanite differ considerably, the latter deposit yielding lighter oil with probably at least fifty per cent. of saturated hydrocarbons, while the shale-oil is very rich in unsaturated hydrocarbons, probably at least seventy per cent., and is generally of higher specific gravity and higher setting point. Again, a torbanite does not yield much ammonium sulphate, possibly not more than 10 lbs. per ton, while an oil-shale often yields over 50 lbs. per ton and sometimes more than 70 lbs. These differences are of course most conspicuous when the torbanite is fresh, *i.e.* when the gels show little or no sign of deterioration or being resolved, but even in a highly degenerated torbanite, where the gels have broken down and are showing their inorganic constituents, the percentage of saturated hydrocarbons remains high, and large quantities of good paraffin wax can be extracted from the crude distillate. These facts are well established by the results of numerous retorting tests on a commercial scale, and subsequent chemical analyses of the oils. As will readily be understood, a torbanite, especially if fresh, can be retorted at a lower temperature than most oil-shales.

The richest torbanites in the world are the so-called oil-shales of New South Wales: they are not oil-shales in any sense of the word. The failure up till recently of attempts to retort them on a commercial basis was largely due to the facts that an unnecessarily high temperature was used, and that retorts of the Scottish type, suitable for a highly inspissated oil-shale but not for a fresh and very rich torbanite, were employed.

The relations of torbanites to coals and to oil-bearing strata are instructive. A pure vegetable deposit will reach the coal stage under depth-temperature and pressure more rapidly than an impure, and thus we often find coal and torbanite in juxtaposition in the same seam. Under sufficient pressure and effective sealing the vegetable deposit, provided it has not reached the coal stage, will become petroleum and impregnate the neighbouring porous beds. But if while partly carbonized and partly uncarbonized, it be subjected to sufficient pressure and effective sealing, and if mineral colloids be present in sufficient quantity, the uncarbonized vegetable matter will develop globules of petroleum and form gels *in situ*, the result being a torbanite. In New South Wales and South Africa the torbanites occur low in the Coal Measures and associated with coals, but not in the upper beds of the Coal Measures. In Scotland the Torbane-hill Mineral occurs just above the

Millstone Grit, far above the Oil-shale Groups and above the Carboniferous Limestone coals but below the Coal Measures.

Of all districts in England where torbanites are common North Staffordshire is the most conspicuous. Towards the top of the Coal Measures in that county torbanitic bands are frequent, and one very rich torbanite (in the Cannel Row Seam) has been recognized. In the lower Coal Measures beneath, seepages of crude petroleum have been recorded in many localities and at several different horizons; they occur chiefly in porous beds forming the roofs of coal-seams or not far above coal-seams, *e.g.* the Cockshead, Bowling Alley and Bullhurst seams. Similar if not quite such striking evidence can be obtained in other counties, and it becomes clear that we can recognize a *torbanitic stage* in the history of the hydrocarbon or carbonaceous contents of a series, though without the essential conditions no actual torbanites may exist. Consequently torbanites are in a sense "indications of petroleum," in that they are evidence of an attempt to reach the petroliferous phase in strata whose previous history prevented the development from being entirely successful. Torbanites high in a thick series, higher even than the oil-shale phase, may point to the occurrence of the petroliferous phase at greater depths and in lower horizons.

But quite apart from the possible value of torbanites and torbanitic developments as indications, the light that these deposits when studied microscopically throw upon the subject of the origin of petroleum renders them well worthy of the most careful research work; possibly by following up the clues already obtained, and making micro-sections of strata where the lignitic and petroliferous phases overlap, a wealth of new and striking evidence might be brought to light.

CHAPTER IX

STRATIGRAPHY

In the foregoing chapters an account has been given of the principal subjects which the prospecting geologist must study in the field before he will be thoroughly competent to advise a company in the exploitation of petroleum. The necessity of elucidating lateral variation has been dealt with, the working out of geological structure has been treated at some length, and the various kinds of evidence upon which a series can be determined to be petroliferous have been described. But this is not sufficient; the geologist must leave little or nothing to chance or guesswork. It remains to correlate the facts that have been collected and to get at least a general grasp of the stratigraphy of the country or area examined.

This is not a matter of merely academic interest, but is of very practical utility, for though the directions of variation may be known, though the petroliferous nature of the series be assured, and though an exceedingly favourable geological structure be discovered, there may not be any oil-bearing rock of importance beneath the surface within reach of the drill. Thus, in Lower Burma a well might be located on a good anticlinal or dome structure, among what used to be known as the "Prome Series," which is undoubtedly petroliferous, and on drilling being commenced the well might very shortly penetrate into the Sitshayan shales, a marine group of great thickness which has never yielded petroleum. Or again, in either Lower or Upper Burma, an area of excellent structure high up in the Pegu Series might be tested where the depth to the nearest petroliferous bands might be so great as to make it impossible to reach them, or if possible, at an expenditure of time and money that would effectually prevent the field from being remunerative. Instances of failure under such conditions are only too frequent, and similar cases can be mentioned from Trinidad, Persia, and Baluchistan. In fact the writer, even with his limited experience of oilfield exploitation, has come across cases of failure owing to neglect of stratigraphical study in every field with which he is intimately acquainted.

It is essential, therefore, that the main stratigraphical groups of a series should be determined, and the geologist must be able to recognize within reasonable limits the position in the series of any horizon that he has to study.

In the course of field-work the geologist will necessarily gather a great number of facts of stratigraphical importance, especially during his study of the lateral variations, for it is those variations which complicate the issue, and make the establishment of a stratigraphical sequence a matter of no small difficulty. A correlation or tabulation of the facts is necessary, and as each new area or district is examined something will be found to add to or modify the correlation previously attempted. Finality, if the area be large, is almost impossible to attain, but the broad lines may be laid down to be improved, modified, or confirmed by future observers.

Where sections through the entire series in which oil occurs are to be observed, the geologist will do well to examine them as soon as possible; he then starts with a sound basis for generalizations. Measurements of the thicknesses of groups of different types of sediment should be made wherever possible and noted for each particular district. Such measurements need not be made on the ground if evidence be abundant and the area be mapped carefully on a large scale; sufficient accuracy will be assured by measurements on the map. Vertical sections of the strata observed should then be constructed for each district or locality.

Lithological characters must be studied closely, but too much reliance must not be placed on them for purposes of correlation; for if variation be rapid, precisely similar conditions of deposition will be found to have occurred at different epochs in different areas, and may occur again and again in the same area. Thus almost any particular variety of strata may occur at almost any horizon in a thick series, and to found any generalization upon resemblance in lithological characters, unless the rocks can be actually traced along the strike from one area to another, may lead to fatal mistakes.

State of Mineralization.—In a thick series, however, there are some points that may be noted with great advantage, and of these first of all comes what may be generally expressed as the "state of mineralization." When one is dealing with a series of from 5000 to 10,000 feet of strata—and the prospecting geologist will probably have to study a mass of sediment somewhere between these limits—it is only natural to expect that the older deposits have been more greatly affected than the younger by the conditions of temperature, pressure, and circulation of underground waters to which they have been subjected, and the longer period during which these conditions obtained. Thus harder and more compact strata will be observed among the lower horizons than among the upper, even when the sediments are of practically the same composition. Jointing, again, will be more perfectly developed in the older strata, especially in the argillaceous rocks, which are more susceptible to pressure than arenaceous rocks. Thus a concentric weathering and exfoliation may be prevalent among clay groups in the lower part of a series, and altogether absent from similar clays among the higher horizons. The formation of veins, whether of selenite or calcite in clays, and the slickensiding of these veins owing to minute movements, is another point to be noted. *Ceteris paribus*, these are always more conspicuous among the older horizons. If the series contain lignites or coals, they and their underclays usually furnish easily recognizable evidence, the tendency being for the older carbonaceous deposits to have become harder, blacker, better jointed, and, as proved by analysis, to have lost water to a greater extent than the younger, while the underclays develop at least the rudiments of stratification, which they may not exhibit till subjected to considerable pressures.

Among arenaceous strata the solution of iron compounds or calcium carbonate, and their redisposition in cementing laminæ, or concentration into concretions, are effects which have required time as well as the necessary conditions as regards pressure, temperature, and presence of carbonated water; so younger strata may give very little evidence of such action, the effects of which are common enough in strata of greater age.

All these minor points, none of which is of great importance in itself, may by their cumulative evidence enable the field-student to detect the difference between a lower or middle horizon and an upper horizon in the series, or between upper or middle and lower horizons, so that in dealing with a considerable thickness of strata, exposed in an inlier and perhaps unconformably overlaid, some idea may be at once suggested as to the position in the series of the horizons exposed. It must be remembered that these points of inquiry are of chief value in Tertiary strata, where the youngest rocks are very little altered since their deposition. Where folding has been intense, and on a large scale, the mineralization of strata has naturally proceeded further than in undisturbed regions, and this must be taken account of when comparing strata from different areas.

Alteration in Character of Sediment.—Frequently, also, it may be found that the detritus from which sediments are formed has altered in character as the series is ascended: pebbles of some particular rock may be found in the upper or lower beds alone; if this is found to hold good over a wide area it becomes of great importance as proving that different strata were being denuded at different times. Thus in the Yaw sandstones at the base of the Pegu Series, pebbles of agate are frequent in some parts of Upper Burma, but throughout the rest of the series they are absent, and it is not till the post-volcanic stages of the succeeding and unconformable Irrawaddy Series that agate pebbles are again observed in the Tertiary sediments. Similar instances could be given without number, but this will be sufficient to illustrate the point that the constituents of an arenaceous group may on occasion furnish a clue to its age.

Details of this kind may be noted on the vertical sections made for different districts, and may be of great help in establishing the stratigraphical relations of different groups.

There is usually, as is familiar to every geologist, what is known as a cycle of deposition during the laying down of any great series. The most usual form that such a cycle takes during the formation of a great geosyncline is that at any one localitity there is first a period of rapid sedimentation when deposition keeps pace with or even overcomes subsidence, then a gradual victory of subsidence over sedimentation causing less rapid deposition under deeper-water conditions, and finally, as subsidence becomes less marked, a recurrence of shallower-water conditions with heavy and rapid sedimentation.

Thus a series studied in any locality may be found to consist of a lower group chiefly of coarse and arenaceous sediment of littoral, estuarine and even fluviatile origin, a middle group chiefly marine and largely argillaceous, and an upper group, again of littoral, estuarine and fluviatile sediment.

The converse of this cycle, *i.e.* a succession of depression, elevation and again depression, is no doubt just as frequent, but as the second period of depression, if it does not come to an end, means that sedimentation is still being continued, the results of the cycle cannot be observed on land, and so the cycle is not regarded as complete.

Now in any cycle such as that described it must be remembered that there is always a landward side from which the sediment comes, and a seaward side towards which the sediment is poured, and beyond the last point at which the sediments can be studied there is still a continuance of deep-water conditions. Therefore, in dealing with such a cycle, it is evident that we are merely noting the landward margin of an area of sedimentation and the fluctuations between deposition and movements of elevation and depression—which are complementary, *i.e.* a broad folding movement—can only be studied in that part of the geosynclinal subsequently brought above sea-level.

It follows that any gain by sedimentation over depression will be marked by an advance of littoral over marine sediment, any loss by a retreat of littoral sediment. Thus if we take the simplest case of a cycle of three main groups, arenaceous, argillaceous, and arenaceous again, it is evident that in different districts the incidence of each group takes place at a different time. To put it briefly, the sedimentation planes between the different groups transgress the time-planes which are the true stratigraphical horizons.

This is best seen when we are considering the advance and retreat of deltaic conditions in a gulf or inland sea.

In actual experience, of course, there are usually many complications, local retreats and advances of the littoral or deltaic sediment, so that to establish exactly what beds are to be assigned to a certain main group may become a matter of great difficulty, which each observer solves empirically for himself. Each group may at one place or another have a distinct minor cycle, and in some cases the minor cycle may become more conspicuous than the major cycle and so lead to very serious confusion between strata of widely separated stratigraphical horizons. It is for this reason that it is necessary to found all correlations as accurately as possible upon stratigraphy and to deal with variations on each geological horizon as they are proved to occur.

At the same time the recognition of a cycle with its main groups is often of great practical utility so long as it is not carried too far at the expense of stratigraphical study, since owing to progression of sedimentation the conditions most favourable to formation and accumulation of petroleum will follow the main groups of the cycle and not the stratigraphical horizons.

The Tertiary Series in Mekran, Baluchistan, affords a simple instance of a normal cycle of this instance, probably without any great lateral variation along stratigraphical horizons. The Pegu Series of Burma affords another but more complicated case, as a large gulf has been filled by progressive sedimentation, where at one end we have nothing but littoral, deltaic, and even fluviatile and terrestrial conditions, while the other end is and presumably has been entirely marine throughout. There is also a distinct minor cycle in the upper group in Lower Burma. Trinidad affords a perfect example of a similar cycle upon a much smaller scale, and with a more purely local significance.

In other countries the attempt to recognize cycles of this nature might lead to very dangerous generalizations. For instance, a study of the Cretaceous Series in Western Canada and from the Rocky Mountains eastward, reveals a cycle so complicated by minor cycles that all practical usefulness from the petroleum point of view of deserting stratigraphy to follow lithological divisions is destroyed.

Perhaps, however, the greatest danger to the geologist in pinning his faith to lithological groupings is that so much is left to the individual observer. Where arenaceous and argillaceous sediments in sufficiently thick local groups alternate the best conditions for oil formation and accumulation, given the requisite structure, are found. Such alternations may be prevalent throughout a great thickness of sediment between two of the major groups of the cycle, which we may call A and B. Now should the geologist become obsessed by the idea that the petroleum is more likely to be found in Group A than in Group B or *vice versâ*, the tendency will be for him to throw all of the favourable alternations into his favoured group at the expense of all considerations of stratigraphy. Still worse, he may be tempted to beg the question by referring to the mass of alternations as "passage beds," which they undoubtedly are in a sense, and will have difficulty in maintaining any pretence at correlation when he reaches a locality where the main groups of the cycle are sharply defined. Indeed, in some series, such as the post-Cretaceous rocks of Northern Venezuela, some 8000 feet of beds might have to be regarded as "passage beds," resting upon an unconformability and covered by Recent sediment, a very *reductio ad absurdum.*

This method of classification and correlation into main lithological groups in a cycle of deposition has been dwelt upon at some length, because it is often of practical value during the first pioneer survey of a country, and confined within these limits it may be of great benefit to the young geologist, but if ever it leads to the disregard of true stratigraphy it will almost inevitably cause confusion and possibly very serious practical errors. It is for this reason that any facts of stratigraphical importance must be noted; even small details may help eventually in a correlation of strata over large areas.

Fossil Evidence.—Of all aids to correlation and the working out of a stratigraphical sequence that will hold good over large areas, there is nothing more valuable than fossil evidence, provided that it is abundant, and that it is made use of in a practical way, as the handmaid rather than the mistress of stratigraphy. Let no practical geologist take upon himself to despise the evidence that he may glean from fossil fauna. Their collection and study may entail a great deal of extra trouble, and many a weary day spent indoors, but any definite

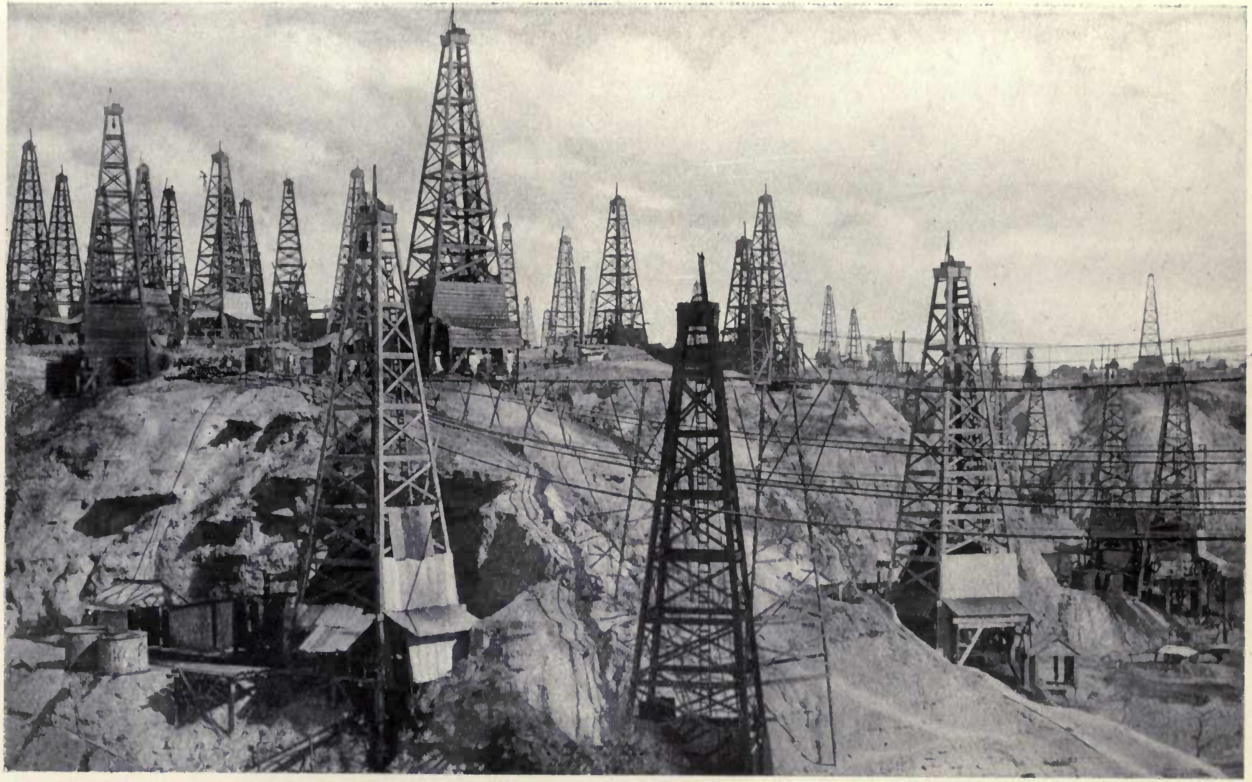


Photo. by M. Croulíansky

A CORNER OF THE TWINGON OIL-RESERVE, BURMA.

results obtained are certain, and may enable correlations to be made that cannot be accomplished by any other means.

The writer confesses to have little patience with the zoological side of palæontology, and even to be indifferent as to the name that may be given to the fossil part of any particular organism, but he has had experience of what can be done in the way of correlating isolated and far-separated areas by the careful mapping of fossiliferous horizons and the collection of their fossil organisms, even where faunal change in time is slow and the species many and often ill-preserved.

Even if the field-student be not interested in palæontological work, even if he be ignorant of the generic names of the organisms, he will do well to collect and label them carefully, and note on his vertical sections the horizons from which they were obtained. Let him call them "Tom, Dick, and Harry" if he will, so long as he can recognize them again and can point to the horizons from which they were collected.

It may be of interest, and of use also, to the petroleum geologist if a brief description be given here of the methods of handling palæontological evidence, originated and put in practice by the Burma Oil Company's Geological Staff.

In Burma one of the chief difficulties is in the correlation of different fields, as the petroliferous Pegu Series appears frequently in widely separated inliers. These inliers are overlaid unconformably by the fluviatile Irrawaddy Series, during or previous to the deposition of which there was extensive and sometimes very great denudation of the underlying strata. Thus the local base of the Irrawaddy Series may be found resting upon almost any horizon in the Pegu Series, and measurements downwards from the base of the upper series are useless as an aid to the determination of horizons in the Pegu strata as a whole. The amount of pre-Irrawaddy denudation varies greatly within short distances. Added to this there is a lateral variation in the Pegu Series so great that correlation of areas by a study of lithological characters is practically impossible, unless the areas are close together, while the main groups of strata in any field thicken and thin out with bewildering rapidity, so that the whole series, even where the upper part is not removed by denudation, varies greatly in thickness in different districts.

The area examined by the Geological Staff of the Burmah Oil Company up to date is approximately 40,000 square miles, most of it, however, covered by younger deposits than the petroliferous series. The Pegu Series at its greatest development reaches a thickness of at least 10,000 feet. It will be readily understood that the problem of working out the stratigraphy, so that the thickness of strata containing petroliferous beds should be known in each district, and the horizons exposed in each inlier identified, presented many difficulties.

Luckily there was a considerable mass of evidence from boring journals available, but it would have been of little value without palæontological evidence, which is abundant, almost every inlier containing at least one and generally two or three rich faunas.

Some means had to be devised to enable correlations of isolated areas to be made, and palæontological evidence, if available in sufficient quantity, was obviously suggested. It was ten days of continuous rain when encamped in a very fossiliferous district that first turned the writer's thoughts towards an inquiry as to whether there was sufficient faunal change through the Pegu Series to allow of its being subdivided into zones.

Dr. Noetling of the Indian Geological Survey had published seven years previously a Memoir ("Palæontographica Indica," Vol. I) on the fauna of the Burmese Tertiary rocks, describing and figuring two hundred and eight species, and attempting a stratigraphical arrangement of the sections examined up to that time. Comparatively little of Burma had been gone over by then, and many of the fossil collections were made by previous observers, the localities from which some of the faunas were obtained were but vaguely known, and the relative positions of different beds in the series were uncertain. Thus in spite of the ability with which Dr. Noetling marshalled the evidence, he was handicapped at the start by mistakes in stratigraphy inevitable when no large-scale mapping is done. The mistakes were also made of referring every section examined in Burma to a type-section in the Prome District, of arbitrarily subdividing the Series into a supposed fossiliferous and non-petroliferous upper division and a petroliferous and non-fossiliferous lower division, and of treating the local faunas as "zones." Every geological observer who has done work in Burma since the publication of Dr. Noetling's Memoir, and has started with it as a basis, has helped to bring about almost inextricable confusion, and though great credit is due to Dr. Noetling for his painstaking work, we have in Burma another instance of the danger of trusting too implicitly to the work of a Teutonic scientist, and bowing to authority rather than beginning afresh on a basis of the stratigraphy as ascertained from carefully mapped sections.

The Geological Staff of the Burmah Oil Company, when driven perforce to study fossil evidence in the attempt to correlate different areas, began by making vertical sections of each field surveyed, marking the horizons of each fossiliferous bed and each oil-bearing band. Mapping was usually done on the six-inch, but occasionally on the eight-inch scale, so it was possible to make fairly accurate estimates of the thicknesses of strata exposed. The faunas collected were then compared with Noetling's faunas treated as if they were "zones," but arranged in a somewhat different order from that published in the "Palæontographica Indica," as it very soon became apparent that some modification in his stratigraphical arrangement would have to be made.

Areas where many fossiliferous beds at different horizons were found soon demonstrated that there is considerable faunal change in time relation in the Pegu Series, and a number of rough graphs or diagrams were made use of to illustrate this, still using Dr. Noetling's "zones" as a basis. The "zones" A, B, C, etc., were arranged vertically, and distances, A*a*, B*b*, etc., were measured off horizontally in proportion to the number of species common to the zone in each bed (Fig. 10).

Joining the ends of these horizontal lines we get a figure *abcdef*, which in the case illustrated indicates that the fauna of the bed under examination resembles the fauna of zone C most closely, but is probably somewhat higher in the series. The method is rough and open to many objections, but if the zones contain a sufficient number of species, and the fauna to be examined is a rich one, an ambiguous diagram such as Fig. 11, which leaves it doubtful whether the bed should be placed near the top of the base of the series, is hardly possible. Another advantage is that the breadth of the diagram shows at once if the fauna be a rich one or not; the greater the number of species in a bed, the more weight is naturally given to the evidence obtained from it.

Many difficulties had to be encountered. For instance, the discovery of species not described by Noetling tended from the first to complicate matters. This difficulty was partially got over by procuring such books of reference as were available: Dr. Martin's beautiful figures and descriptions in "Die Fossilen von Java" proved of great assistance.

Then it was found that Dr. Noetling's zones did not make a satisfactory basis, some of his faunas are littoral, some

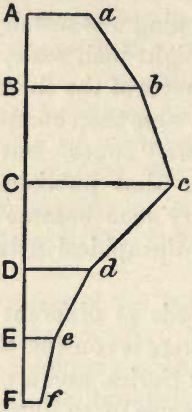


FIG. 10.

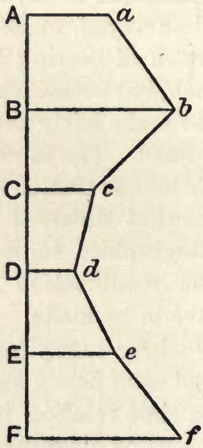


FIG. 11.

laminarian or pelagic, and some indicate brackish-water conditions; some are very rich in gasteropods with few lamellibranchs, and others contain numbers of lamellibranchs while gasteropods are poorly represented. It became evident that true zones were required, not faunas from single beds.

Several sections were mapped and measured from the base to the top of the Pegu Series, and all fossiliferous beds in them carefully collected. It was possible then, by a comparison of the vertical sections, to combine them and place many of the faunas in their true relative positions. The measurements of the thicknesses of groups were of great use in this, though owing to the thinning and thickening of different parts of the series no fossil bed could be placed in the series entirely on such evidence, unless it was confirmed by palæontological data.

A range-table was tentatively constructed; it contained between 280 and 300 species arranged horizontally, while the horizons were arranged vertically. A small diagonal cross marked each occurrence of a species, and every occurrence of the same species lay upon a vertical line indicating the range of the form so far as it has been ascertained. The majority of the forms dealt with were gasteropods, which were not only more easily identified than the lamellibranchs, but which seemed to show more marked changes in time relation. The lamellibranchs, however, proved of great value, though the ranges of some forms are apparently very long. Echinoderms, crustacea, and corals proved very useful, but they do not always occur in sufficient numbers in the littoral beds which are usually the most fossiliferous members of the Pegu Series. Fish, mammals, foraminifera, and one solitary brachiopod have been made use of; in fact, the occurrence of every organism found was recorded on the range-table.

Dr. Noetling's faunas were made use of after being placed among the faunas as nearly as could be ascertained in their true stratigraphical positions.

After the range-table was constructed, it was divided horizontally into seven zones by means of horizontal lines at convenient intervals.

When any new fauna was discovered, and the species identified, it was compared with the faunas of the several zones by means of the graphs or diagrams mentioned above. There was very seldom any doubt as to the zone to which a fauna naturally belonged. Having ascertained the zone, the fauna was then compared with the chief faunas in the zone and its relative position towards them ascertained, and if there was no doubt as to its position the new fauna was at once put upon the range-table. Comparison of vertical sections was of great assistance in the placing of a new fauna.

The first range-table served very well, but it soon became out of date. Faunas from all parts of Burma were constantly being brought in, and great numbers of entirely new species came to light. In fact, evidence accumulated so rapidly that additions and modifications were constantly being made. The attempt to reconcile carefully-measured sections with Dr. Noetling's stratigraphical arrangements proved a matter of difficulty, and after the same sections that he describes had been carefully mapped, new vertical sections were substituted for his, and it was decided that when a new range-table had to be constructed Dr. Noetling's faunas should be omitted, and the stratigraphical arrangement of fossils based upon the four or five complete sections from base to the top of the series which were available.

The new range-table deals with approximately one hundred rich faunas and numberless beds containing only a few species. The number of species and distinct sub-species or variations is between 450 and 500. The work, the magnitude of which only gradually became apparent, can perhaps never be complete; the collection in the Company's geological office numbers many thousands of specimens, nearly all of which are in a good state of preservation. All doubtful identifications have been rejected and are not entered on the range-table.

The length of range of many of the forms, and these often among the commonest, has proved disappointing, but in this the accumulation of material has been of benefit, as with more and better specimens it is often possible to detect variations and to split a species into two sub-species, one being characteristic of the lower part of the series and one of the upper.

The occurrence of certain types in certain provinces and apparently not in others was one of the initial difficulties, but this has gradually yielded to the effect of more and more evidence being brought forward: the fauna of the Pegu Sea at any epoch seems to have been fairly constant over the area in which it has been studied.

The series is now divided into five main zones, and further subdivision is possible. Though seldom more than sixteen or twenty species are found only in one zone, the ranges of many of the forms are sufficiently short to be of great stratigraphical value. Any mixed fauna of twenty to thirty species can usually be placed without any difficulty in its true stratigraphical position, and a difference of 200 feet in horizon between two rich faunas can be shown by diagrams. The collection of fifty species from one bed is by no means a rare occurrence in Burma.

The methods employed in dealing with such a mass of palæontological evidence are at the best rough and ready, and may not commend themselves to palæontologists generally, but the systematic use of fossil evidence for practical purposes connected with oil development has been the point always aimed at. Many species have no doubt been incorrectly named, many even of the genera may not have been determined beyond the possibility of doubt, but the ten thousand feet of the Pegu Series have been divided into zones which have held good up to the present, the effects of lateral variation have been abundantly proved, the advance of the delta has been determined beyond the possibility of doubt; it is possible to state with a fair degree of accuracy what zones in each district will be petroliferous and what zones barren, and every bed with a rich fauna can be placed in the series within one or two hundred feet of its true position, and datum lines for the correlation of any new field are furnished. Many details also of the geology of Burma, details of which it would not be in the interests of the Burmah Oil Company to permit the publication at present, have been brought to light.

It is not intended that this palæontological work of the Burmah Oil Company's Geological Staff should be taken as an object lesson by the field-student; this brief account of it has been given merely to show what practical value can be derived from the study of fossils by a staff, none of whom would claim to be specially qualified as a palæontologist. It is urged upon the geologist who is engaged in oilfield work to collect such fossils as he may find, and to label them carefully for future study. They may prove of great assistance at some future day, although apparently of little interest or importance at the time that they were collected. So long as palæontology is kept in its proper relation to field-mapping, so long as generalizations are not founded upon the sporadic occurrence of a few species, but on evidence from a large thickness of strata and a wide range of organisms, every fact that can be brought to light and tabulated will be of service.

The idea of a range-table is to safeguard against sources of error, for a few wrong identifications from a bed containing many species may not affect the final result appreciably. The more species collected and identified from a bed, the greater certainty will be attained in assigning it to its stratigraphical horizon. Much too great importance is often given to the occurrence of a single fossil species. The geological record is at best very imperfect, and the fact that a species has been found in one district or country characterizing and confined to a certain zone does not necessarily mean that in every other country or district where the same species occurs it must be in the same stratigraphical zone.

Quite apart from the question of migration of faunas, a subject that has been made far too much of in speculative geological literature, the finding of a single species may be due to so many accidental circumstances that to found any important generalization upon its occurrence in any locality is always a risky thing to do. For that reason a range-table, provided sufficient evidence has been collected, is a far safer and surer guide to stratigraphical horizons.

It is not intended in the above statement to cast doubts upon the fact that migrations of faunas do take place, but the time occupied in such migrations is probably very small compared with the time necessary for the deposition of any considerable thickness of strata. Therefore to depend upon migration to explain facts that can be much more simply understood by a study of lateral variation may lead to entirely incorrect classification and subdivision of a geological series.

Even when species from different countries cannot be identified as the same there is often a strong resemblance in type and character of the species of a genus that existed contemporaneously in different parts of the world. Thus in such genera as Voluta, Conus, Turritella, Oliva, Fusus, and other common forms the writer has noticed very similar types occurring in strata of approximately the same age in such widely separated countries as Burma, England, and Ecuador, though no doubt different specific names would be given to specimens from the different countries. The variation in time of these types also seems to have followed similar or almost identical lines. It is a very old proposition, but never more aptly illustrated than in palæontological work, that a correct conclusion is more easily reached by considering a great number of minor points, none of which may be in itself of supreme importance, but the cumulative effect of which is great, than by seizing upon three or four salient facts and founding a generalization upon them.

CHAPTER X

LOCATION OF WELLS

Any practical operator, manager, field-superintendent or driller, who has been good-natured enough to read so far in this little book may well exclaim "Now at last we come to practical politics: what can this geologist tell us about the locating of wells?" With the spirit of such a reader the writer heartily agrees. All that has gone before is leading up to this one important matter, the choosing of the sites for oilwells, so that the oil-bearing strata may be struck with a minimum of trouble and expense, and under conditions that should yield a maximum production.

It is, of course, in the case of the first test-well of a new field, or presumed field, that the importance of carefully selecting a site is most forcibly brought home to us, and it is this aspect also which appeals most to the general public. The geologist who undertakes oilfield work will soon weary of the oft-reiterated question, "How do you know where to put a well?"

There are many methods of actually making a first selection. It is told of one well-known and very successful exploiter and driller in the United States that he frankly stated that his method was to put on an old and cherished hat, and to gallop a rough horse about the countryside or farm till the hat dropped off. On the spot where it fell he drilled the well. The story is at least *ben trovato*, and it is possibly quite true.

The writer knows one highly productive and very valuable field, miles from the nearest surface indication, where the first test-well site was selected in almost as haphazard a fashion. Drillers and field-superintendents had met to make the location, and the area in which a spot was to be selected was generally determined, but with characteristic caution none would venture an opinion before the others as to what exact spot should be fixed upon. At last, one bolder spirit than the others spoke up and said, "Well, boys, if it's all the same to you, let's put the well where that crow sits down," pointing at the same time to a crow that was flying about them. The crow alighted, the spot was marked, and the well drilled with remarkably successful results; it was still producing after eleven years. A flight of a hundred yards or so further to the eastward would have put the well beyond any hope of striking oil.

Well-sites, in fact, have been selected for very many reasons; the colour of the soil or the proximity to an oilshow has frequently been responsible for the erection of a derrick at a particular spot. The divining rod has been utilized occasionally, and sometimes with successful results, while complicated instruments have been invented and put on the market to enable any one to detect the presence of oil beneath the surface, but as to whether or no there is any scientific basis for the working of such instruments the author must plead ignorance.

But the ordinary workaday geologist must not depend on quasi-supernatural aids nor little understood inherited instincts. By his geological map he must stand or fall, for he will soon appreciate the fact that, however good and careful his work may be, it is upon the wells that he locates, especially in new fields, and upon the results obtained from them, that he will be judged. An error of judgment made, a fact lost sight of, a calculation not checked and rechecked, an allowance not made for some condition that may be inferred but cannot be observed, and the well may prove a failure, with the effect that his reputation as a practical man may suffer undeservedly.

Several kinds of electrical apparatus have been tried in recent years, the inventors claiming to be able by means of them to detect the presence of petroleum underground. In some cases it is even stated that the depth to oil-bearing rocks can be predicted and the quantity of oil great or small estimated. Unfortunately, however, no records have been published giving the certified results of actual experiments, and the general opinion among practical oil-men seems to be

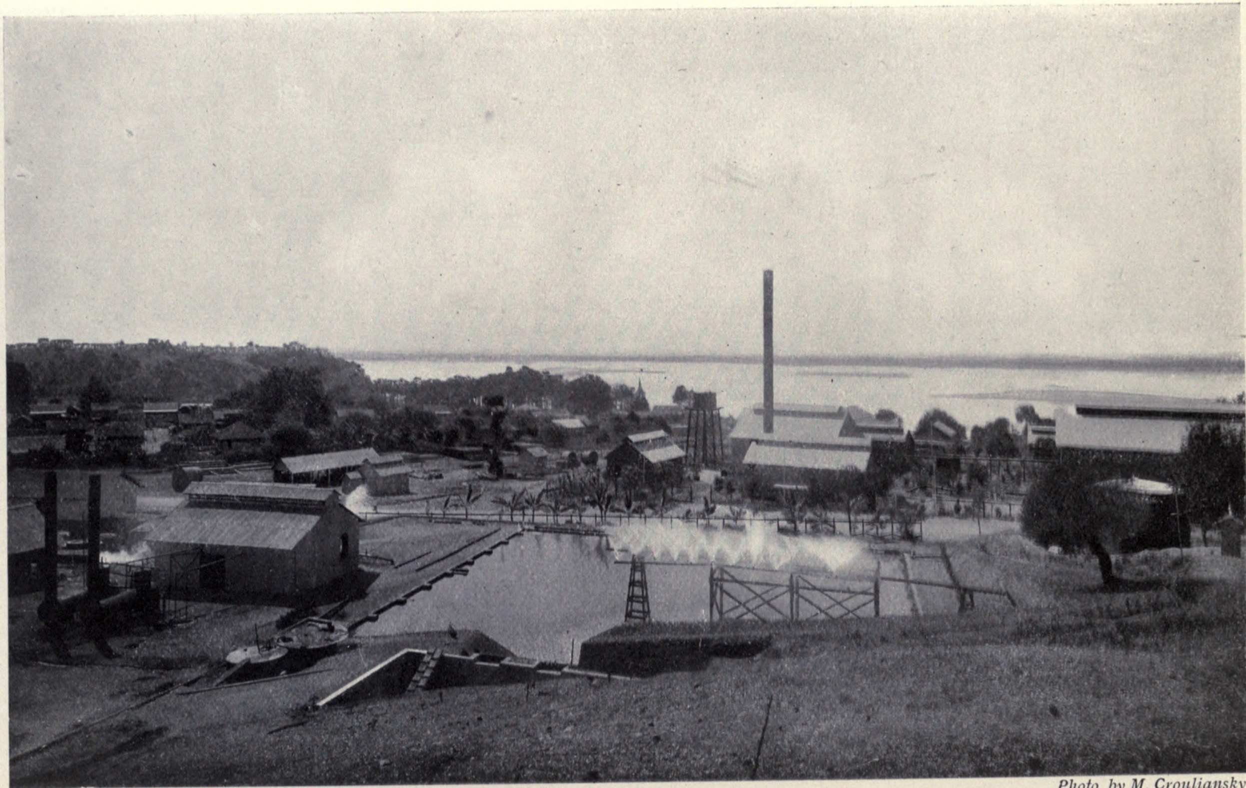


Photo. by M. Crouliansky

THE PUMP STATION, NYAUNGHLA, UPPER BURMA.

The field-end of the Burma Oil Company's famous pipe line.

that these electrical inventions are humbug, and the inventors either fraudulent or at best cranks. This opinion may be entirely wrong, but while direct evidence is lacking it is perhaps as well to be sceptical. The writer has only examined one electrical oil-finding apparatus, and has made no experiments with it. It has been well advertised, and has found a sale among people who are unfamiliar with both electricity and petroleum. It is a very neat and simple little instrument, but as to what electrical quantity it professes to measure the writer must plead ignorance.

If it were possible to make some apparatus that would record the resistance to an electric current passing through the strata, or the electric charge that could be communicated to certain selected portions of underground strata, it might be possible to differentiate between oil-bearing and water-bearing rocks, but it would probably be cheaper and certainly more conclusive to drill a well than to attempt elaborate electrical experiments underground.

There seems, however, to be one possibility of detecting the presence of oil beneath the surface, and that is by a study of magnetic variations and density. It has been shewn that the lines of equal variation of the compass needle from true north exhibit strange abnormalities in the neighbourhood of some of the great oilfields in America. Possibly such abnormalities, which have not been worked out in great detail, may be due to topographic causes, lines of mountain chain, etc., quite apart from the accidental presence of oil. But it seems possible at least that the density of the magnetic field may be affected by the presence of an oilpool. When a good conductor, such as a piece of soft iron, is placed in a magnetic field there is a drawing in of the lines of magnetic force towards it and through it. That is to say, the magnetic force per unit area is increased in and in the neighbourhood of the conductor; in other words, the density of the magnetic field is increased. When a non-conductor is placed in the field the opposite effect is observed, the lines of magnetic force are spread out further and the density of the magnetic field is decreased in and around the non-conductor.

Now water is a conductor and petroleum a non-conductor. Therefore, if a definite area underground is impregnated with petroleum, possibly one oilrock over another for a thickness of one or two thousand feet, and if the vertical component of the earth's magnetic force be plotted round and through the field, a decrease in the density should occur, and it should be possible to design some very delicate instrument to detect the difference in magnetic density between the area overlying petroleum and that overlying the surrounding water-bearing strata. Such an instrument would probably give readings in quite empirical units, of course showing a decrease in magnetic density towards the centre of an oilfield, with perhaps a fairly sudden increase at the margin. It would probably be convenient to deal only with the vertical component of the earth's magnetic force.

The writer is unaware as to whether such an instrument has been designed or not: it seems at least to be theoretically possible, and it might be of use where a favourable geological structure has been discovered in a locality that is doubtfully within oil-bearing territory. For the locating of a well to test new territory such an instrument would not be necessary, the location having to be made on geological evidence, but it is possible that evidence as to the existence of petroleum underground, for instance, in a dome structure already carefully mapped out, could be obtained by the use of an instrument to determine magnetic density.

However, it is the writer's belief that it should be within the geologist's power to decide the margins of an oil-belt with a fair amount of accuracy, and thus to have no need to depend upon electrical or magnetic instruments.

The popular idea that petroleum is a very capricious and uncertain mineral, and that the only way to be sure of finding it is to drill a borehole, is rapidly dying out, but still it is not possible to drill for oil with the same confidence with which one can drill for water. It is often impossible to be sure whether there is petroleum beneath the surface or not, but fortunately it often is possible to be quite certain that oil will *not* be obtained by drilling.

When the series has been proved to be petroliferous in the particular district, when the stratigraphy has been worked out, a much better idea of the capabilities of the field will be obtained without delay.

It is possible that in very few cases is gas stored at the crest of an anticline to the exclusion of oil, but it is quite probable that gas may be struck before the oilrock is reached, and the pressure may be great enough to cause damage to plant, if not even loss of life, when a well suddenly taps such an accumulation of gas under very high pressure.

In those cases where large mud-volcanoes occur on the crests of anticlines, similar precautions must be taken in locating the first well. High gas-pressure and possibly flows of mud may make the drilling very difficult, if not impossible, on the crest of the flexure, while a well slightly down the flank may not suffer from the same disadvantage. The geologist must judge from the results of wells drilled under similar conditions in the same country, or from his experience in other countries, whether there be any danger of a well proving troublesome in this manner.

When the dome or anticline is asymmetrical the well must be placed not on the crest but on the flank on which the gentler dips occur. This is owing to the hade of axial plane of the flexure, and the reason is obvious when a horizontal section through the fold is drawn to scale. Mr. E. H. Pascoe has explained this point very clearly in the "Records of the Indian Geological Survey," Vol. XXXIV, Part iv, 1906, where he gives a formula by which the distance from the crest at which a well should be located on an asymmetrical anticline can be calculated as follows :—

$$l = d \tan \theta + \lambda$$

where l is the distance from the crest to the well, d is the depth of the well, θ is the angle of hade of a plane through the apex of the fold, and λ is the distance between what he calls the "apex-locus" and the "crest-locus." Thus a well at A (Fig. 12) will just touch oil in the petroliferous bed 1, while a well at D will strike oil in the oilrocks 3 and 4, but not in the higher beds 1 and 2. The angle θ must be found by observation : it is half the difference between the steepest dips observed either side of the crest *in the same bed*. Thus, if the maximum dip of a bed on one flank is 90°, and on the other flank 10°, θ will be $\frac{90° - 10°}{2} = 40°$.

This formula is of great practical value in determining the best position for a well, when some evidence is to hand from the other wells in the vicinity. It leaves, however, several details to be worked out practically. Thus, unless the depth *d* to be drilled is known approximately, it is impossible to find a value for *l*. Again, the distance λ, which will also vary according to the depth, must be found by calculation; it depends on the shape and sharpness of the flexure, which may vary greatly in different localities. It should be possible to

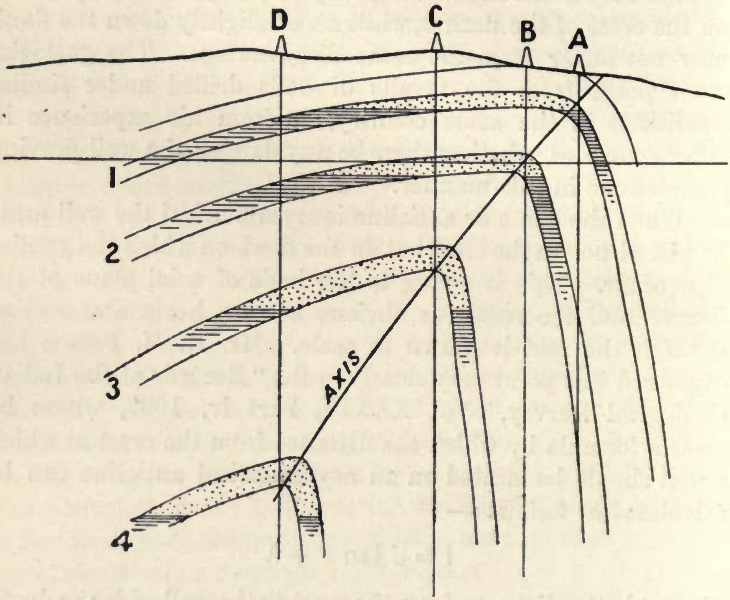


FIG. 12.—Section of Asymmetrical Anticline. Dotted portion shows extent of oil-impregnation.

calculate λ from observation, when the strata are well exposed. It will almost certainly decrease gradually as lower and lower horizons are reached.

But the calculation of *d* is a matter of greater difficulty, unless evidence from other wells is available, or the oil-bearing horizons are known through very careful stratigraphical work. Thus in a new field that is to be tested it will be expedient to place the test-well so that the crest will not be crossed at the greatest depth to which it is proposed to drill. This may necessitate the missing of the oilpools at shallow depths, so the geologist must consider each case on its merits and locate his well for deep or shallow oilrocks as is most convenient or most likely to prove of value to the company developing the area. As a general rule, it will be found better to exploit the shallow sands first, once the presence of oil has been proved, stating the depth to which each well is to be drilled, while another well can be located further from the crest to test deep oilrocks.

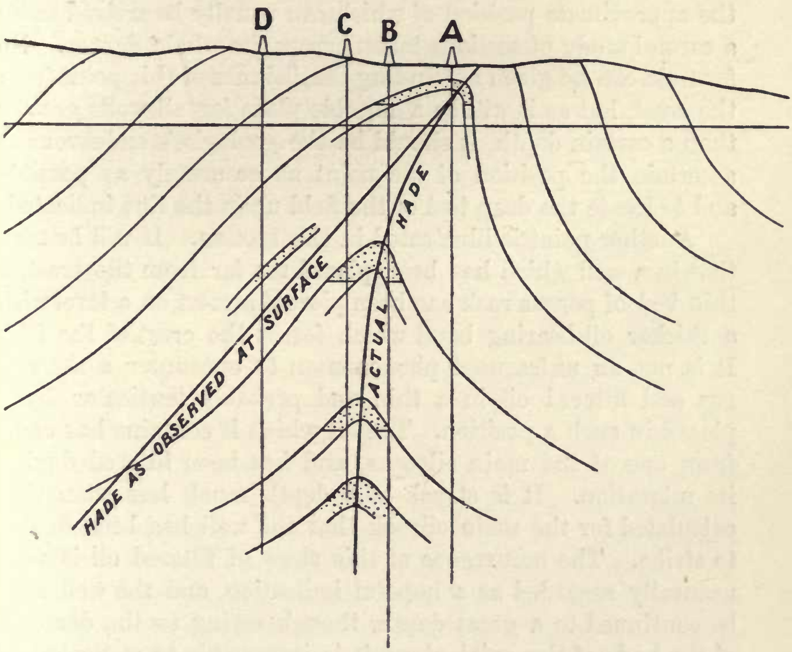


FIG. 13.—Asymmetrical Anticline, showing decrease in Hade of Axis. Dotted portion shows extent of oil-impregnation.

One point with regard to asymmetrical anticlines and domes seems to have been lost sight of very frequently, and that is, that the hade of the axial plane in any flexure is not constant. Tracing the axis along the flexure, the hade is seen to decrease or increase, but it is not so readily admitted that traced downwards into the heart of the fold the hade must decrease. Yet when we consider that the flexure has been caused by tangential stress, it is obvious that the hade of any asymmetrical flexure must decrease downwards, and finally disappear altogether. In Fig. 13, which represents an asymmetrical fold on a scale sufficiently small to include practically the whole of the flexure, it will be seen that the hade of the axial plane decreases rapidly, and that to calculate on its remaining constant and to drill on that theory would be to court failure. Again, it will be seen that at a certain distance from the crest the hade beneath the surface has practically died out; no well need therefore be drilled further from the crest than this point, the approximate position of which can usually be arrived at by a careful study of sections taken across the whole flexure. No formula can be given for finding the distance of this point from the crest, but as it will be a suitable place for all wells greater than a certain depth, it should be the geologist's endeavour to ascertain the position of the point as accurately as possible and to locate the deep test of the field upon the line indicated.

Another point is illustrated in the section. It will be seen that in a well which has been placed too far from the crest, a thin bed of porous rock has been pierced almost on a level with a thicker oil-bearing band which forms the crest of the fold. It is not an unfrequent phenomenon to encounter a show of gas and filtered oil in a thin and probably lenticular band placed in such a position. The oil which it contains has come from one of the main oilrocks, and has been filtered during its migration. It is struck at a depth much less than that calculated for the main oilrock that the well has been drilled to strike. The occurrence of this show of filtered oil is very naturally regarded as a hopeful indication, and the well may be continued to a great depth, though owing to the decrease of the hade of the axial plane it is impossible to strike oil in the main oilrock. Instances of this have come under the writer's knowledge more than once, and till the whole underground structure of the field has been clearly proved, it may be impossible to satisfy oneself, or those responsible for the exploitation of the field, that the show of filtered oil need not be a hopeful indication at all.

A geological map is an expression of fact so far as it has been ascertained, but a geological section is necessarily to some extent an expression of opinion, a prediction, an estimate, a conjecture, and therefore not entitled to the same weight regarded as evidence, and the deeper the section the more pertinently does this distinction apply. This may seem to be rather a sweeping statement, since the section is constructed from evidence given on the map, but a little consideration will show that it is justified, for the little that is seen on the surface is but slender evidence upon which to give in detail the structure at a depth of two or three thousand feet. Yet there is a tendency with many people, including some geologists, to regard map and section as of approximately equal value.

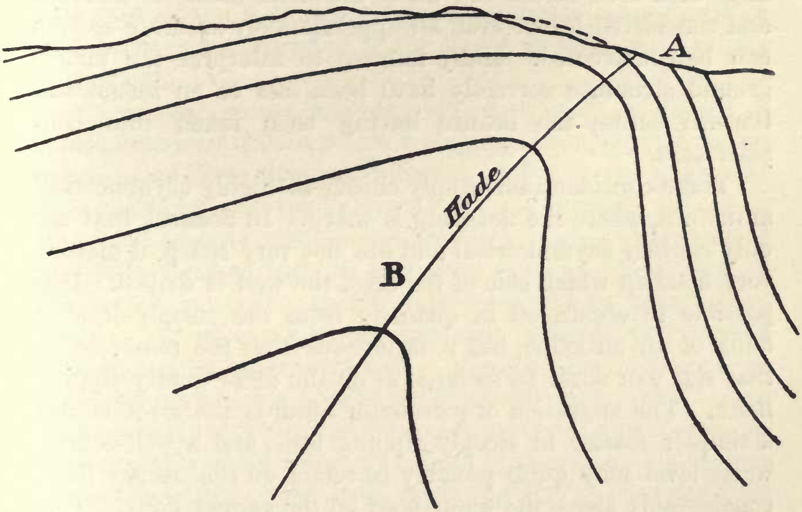
In oilfield work the construction of sections becomes very important, as upon them the location of wells will depend. When dealing with an asymmetrical anticline, with one very steep flank and a very narrow productive area, it is only too easy to locate wells off the oilpool by trusting too implicitly to the large-scale sections that have been drawn. Various geometrical methods have been devised to obtain correct sections at any reasonable depth in such cases, but every one of which the writer has had experience has some failure to set against it, that is to say, some case of a well located incorrectly by depending upon the section as if it represented fact rather than opinion. It is unnecessary to explain any of the geometrical methods here; they are all fairly obvious, and given ideal conditions quite reliable. But there are nearly always complications introduced that are difficult to foresee or estimate: strata do not necessarily obey the mathematical rules that are laid down for the construction of sections. For instance, there is, as has been seen (Fig. 13) the decrease of hade downwards, and the rate of decrease of hade, which varies in different flexures and in different parts of the same flexure. It is obviously very difficult to calculate.

Then there is the fact that flexures do not become progressively sharper with depth at the rate that might be expected theoretically. Where beds of different consistency and coefficient of elasticity alternate, *e.g.* sandstone and clay beds, there is always a little shearing along bedding planes between beds near the apex of the flexure. Owing to this the apex, though no doubt it becomes sharper the greater the depth, never becomes quite so sharp as it would if the series acted like a perfectly plastic body. This point is seldom taken into account in constructing a deep section, and it is very difficult to decide how much importance should be attached to it.

Again there is the stretching of strata near the apex in the upper beds, a fact that has thrown out the calculations of those who pin their faith to geometry in many instances. This stretching is only of importance on sharp folds, and when these are also highly asymmetrical it has often been mistaken for compression of the softer beds to a smaller thickness on the steep side of the fold, where the strata may be vertical or even overturned. The theory appears to be that the softer strata lying nearly normal to the tangential compressing force have been powerfully deformed and reduced in thickness. The writer has seen carefully constructed sections in which this presumed compression has been shown reducing the thickness of a clay group to one-half or even one-third of its normal thickness as measured on the gently dipping flank. It is possible that exaggeration of the dip on the gentle flank may account for part of this discrepancy, it being very easy to exaggerate gentle dips and thus measure a greater thickness, while it is, of course, very easy to measure the correct thickness of a bed dipping vertically. But if such compression really did take place it would modify profoundly the physical state of the compressed bed; it would be cleaved, and every fossil would show distortion.

Those geologists who believe in such a compression fail to realize that the beds have reached their present position by flexuring, and the pressure that caused the flexuring has been constant at all points in the bed. After the soft bed has reached a vertical position on the steep flank, further pressure will increase the sharpness of the fold and may cause shearing and strike faults with reverse hade in or near the margins of the softer beds, but compression to any important extent is not possible so long as the beds are free to fold. In metamorphic strata, where reconstruction or rearrangement of the particles of the bed is possible, a compression effect can and does take place, but the strata give unmistakable evidence of such rearrangement or reconstruction.

The so-called compression is really a stretching of the beds at the apex by infinitesimal shearing movements, and it naturally takes place to the greatest extent in those beds most easily deformed. The deformation decreases on each side of the apex, but while on the gentle flank this decrease may be observed, on the steep flank the beds plunge underground quickly and the decrease in deformation, or apparent increase in thickness, cannot be seen. Thus, in section-drawing, to continue the beds on the steep flank downwards at the same thickness as measured near the apex may be a very serious mistake; it is a mistake that has detracted from the value of many a section otherwise most carefully prepared (see Fig. 14).



Stretching of Strata observed at A.
Thickening of Strata probable at B.

FIG. 14.

The writer has found no golden rule for section-drawing through a sharp asymmetrical anticline, and he has found it impossible to depend upon any rigid geometrical method. When any factor that cannot actually be measured has to be estimated, *e.g.* hade, rate of decrease of hade, stretching, shearing, etc., he has found the most reliable method is to take limiting cases, to arrive at a maximum and a minimum for each of the unknown factors—this is not so difficult as it might appear at first; there is always some helpful evidence available—and then strike an average and construct the section accordingly. This method has certainly succeeded in cases where a rigid geometrical construction has failed to indicate the correct location for a well. It is a rough-and-ready method, no doubt, and it may entail a good deal of extra work and calculation, but it is after all mere practical common sense, which is as necessary in section drawing as in any other function of the geologist.

One very important point must be noted: evidence from a large area both across and along the strike must be collected and considered before even an approximately accurate section can be constructed. Many failures to interpret the underground structure correctly have been due to an insufficient breadth across the flexure having been taken into consideration.

These considerations apply chiefly to highly asymmetrical anticlines, where the flexuring is sharp. In flexures that are only slightly asymmetrical and are not very sharp, it matters very little on which side of the crest the well is drilled. It is possible to obtain oil in quantity from the steeply-dipping flank of an anticline, but it is obvious that the reservoir on that side can never be so large as on the more gently-dipping flank. The migration of petroleum towards the crest is also a simpler matter in steeply-dipping beds, and a well-defined water-level may quite possibly be found on the steeper flank considerably above the water-level on the gentler flank. This is due to the hydrostatic pressure of water, which, according to theory, probably underlies the oil; in steeply-dipping beds the separation of oil and water by migratory movements along or up the bedding planes is naturally favoured more than in gently-inclined beds. Accordingly, it is always as well to make locations on the gently-dipping flanks of anticlines whenever they show asymmetry. Another reason of a practical kind emphasizes this desirability; the mechanical difficulties of drilling through steeply-dipping strata are, in most cases, much greater than when the strata are gently inclined, and the tendency of the bore to depart from the vertical position, and for the sides of the borehole to cave, are always greater the more steeply the strata are dipping.

The asymmetry of a fold very frequently changes when it is traced some distance, and the actual hade of the axial plane may change from one side to the other; hence in every locality the amount and direction of hade must be ascertained as carefully as possible and locations made according to the circumstances in each case. Where there is any doubt as to the position of the crest at any particular depth, to make sure of reaching the oil horizon on the gently-dipping flank rather than on the steep flank should be the geologist's endeavour. Except in long anticlines with little or no sign of dome structure, and where the oilpool is consequently very narrow, there should be little danger of missing oil if the effects of hade are carefully worked out.

When flexures are intensely folded, or even overfolded, as in some cases in Galicia where a single oil-bearing stratum has been pierced three times at different depths in the same well, the conditions are apt to become so complicated that it is impossible to state any general proposition that will serve as a guide in locating wells so as to give the best yield. But it is as well to remember that a water-level will be found somewhere in almost every oil-bearing rock, however well isolated by surrounding impervious beds. The geologist, in estimating the area from which a production of petroleum is probable, and the area likely to be drained by a well, must go by such evidence as is available either from other wells in the same area or from productive wells in other areas, assuming that an oil-water-level will be discovered, and leaving the local variations in this hypothetical plane between water and oil to be proved by actual drilling. Local variations due to differences in porosity, splitting, thinning out, or lenticularity of porous beds, and seepage across fault-planes are very common, but cannot be reckoned upon till proved by the evidence from a number of bores.

In locating wells to prove the extent of a field in which oil has already been struck, the geologist must use his common sense when guiding evidence is deficient. Thus if an anticline exhibits dome structure, that is to say, if well-defined pitches point to the length of the field not being excessive in comparison with its breadth, the oil reservoir in each productive stratum will be deep, and it may be possible to locate profitable wells far down the flanks or pitches of the flexure, while if the fold be little affected by pitches a shallow, long, and narrow oil reservoir may be expected. In any case the geologist will find it expedient to feel the way cautiously towards the limits of an oilpool, rather than to locate wells rashly in the hope of proving a wide field at once. It is hardly ever profitable to drill an unsuccessful well, as the evidence it furnishes is almost entirely negative, and does not necessarily assist those in charge of drilling operations in defining the limits within which profitable productions can be obtained. On the other hand, when water and oil are found in the same stratum when pierced by a well, when the occurrence of the two liquids can be demonstrated in intimate association, very valuable evidence as to the extent of the oilpool may be furnished. As stated above it is useful and even necessary to assume that there is a regular level between oil and water in each bed, a horizontal plane above which oil, and below which water, will be struck, but in actual practice, especially where the oil is of high specific gravity, it may be exceedingly difficult to determine where such a plane can be drawn in horizontal sections. In simple and well-defined structures, where the porosity of the oilrocks is fairly constant and the oil of light gravity, there may be little difficulty, but even in such a case the plane may be at different levels on opposite sides of an anticline. It is a useful convention, but it must not be regarded as a hard and fast line which cannot be affected or altered by local conditions. There are many cases on record of water being struck in a well and pumped for months before oil has made its appearance in any appreciable quantity, and yet the well has finally yielded oil without any admixture of water and continued to give a profitable production for years. Thus the actual striking of water where oil is expected does not always mean that the well is a failure. Again, what is called a "freak-well"—a deplorable phrase—may be brought in outside what has previously been accepted as the limits of profitable drilling. Of such freaks there is always an explanation, though it may be by no means obvious; in many cases such so-called freaks could have been foretold, had the geological conditions been studied with sufficient care.

Many of the discrepancies between predictions and results nowadays are attributed to lenticularity of the oil-bearing strata. Oilsands are doubtless lenticular, as deltaic and estuarine deposits must necessarily be, and as for that matter every clastic deposit in the world must be. Among the rapidly deposited sediments of a delta thinnings out and variations are naturally especially conspicuous, but, all things considered, the lenticularity of oilsands is being made too much of. To shelter oneself behind "that comfortable word" lenticularity when predictions as to the depth and position of oil-bearing strata, or the prospects of a well, have gone astray is a confession of weakness, ignorance, or, still more probably, the want of careful detailed mapping, which the geologist should be ashamed to make unless he is in a position to prove out and out that such lenticularity exists. As a general rule, if he can prove striking lenticularity in the beds exposed at the surface he may be justified in assuming it among beds of similar character and mode of formation underground. In any case he should be able to ascertain the general conditions of lateral variations, and should thus have the key to any problem involving the sudden thinning out of beds of porous strata capable of containing petroleum, or the sudden appearance of such strata. To depend upon well-records for such evidence is at the best to obtain information at second hand, and it is not in every field that well-records can be implicitly relied upon, the personal equation entering into them to such an extent that, even where carefully kept, they may leave many essential points doubtful. To advocate drilling down the pitch or the flank of a flexure in the hope of striking a lenticular bed impregnated with oil and sealed from the invasion of the dispossessing fluid, water, by being surrounded by impervious strata, is to reduce geological science to the level of guess work. Yet wells have been successfully brought in under such conditions and have proved very remunerative, though the locations have been disapproved of by geologists on grounds perfectly justifiable. It is such instances that have often discredited geological work in the minds of practical and unscientific oilmen, and it makes the geologist's task all the more arduous to know that unexpected and even unprecedented conditions may falsify the conclusions at which he has arrived after the most careful consideration of structural and practical evidence from every point of view. It is for this reason that the study of lateral variations has been insisted upon with such emphasis; oilsands can be shown to be splitting up, thinning and dying out by evidence visible at the surface, and the directions of such splitting, thinning, and dying out can be ascertained beyond question; is it unjustifiable to assume that similar variations must exist beneath the surface, and that from what can be actually seen we may interpret the subterranean anomalies of which we only obtain direct evidence through the drilling of wells? Lenticularity of beds may be a very important factor in oilfield work, but to assume it as an explanation of facts that have not been anticipated may be merely a begging of the question. In locating wells upon an anticline, especially if it be of considerable extent and length, all these matters must be considered, and it is rash to assume that an oil horizon proved at one end of an anticline must necessarily persist to the other end, even where the structure is eminently favourable for a production of petroleum.

In locating wells upon a monocline or a terrace-structure, the geologist has, as a rule, a very simple task. He will be guided first of all by any local variation of dip or strike that may be observed, and secondly by the presence of surface indications. Where the dip decreases locally, or where there is a sudden change of strike, especially if the bend in the strike is concave towards the direction of dip, the locality will generally have better prospects of production than areas lying to either side. In a terrace-structure, where the oil-bearing strata do not crop out at surface, this has been proved in many instances; in monoclines attention is usually called to such favourable localities by the "shows" at outcrop, for it is at such changes of dip or strike that the petroleum tends to be concentrated and frequently appears at the surface.

It only remains to calculate at what depth it will be advisable to strike the oil-bearing rocks, to measure off a sufficient distance in the direction of dip, and mark the location. On terrace-structures it may not be possible to calculate the depth, and the procedure will be as in the case of gentle anticlines with a slight degree of asymmetry.

When locating on a monocline it may be taken for granted that a water-level will be found somewhere, though it is possible that both oil and water may be encountered together throughout a considerable thickness of strata. This depends largely upon the specific gravity of the oil, and, as by gradual inspissation at and near the surface the oil in an outcropping petroliferous band must, however slowly, lose its lighter constituents and become heavier, a final stage may be reached when the oil approximates in specific gravity so nearly to that of water that replacement by the latter cannot be complete: consequently a definite water-level, even if proved in one locality, may not be constant over any considerable distance in the outcropping oilrock. But it is as well to assume that a water-level will be reached sooner or later, and therefore the oilrock must not be struck at too great a depth. At too shallow a depth gas-pressure may not be great enough to ensure a good production, and the oil may be too much affected by inspissation. It follows that the making of a location requires the exercise of judgment and will be governed chiefly by experience of results obtained in similar strata and structures and with similar oils. Localities where the dip is lowest will be selected in preference to those where the inclination of the strata is considerable for several reasons; in the first place because it is then possible to place the well further from outcrop for a given depth, and secondly because seepages at outcrop may not have depleted the petroliferous bands to such an extent. A depth of 400 feet is very suitable for a first well when the strata are inclined at an angle of 20 degrees or less. This gives a minimum distance from outcrop of between 1100 and 1200 feet. If the strata dip very gently, the depth need not be so great in a first test. After one successful well has been drilled, the next can be placed to strike the oilrock at greater depth, and the limits of the area which will prove profitable to drill felt for cautiously.

With beds dipping at 45 degrees or more, 600 feet will not be too great a depth for the first test-well. In the case of light paraffin oils, as has been explained before, such tests may be quite unsuccessful, but with oils of asphaltic base excellent results may be obtained under such conditions.

The calculation of depth is a matter of great importance, especially as the shutting off of any water-sands that may be found above the oilrocks is absolutely essential if good results are to be obtained. Given a careful geological survey of the area there should be no difficulty in calculating the position of the oilrocks and the water-sands beneath the surface at any point, and it may be possible even to draw contour lines showing the approximate depths. But the field-student must be warned against projecting the angles of dip as observed at the surface and so attempting to delineate the underground structure. Such methods as those used by the mining engineer in calculating at what depth a shaft must be sunk in any locality to strike a lode will, if applied to oilfield work, often give results so inaccurate as to be useless for practical purposes. It must be remembered that any monocline or any inclined bed represents part of the great curve of an earthwave, and that the part seen at the surface is infinitesimal compared with the part concealed beneath, so that the angle of dip, however carefully measured, may not be very useful as a guide. The drawing of horizontal sections to scale, when there is sufficient evidence, will make this obvious at once, and will emphasize the futility of projecting a dip as seen at surface, as if it continued indefinitely without increase or decrease. It is expedient, therefore, to make a careful horizontal section before attempting to make locations, provided, of course, that the section is *made to scale from a geological map*, and is not merely the diagrammatic absurdity produced by an observer who has made no serious attempt to map the ground geologically. Thus we come back to the proposition stated above that the location of wells should depend entirely on the geological mapping, and provided that this has been done with reasonable care there can be little doubt as to where a test-well should be placed.

It would serve no useful purpose to take every kind of geological structure, and give in detail an account of the conditions which should determine the site for a well: in spite of elaborate classifications of structure, all structures known in an oilfield can be considered under two or three comprehensive heads. But a few words are necessary about areas where faults are a conspicuous feature. Great care must be exercised in locating wells in faulted areas, not only because the fault plane if pierced during the drilling may be the cause of great mechanical difficulties, making the keeping of the bore vertical and the sides from caving by no means easy tasks, but because the presence of faults in the near neighbourhood may have great effects upon the production of the well. The theory that faults affect a field adversely by allowing migration of oil along the fault-plane has already been dealt with and disposed of, but by allowing communication between separate oilsands *across* the fault-plane a dislocation of the strata may have remarkable results (Fig. 15). The field-work of several observers has proved that many of the greatest fountains in the Baku field lie close to the line of a fault, which has made possible communication between separate oil-sands, which are both thick and numerous, so that a well on

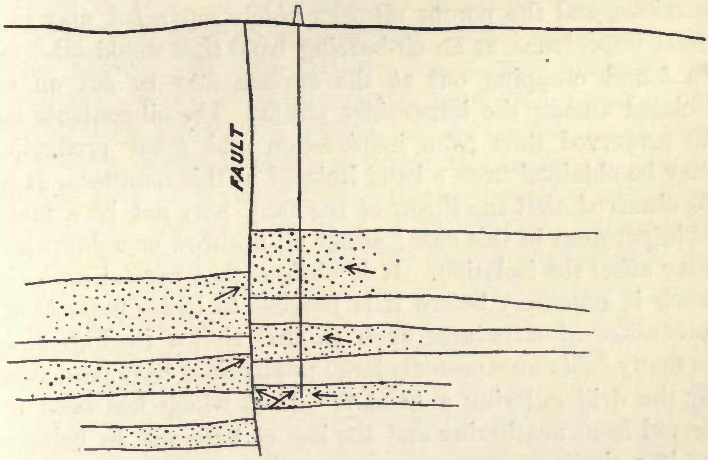


Fig. 15.—Diagram showing how a small fault may enable a well to tap a great thickness of oilrock locally. Arrows show movement of oil and gas.

or near the line of fault is able to derive oil from many horizons, and to tap them, so to speak, all at once. A somewhat similar case can be cited from the Yenangyoung field in Burma, where Mr. B. F. N. Macrorie, of the Burmah Oil Company's Geological Staff, has shown how small faults of little structural importance have assisted in raising the production of certain wells far above the average, and limiting the productiveness and life of others.

As a general rule it may be taken that it is always preferable to drill on the upthrow side of a fault rather than on the downthrow side. The reasons for this are easily understood when it is remembered that any fault can be theoretically replaced by a sharp fold; on the downthrow side the throw of the fault may be sufficient to bring the horizon of an oil-bearing band below water-level, while with normal faults, hading to the downthrow side, the well may encounter the fault plane and get into considerable mechanical difficulties. In many cases what is seen as a fault at the surface becomes a sharp fold when traced downwards where the elasticity of the beds is greater, especially when thick and soft masses of argillaceous rock are present. Faulting when it occurs in a series where by far the greater part of the strata is impervious, and the porous oilrocks widely separated, may be of great importance, as an oil-bearing band that would otherwise be found cropping out at the surface may be cut off and isolated among the impervious strata. The oil contents may be preserved thus from inspissation and great productions may be obtained from a band isolated in this manner. It will be observed that the throw of the fault may not be a matter of importance in this case; either an upthrow or a downthrow may effect the isolation. It is obvious that careful geological work is necessary before it is possible to locate wells to take advantage of structures such as that shown in Fig. 3, but in many fields unexpectedly large productions have been struck by the drill entering a band of oilrock which has been preserved from weathering and the loss of light oils by being cut off in a similar manner.

Faults, generally speaking, unless they are dislocations of great size and throw, are more helpful than harmful in an oilfield, for the simple reason that in most productive fields the total thickness of impervious strata is in excess of the total thickness of porous rocks. Their presence may complicate the geological map and make the calculation of the depth to be drilled in a well more difficult, but their presence need not have any deleterious effect upon production.

Questions of accessibility, proximity to water supply, expenses of road-making, etc., must all be taken into account when making a location for a test-well in a new field, but all these matters, though serious items in expenditure accounts, must be regarded as secondary to finding the site most favourable according to the geological conditions. The young geologist may have pressure brought to bear upon him to fix upon some alternative location which seems "almost as good" as the one he had originally selected, or which may perhaps be in a locality where the prospects of obtaining oil are doubtful, but which is much more easily accessible and will not necessitate any great expenditure in road-making, transportation of plant, and furnishing with a water supply. He will do well to resist all such suggestions, because it is a short-sighted policy that advocates a first test-well in any but the most promising locality available. The cost of drilling a deep test-well in a new field is usually so greatly in excess of the expenses incurred in road-making, providing water supply, etc., that these may be disregarded. If the more accessible site be chosen, and after months, or, if any difficulties be encountered in the drilling, perhaps more than a year, spent in completing a deep test without successful results, another well costing probably nearly as much and taking as long to drill will have to be tried before the area can be considered fairly tested. On the other hand, if the best site, geologically speaking, be selected at first, and the test be unsuccessful, the area may be abandoned at once, and all the time and expense of drilling a second well saved. It may often be difficult to convince field-managers or managing directors that an area can be thoroughly tested by the drilling of one well, but if the geological work has been done thoroughly one test should be sufficient in almost every case, and when the first test is unsuccessful the throwing away of time and money by making further tests is a matter the blame of which must be largely at the door of the geologist, unless his advice has been arbitrarily overruled.

It is not always sufficient to select the best spot from a structural point of view in making a location for a test-well, or in grouping wells for production in a proved field: it may be of great importance to ascertain from which direction the oil is principally coming, or will come once production begins, and a location may have to be made more in accordance with such evidence than on structural data.

Even in the case of a symmetrical dome or anticline there may be great differences in the supply of oil from different directions. One flank may be shorter than the other, the oil-sands may be lenticular and thinning in one direction, the field may be an outlying one with a known petroliferous area on the one hand and unproductive ground on the other, the proximity of faults may isolate the field or retard migration in one direction; all such factors must be considered as possibly influencing the supply of oil towards a well site.

Evidence as to the direction of migration of the oil may not be easy to obtain, but sometimes it is quite obvious. The simplest case is that of an anticline where oilrocks crop out near the crest, giving good seepages on one flank and little or no sign of oil on the other. This may be due to differences in the dip of the strata or other structural causes, or it may be due to the direction from which the oil is coming. Such cases are common in many oilfields, and every practical petroleum geologist will recollect some instance; where the fold is symmetrical and no great lateral variation has been proved the hint as to the direction of migration must not be ignored.

The writer, in an official Government report upon a particular sector of an anticline till then unknown but now at least locally famous, once stated that the southern flank would probably prove much more productive than the northern. The structural evidence was then very obscure, but the copious seepages to south of the crest gave unmistakable evidence. Some years later that very sector came to be developed, and it fell to the writer to make the locations for the first test-wells. New structural evidence from road-cuttings was available, but the detailed structure was still somewhat obscure. For the first wells he trusted chiefly to the structural evidence: the results were light productions of fine, somewhat filtered oil from thin sands below the horizon of the main oil-bearing rock. Later he gave greater weight to his own prediction, with the result that very large productions of a heavier oil were obtained from *an outcropping oilsand on the steep flank of a fold that proved finally to be very strongly asymmetrical.*

The explanation of this interesting result is perfectly simple: the oilsands are thinning out very rapidly just at the crest of the flexure, and though the southern flank is very steep—vertical in places—it rises from a shallow basin containing a great body of petroleum. All the oil migrates northward.

Other structural explanations, some of them very far-fetched, have been put forward with regard to the prolific little field that has been developed on this sector, but the main facts are as stated above, and there is no need to drag in supposititious faults and unconformabilities to account for results that did not seem quite normal or natural at first sight.

If there be a moral to this little piece of authentic history it is to study the direction from which oil reaches the surface, and to have the courage of one's convictions in locating wells even though it should necessitate occasional departures from stereotyped theoretical procedure.

Very frequently a geological adviser finds himself in the position of having to advocate the testing of an area to a certain depth, and after that depth has been reached without striking oil it may be necessary to say at once, and as definitely and strongly as possible, that there is no further hope, and that the area should be abandoned. In such a case, if the well be "in good shape" to be carried much deeper, there may be considerable hesitation on the part of those responsible for the practical operations in deciding to abandon it. The geologist, having the courage of his own convictions, should make things as easy for the field-manager as he can, by putting the case clearly and concisely before him. Little blame can be attached to the unsuccessful testing of a new field by drilling one well, as it is often impossible to make sure of the petroliferous character of part of a series in any particular locality without evidence from a borehole; but to allow a second unsuccessful test to be drilled, or the first to be continued to a great depth when it has no further prospect of striking oil, is a confession on the part of the geologist of the uncertainty of his own judgment or his ability in reading the evidence obtained during the geological mapping of the ground. Hence it becomes of the utmost importance that no testing of a new field should be commenced till the geological examination has been made in detail and the location made in the best possible place to obtain a production of oil. Were the importance of this principle more fully realized, the popular idea of the capricious nature of petroleum would be shaken, and might even be relegated to the limbo of scientific fallacies.

After a successful well in a new field has been drilled, the second test should be placed so as to develop as large an area as possible without taking the risk of getting beyond the margin of the oil-reservoir. This is to enable some idea of the area available for drilling to be obtained at once. When there is great doubt as to the extent of a field, the best policy to adopt in developing it must necessarily be uncertain, but with a fairly accurate idea of the minimum size of a new field, drilling programmes and transportation of plant can be taken in hand in the most economical and adequate manner. The only exception to this is when the petroleum is required, and can be handled, at once; new wells may then be started near the first test. This, however, is a state of things by no means usual in new fields.

Second and third tests should not be located directly down the dip from the first producing well, but at some distance to the side, so as not to interfere with the supply of oil to the first well. The natural migration of petroleum will be up the dip-slopes in most fields, whether in monoclinal or anticlinal structures. If the first test-well has been placed on one flank of a symmetrical anticline, the second may be located on the other flank, in order to obtain information as to the breadth of the field. In a dome structure the second test should be made in the direction of the larger axis of the dome.

The distance at which wells may be placed from one another without mutually affecting their production is a question upon which it is impossible to dogmatize, as it depends upon so many factors, such as the porosity of the oilrocks, the grade of the oil, and the gas-pressure, which may be different for any different field. It may be taken as an axiom that in any given field there is a certain minimum number of wells which will exploit the area most profitably and economically. To drill more than that minimum number will not ensure the production of more oil in the long run, but less, for though production may be more rapid, gas-pressure will be dissipated more quickly, and thus the motive force that brings the petroleum into the well, and perhaps up to the surface, will be to some extent wasted. Fields such as Spindle Top, in Texas, and Twingon, in Burma, might have had very much longer lives and produced much more oil with a fraction of the expense, had there been any regulations to prevent over-drilling.

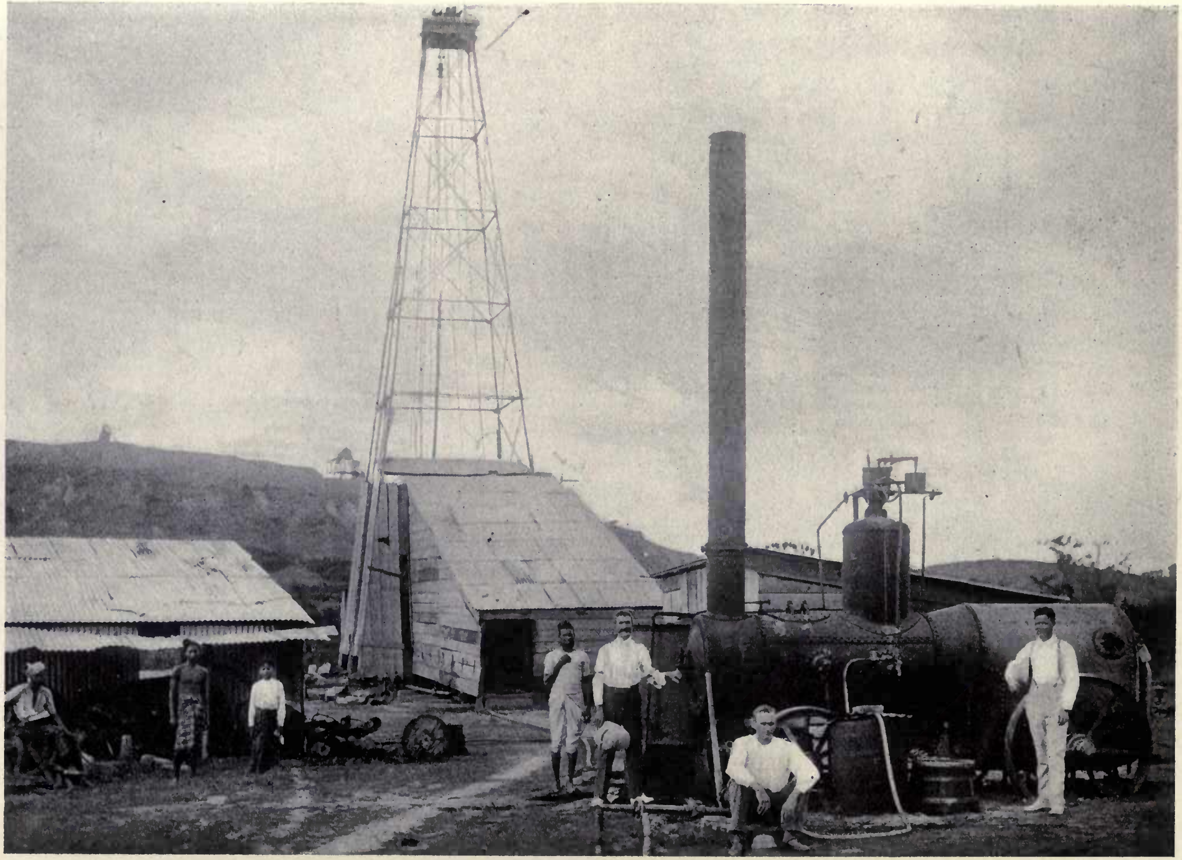


Photo. by M. Croulîansky

A Canadian steel-derrick at Minbu, Upper Burma.

The effect upon a well of drilling another well or wells close to it is not always what might be expected. Sometimes the new well reduces the production from the older well, sometimes it has the effect of increasing it. Occasionally the new well obtains no production at all. The reasons for such anomalies must be sought in the particular conditions, especially as regards geological structure, in the locality.

This has been clearly explained by Mr. J. T. Smith, editor of the *Petroleum World*, in a most interesting and suggestive article.

Before any well is drilled in a new field the contents of the porous strata, water, oil, and gas, may be considered as in a state of equilibrium. The gas probably does not exist as such, but is largely occluded in the other liquids, though it may extend over a much greater area than that in which oil is found. As soon as a well is drilled the equilibrium is disturbed; a sudden disengagement of gas takes place and rushes towards the outlet from all sides, bringing oil or water with it. If the well be situated exactly in the centre of the oil-reservoir, if the thickness and porosity of the oilrock be the same in all directions, and if the dip be exactly horizontal or the structure be a perfectly symmetrical dome, the rush of oil and gas towards the relief of pressure afforded by the bore-hole should be equal from all directions.

It is obvious that such conditions are only theoretically possible; in practice there must be slightly different conditions on different sides of the well. Consequently there will be greater pressure, greater supply, and greater facility for migration from one direction, and the well, though drawing supplies of gas and oil from all round, will receive its chief supply from one direction.

When the well settles down to a steady production, a regular migration of oil and gas chiefly in the one direction will be established. Such a migration soon improves the facility of movement, either by establishing what, for want of a better word, may be called "channels," or because the steadier flow prevents paraffination and clogging of the pores, which may take place where the flow is slower and less regular. Thus a well in regular production will soon select its sphere of influence in the strata, and the area that it drains will not be exactly circular but will be elliptical, with the bore-hole probably situated somewhere near one of the foci of the ellipse.

A study of the geological structure may enable the expert to determine with some degree of accuracy the direction of the longer axis of the ellipse. Thus, if the well be located on the gently inclined flank of an asymmetrical anticline, it is easy to calculate from which side the greatest supply of oil and gas will come, and if the thickness and porosity of the oilrock be the same in all directions—an assumption which must be made until evidence to the contrary is obtained—a good working idea of the orientation of the elliptical area can be obtained. Similarly if the well be in steeply dipping strata, or on the pitching end of a long anticline, the elliptical area of supply can be at least guessed at.

Now, in locating the next well these matters must be carefully considered. A well placed near the first so that without actually interfering with the sphere of influence of the first it helps to increase the migration of oil in the same direction, may not only obtain a good production for itself, but may actually increase the flow from the first. Third and fourth wells may have a similar and cumulative effect if similarly located, and much unnecessary drilling and wasteful exploitation work may be avoided. On the other hand, a well situated on the prolongation of the axis of the ellipse, or actually on the axis, will either interfere with the supply to the first well, or will be interfered with by it, according to which focus of the ellipse is occupied by the original well.

Of course, in practice there are many conditions that complicate such theoretical calculations and cause irregularities in production and results that cannot always be accounted for, but the theoretical case of an elliptic area of supply must be taken as the basis, the limiting case, upon which, in the light of experience gained in the field, the drilling programme may be gradually worked out.

When an oilfield is in the hands of one company or owner it does not matter very greatly what system is employed for draining the territory, but even in such a case there must be a theoretical minimum number of wells sufficient to obtain all the oil that can be abstracted with profit. Every well above that number is an unnecessary expense. Thus the location of wells even in an established producing field must not be done at haphazard but on a well-considered system, and the distance between wells may be varied considerably according to circumstances depending largely upon what has been learnt about the elliptical areas of influence.

When more than one company are operating in a field in small plots of ground contiguous to each other and perhaps inextricably dovetailed, the process of what is called "off-setting" is frequently put in operation. This means that on one company bringing in a good well, the others drill other wells around it as closely as possible in order to share in its success, or, to put it frankly, to obtain all the oil they can from the same area before the first well shall have drained it. Thus five or six wells may be located in an area for which one was sufficient.

This "off-setting" is very wasteful, and is often entirely foolish, unless the wells be located with regard to the direction of migration of oil and gas in the locality. Of, say, six wells placed round a new and successful producer, two may have the effect of increasing the production of the original well, two will probably obtain a very meagre production, if any at all, and only two can hope to rival the first even under the most favourable conditions of structure. In some cases off setting, when it can only be done on one side, may be an actual advantage to the owners of the first well, and an entirely useless expense to the enterprising off-setters.

Where Government regulations prevent the drilling of wells by competing owners within a short distance of each other the evils of off-setting may be obviated, but it is not in every country that such common-sense legislation has been passed and put into force before the evil it is sought to guard against has become the recognized practice. The frontispiece of this book shows only too clearly a case of several operating companies playing "beggar-my-neighbour," with a minimum of restriction.

But while human nature remains what it is, "off-setting," however ill-considered and generally useless, will doubtless be continued, and it is impossible to give any rule as to the minimum distance between wells that can be generally applicable. Each field has its own peculiarities that must be considered.

With light paraffin oils, high gas-pressure and porous sands a distance of one hundred yards between wells will probably be found a convenient and sufficient distance. When the sands become partly exhausted or clogged near the bottoms of the wells by the deposit of solid paraffin, new wells may often be drilled with profit between the old producers. In shallow fields with asphaltic oils, and in oil-bearing limestones, wells may be placed considerably closer without seriously affecting each other, but in each field the requisite minimum distance must be ascertained by experience.

In calculating the number of producing wells which a proved area will carry it is advisable to allow for a distance of from 200 to 300 feet between each.

Though it is no part of the geologist's task to give advice as to the methods to be made use of in drilling, practical experience in oilfields will soon make him *au fait* with the chief mechanical difficulties that the driller will have to overcome, and it will be part of his duties to acquaint the field-manager or driller with the nature of the strata through which the well will penetrate.

This will enable those responsible for the drilling to select the best methods for overcoming the difficulties which each kind of rock will present, and the type of rig and tools most suitable will be chosen. Thus through a thick soft argillaceous group it may be found most profitable to use a rotary rig, while drop-drills and under-reamers may suit a variable series containing hard calcareous bands.

The approximate depths of probable water-sands, the presence of hard bands upon which it will be possible to ground casing, the occurrence of soft beds liable to cave into the borehole, are all points upon which the geologist may give information that will be of great value to the practical driller. Again, the angle of dip, if it be high, is an important matter, since steeply inclined beds are frequently liable to cave, and if thin hard beds are encountered dipping at a high angle there may be great difficulty in keeping the bore vertical.

Thus, in return for the information afforded to him by the log of a well the geologist should be able to forewarn the driller of difficulties, and so ensure that they are taken in hand and overcome most expeditiously.

CHAPTER XI

PETROLEUM PROSPECTS IN BRITAIN

THE search for petroleum in Britain affords a very good opportunity for the application of the principles set forth in this little book, and it may interest the reader to deal with the problem and draw his own conclusions, favourable or otherwise, concerning the development work that is now in progress.

There has been during the last few months of this year (1919) much interest evinced as to the drilling, and even some little newspaper excitement.

For the decision to test certain areas with the drill a certain measure of responsibility rests upon the writer, and for that reason, and also because the whole subject has been the nucleus about which much deplorable nonsense has been published, it may be as well to give a short account of what really took place. In what follows the writer has no desire to pose as a critic of any Government Department, nor to censure any one, official or unofficial, for what has been done or what has not been done, but merely wishes to put the scientific facts briefly and accurately as a matter of justice to all concerned.

For many years the writer had been applying the principles set forward, however inadequately, in the preceding chapters to problems of British geology, and had recognized that there was a somewhat slender chance of finding oil in commercial quantity in several districts, but had realized that prospects of success were too speculative to attract capital in normal times. When the great war commenced he foresaw at once that a shortage of mineral oil was inevitable sooner or later, and as opportunity offered continued his researches in greater detail.

A study of the Scottish shalefields led him to the conclusion that there was hope of striking free petroleum in both Linlithgow and Mid-Lothian, and he prepared a long report dealing with the subject generally and in detail, marking the localities worth testing on the maps and even the locations for test wells.

On joining the Petroleum Research Department under the late Sir Boverton Redwood, early in 1917, he prepared an official memorandum setting forth the arguments for and against a certain number of drilling tests in England. The country's supply of oil at the time was deplorably short and it had been realized that little improvement could be looked for in the near future and that every possible source of indigenous supply must be utilized.

Three areas in the Midlands, namely, Ironville and Brimington in Derbyshire and Apedale in North Staffordshire, were specially selected for testing with the drill, and it was explained that successful results in any of these localities might point the way to further tests in areas similarly situated from the geological point of view.

The principles upon which these localities were selected were in full accordance with all that is set down in the preceding pages. In the first place bands of good porous sandstone and grit were known to exist at a convenient depth beneath the surface.

Secondly, these bands of porous rock were known to be separated by and sealed beneath good thicknesses of impervious shale.

Thirdly, there was a distinct probability of sufficient raw material for the formation of oil in quantity being present; in neighbouring areas under different conditions of structure this raw material is found as coal-seams and carbonaceous deposits.

In the fourth place, the geological structure is in each case distinctly favourable to the concentration of any petroleum that might be present. The structures are all of the dome type, but unfortunately they are not of any great size; a concentration area of as much as six square miles being exceptional. There are several faults, some of large throw, which affect these areas, but the downthrows are away from the crests of the domes.

As regards actual signs of petroleum these are not wanting. In the Ironville dome a heavy oil was collected in a sump and utilized for some time, while seepages and indications of oil are frequent in colliery workings in North Staffordshire.

Thus there was a prima facie case for the belief that petroleum might be present in sufficient quantity to be worth developing.

The chief arguments against the prospects of drilling may be summed up in the simple statement that it may be too late, *i.e.* that adsorption, dissipation of light oil, circulation of water, etc., may have removed all but heavy residues of oil and residual gas, and that only relics of impregnation and occasional filtered "shows" will be found.

Considering the question in greater detail several points are worthy of note. The petroleum expert in this case has practically nothing to do. From the maps, vertical sections, horizontal sections, and memoirs of the Geological Survey every necessary detail can be obtained, and though the petroleum geologist may supplement these data from his own observations in the field his rôle is more as an interpreter of the evidence than as a discoverer of anything new or an investigator of anything that has been overlooked. All this may be quite obvious to geologists, but possibly not to the general public, so it is put on record here, and it is to be remembered that the data given in greater detail below are almost entirely collected from Geological Survey publications with a few supplementary notes and observations of the writer.

In the sequence of geological strata in the British Isles there are three main groups of beds which can be shown to have been petroliferous at one time; they may still be proved petroliferous if pierced in suitable structures for the concentration and preservation of oil. Beginning with the uppermost, these are the Portland Sand, the Millstone Grit, and the Calciferous Sandstone (Scotland).

The Portland Sand has contained a sulphurous oil of asphaltic base; traces of its former presence may yet be found at outcrops at certain localities and in bore-holes, but it is rather doubtful whether this formation can be struck in a well at sufficient depth and under satisfactory conditions of structure. So it must be conceded that drilling to tap the Portland Sand for oil would be a very speculative enterprise.

The Millstone Grit, which consists usually of three or four great beds of porous grit and sandstone separated by shales, is distinctly petroliferous in several localities. The oil struck at Kelham in Nottinghamshire occurs in the Millstone Grit, and traces of oil are to be found at the base of the same formation, *e.g.* in an anticline at Skipton in Yorkshire. The only reasonable prospect of striking oil in quantity in England is if the beds of this formation can be found impregnated in well-sealed dome structures. There are other beds in the Carboniferous Limestone Group beneath where traces of oil may be found, but none of these gives any promise of good production.

The Calciferous Sandstone in Scotland is a thick mass of variegated beds below the Carboniferous Limestone. It is divided into the Upper and Lower Oil Shale Groups, and it is in the latter and the lower beds of the former that oil may be found. There are four main horizons at which porous sandstones of sufficient thickness may be encountered: these are in descending order the Binnie, the Dunnet, the Hailes, and the Granton Sandstones. All are subject to great lateral variations and may die out locally, and other arenaceous groups may occur, but one or more of the four is likely to be represented in any vertical section and may attain a thickness of as much as 300 feet. Impervious blaes and oil-shales serve to separate and seal up these arenaceous rocks. Traces of oil or of the former presence of oil are recorded in several localities from the two upper horizons in outcrops, borings, and mine-workings, and the lower sandstones, though not so well known through borings and mining, give some evidence suggesting that they may be petroliferous also.

On general principles it will be seen that the prospects of striking petroleum are better in Scotland than in England, provided that equally favourable geological structures are available in each country.

This brings us to a more detailed study of the structural conditions.

The Carboniferous rocks of Britain were extensively folded at the close of the period of deposition, and are now found chiefly in basins, the major anticlines having been denuded. The great Pennine anticline, which might almost be called the backbone of England, running north and south through the Northern and Midland counties, divides the coalfields of the east and west. It brings up the Millstone Grit and Carboniferous Limestone formations to form the high ground in Derbyshire. Traces of the former presence of oil may be found in outcrops in this great flexure, but these are of little importance except as showing that the strata in the anticline were in the petroliferous phase at one time. Most if not all of these surface indications can be shown to be due to impregnation from the overlying and flanking Millstone Grit, which being highly porous has quickly lost its petroleum contents when subjected to weathering and circulation of water. At lower horizons fine-grained beds of limestone and shale may retain traces of oil and even give rise to seepages long after the porous parent rock has been robbed of its valuable fluid impregnation. It is probable that many observers may have been deceived by the occurrence of such indications in beds of lower horizon than the Millstone Grit, and wells may be drilled in consequence in localities where there is no hope of really successful results. As has been pointed out in other chapters, the same mistake has been made many times in many countries even by experienced geologists, and it will continue to be made so long as people are content to follow oil indications blindly without considering how and why the oil reached its present environment. In North-Western Canada precisely this mistake has been made and has been the cause of some fruitless drilling in the past. It seems likely to be the cause of further unsuccessful efforts in the future.

The major anticlines of Carboniferous strata being thus ruled out of account, it is necessary to consider minor structures. On both sides of the Pennine Chain minor parallel folds are not wanting. In Yorkshire and Derbyshire there is a line of small elongated domes one after another for many miles on the eastern side of the major anticline: of these Brimington and Ironville are good instances. On the western side of the major structure the Apedale antecline is the best of the minor structures.

The faults affecting most of these minor structures cannot be considered as of great importance; they may have been the cause of loss of gas pressure, but as much of the series is impervious shale they cannot have seriously prejudiced the chance of striking oil if any considerable concentration of petroleum has taken place. But it must be remembered that these are at the best small and subsidiary structures with no large concentration areas.

The top of the Millstone Grit occurs at depths between 1000 and 1600 feet in these domes, and the base of it from 2000 to 2700 feet. Below this comes the Carboniferous Limestone formation with thick masses of compact limestone, bands of shale and a few small sandstones, but with no good porous beds to act as reservoir rocks in this part of the country.

In Scotland the structural conditions are on the whole more promising. The Cousland-D'Arcy anticline east of the Mid-Lothian Coal Measure basin affords the best prospects; it is a well-marked anticline with a concentration area of at least eighteen square miles and possesses two distinct domes, one at Cousland and one at D'Arcy. There are a few faults of quite minor importance, that cannot have any deleterious effect. The flexure is broad and gentle and throws off some 3000 feet of strata on the western and 1000 feet on the eastern flank.

The whole oil-shale group to the thickness of 3000 feet or more is beneath the surface.

The Binnie sandstone which crops out on the Pentland anticline six miles west of this flexure, contains crude oil in sufficient quantity to make the stone unsuitable for building purposes, and in the same neighbourhood the occurrence of drops of oil in St. Catherine's Well has been known for many years. Wells testing the two domes have good prospects of entering petroliferous strata at any depth between 1500 and 3000 feet, and it is possible that four or more oil-bearing horizons may be discovered. The possibilities of this structure so impressed the writer that after preparing a lengthy report upon the geological conditions and petroleum prospects in this part of Scotland, he went so far as to mark the localities for test-wells.

Besides the Cousland D'Arcy anticline there are numerous smaller domes in the oil-shale fields on the other side of the Pentland anticline. In some of these evidence of the presence of crude oil has been obtained, and all have some prospect of being productive, but none of these structures has a large concentration area, and so cannot be expected to contain large supplies of oil. Faulting also affects several of the domes, and thick intrusions of igneous rock will make the drilling arduous in several cases.

Drilling by the Government agents is now proceeding (October, 1919) in one of the small domes (Mid-Calder) and at D'Arcy.

It will be seen that in almost every respect Scotland affords more favourable prospects of striking oil than does England, though it has unfortunately received less attention than it perhaps deserves.

The above brief account includes all the geological conditions and areas to which the Petroleum Research Department called attention with the hope of discovering oil in sufficient quantity to make the country less dependent upon imported supplies during war-time. But for one reason or another there were serious delays, amounting in all to about eighteen months, so that it was not till the war was drawing to its inevitable end that the department entrusted with the production of oil supplies took action and employed a firm as Government Agents to do the drilling under what was a practical monopoly. An ambitious drilling programme was then entered upon, and is still in operation at the public expense, and long after the immediate and urgent need of fuel oil and petrol has come to an end. The speculative nature of the undertaking naturally aroused much criticism in scientific circles and among practical men, and it seems to be the general opinion among geologists that though a little petroleum may be found no adequate supply is possible. Some condemned the attempt as hopeless from the start.

Though it is almost impossible to predict results with certainty, it may be admitted that a thorough testing of *three or four* typical areas can be justified on the evidence. Whether as many as ten or eleven areas should be tested simultaneously and at the public expense after the emergency is over is a matter of policy that might well be argued, but about which the writer has no desire to dogmatize. It is a question to be decided by common sense.

The danger in connection with these hoped-for oilfields is that they are already too old. The oil, in whatever quantity it may be obtained, will be of paraffin base, and may not contain any asphaltic constituents. Such oils, unless very well sealed, may have been dissipated and adsorbed to a great extent, leaving little but heavy residues and gas in the porous strata, and light shows of filtered oil in any non-adsorbent fine-grained beds that have been impregnated. Such filtered shows will contain very little petrol and less heavy residue. Sulphur compounds may also be present in fair quantity owing to concentration caused by inspissation. Gas pressure may have been largely lost in the course of geological ages.

The results of drilling so far indicate disappointing results so far as Derbyshire is concerned. In June (1919) two wells had reached such a depth that their prospects of striking oil were rapidly vanishing. The Millstone Grit had been pierced, and beyond a few shows of heavy oil and occasional blows of gas, had given no signs of being productive. But the wells were continued below the horizons in which alone commercial success was possible.

In the Hardstoft well, at a depth of 3077 feet, a show of filtered oil was encountered unexpectedly in a fine-grained bed. This was most unfortunately advertised as a "strike of oil," and by some was considered a "promising indication." The oil, which the writer has examined, is brown in colour, and of rather unpleasant odour. It is light in gravity, and is not accompanied by gas.

Several analyses have been made with slightly different results, as follows:—

Specific Gravity . . .	0·820—0·828
Flash Point	73° F.
Setting Point	0° F.
Petrol	4·5—7·5 per cent.
Kerosene	39·0—41·0 ,,
Gas Oil	20·0
Lubricating Oil . . .	30·5
Paraffin Wax	3·0

This is obviously a filtered oil, the parent oil of which is, or rather was at one time, at a higher horizon. So far from being a "promising indication" it is fairly conclusive evidence that the well is a failure, and it is most unfortunate that undue prominence should have been given in the Press to such a paltry and discouraging show. The occurrence in this oil of very fine, almost colloidal, mineral matter in suspension, which takes days or even weeks to settle, has been claimed as a proof that the oil is not filtered. As a matter of fact, such fine suspensions of mineral matter are typical of filtered oils under such conditions: the writer has noted similar instances in Burma and other countries.

Very similar filtered shows of oil have been recorded from wells on the Athabasca River in North-West Canada, where the borings had penetrated the Lower Cretaceous oilsands and were continued deep into the underlying and non-petroliferous Devonian formation. A somewhat similar but more promising show in Cretaceous strata in Trinidad, after the Tertiary oil-bearing series had been pierced through, led to two or three unsuccessful wells being drilled.

Two at least of the Derbyshire wells can be written down as failures, and the prospects of the others are gloomy. The oil has evidently been present in the Millstone Grit, but it is there no longer in sufficient quantity to be worth exploiting.

In North Staffordshire somewhat different, and possibly more promising, conditions will be encountered, and in the Cousland-D'Arcy anticline in Mid-Lothian very much better results are probable, as time will show. By the time these words are in print the question may be settled finally, but it is to be hoped that wells will not be continued far below the depths at which success is possible.

The author so far departs from the general opinion as to hold it justifiable to drill and test four or five of the wells now in operation, more especially had such work been undertaken at a time of crisis and emergency, when the Petroleum Research Department urged action.

He has some hopes of the Scottish area, but agrees generally with those geologists who have studied the subject that a scientific rather than a commercial success is indicated in the case of most of the borings now being made.

But on the principles which he has tried to make clear in earlier chapters, he has nothing but condemnation for efforts to represent distinctly unfavourable indications as hopeful and promising, and pointing to a possible great success at greater depth. Such a representation has been made and given publicity in a press only too prone to exploit sensational news, and has reached other countries in an absurdly exaggerated form. It has caused a very bad impression in the minds of those who have a first-hand knowledge of petroleum and experience in dealing with it, and it can only cause unnecessary disappointment when the truth finally comes to light.

CHAPTER XII

(For Beginners)

FIELD WORK

In the preceding chapters allusions to geological mapping have necessarily been very frequent, and it is hardly necessary at this stage to insist that the object of all geological field-work must be in the end to make as complete a geological map as possible. No casual examination of an area is sufficient, no spending of a few hours, or even a few days, if the area be large, in examination of sections and oilshows and the taking of notes will qualify the geologist or petroleum expert adequately to advise those who are undertaking development work. It used to be one of the distinguishing points between the amateur and the professional geologist that the former was frequently content with the drawing of a horizontal section, while the latter always pinned his faith to a map, but nowadays the amateur is learning that in any case the map must be made before the section, and that nothing but a map will suffice. In oilfield work the whole concession or area, and frequently a large area outside of it, must be mapped geologically.

In some cases a published geological map may be available, and may be of great assistance, but it is not likely to be on a sufficiently large scale to give the details which are essential, if wells are to be located with accuracy to strike the oil-bearing deposits at the determined depth. The best topographical map available must be procured, and if it be on too small a scale it may at least serve to check distances and compass-bearings in the large-scale map which the geologist will prepare for himself. The smallest scale that is at the same time sufficiently large to admit of mapping in detail will be naturally selected; for most fields and field-geologists the scale of six inches to the mile will be found to meet the case. Eight inches to the mile is also a very useful scale, and in producing fields scales of sixteen or twenty-four inches to the mile may be used with profit, and may, indeed, be necessary; but for all practical purposes, especially in new fields and in wild and unopened country, the six-inch scale is probably the best.

Experienced geologists will pardon the writer for giving some account of the methods of field-mapping that he has found most effective under different conditions, in the hope that some of them may prove of value to the prospector or field-student, for whom this little book has been written.

Many of the details to which much attention is given in large-scale mapping in Britain can be neglected, partly or wholly, in oilfield work, and on the other hand methods and conventions that are not required in ordinary geological mapping may become of the greatest importance when an oil-field is being surveyed. It is necessary that structure be worked out thoroughly, and it is for this reason that the mapping must be done on a scale sufficiently large and in sufficiently great detail to make any mistake in structure impossible. But the nature of the strata and the mapping of outcrops with great accuracy, and determining the exact positions of points may in many cases become matters of minor importance. The determination of the exact position of the crests of sharp anticlines, the angles of hade of the axes of asymmetrical flexures, and the pitches of axes is essential, and consequently observations may have to be taken very frequently and with great care, while the angles of dip on the flanks of a flexure may not be considered of sufficient importance to demand any special care in the taking of observations.

Equipment.—The geologist who undertakes the examination of oilfields must have an effective, but not necessarily an elaborate equipment. The first essential is a good and substantial map-case. The large leather map-case as used by the Geological Survey of Great Britain is a very good model, though it may be improved in details to suit the individual. It allows six square miles of ground on the six-inch scale to be studied at one time, without changing maps, an ample area for all practical purposes. It is slung from the shoulder by a strap and can easily be manipulated with one hand; this may seem a very trivial point, but it is really of great practical importance. Smaller map-cases or mounted and folded maps carried in the hand or in a bag or pocket will be found troublesome to manipulate, and do not conduce to good geological mapping. The tendency will naturally be not to consult the map frequently enough, and the mapping may become more of the nature of taking occasional notes. The possession of a good handy map-case opened and managed with one hand will do much to teach the field-student practical mapping and the reading of geological maps.

Plane tables, though excellent for careful work in small areas, are too cumbersome : the geologist has very seldom sufficient time at his disposal to make use of such appliances, and the slight gain in accuracy obtained by using them is more than counterbalanced by the laborious nature of the work and the waste of time involved.

Cavalry sketching-boards, fitted with a compass and designed for use on horseback, are pretty little toys. They may be of use on a preliminary traverse or a pioneer exploration of new countries, but they are too small for detailed and accurate work, while the compass is usually also too small to take bearings with sufficient accuracy. Furthermore, if the possession of such an equipment has the effect of inducing the young geologist to imagine that efficient geological work can be done on horseback, it may be his ruin so far as practical field work is concerned.

Occasionally, however, it is necessary to do work on horseback, but it is in the nature of military reconnaissance rather than regular field work. The sketch-mapping of roads and routes for marches, marking positions for defence, watering places, camping grounds, etc., is regularly taught in the army and is done, especially in uncivilized countries, on horseback. For this the pace of one's mount, whether at the walk, trot or gallop, must be accurately taken and a time check kept to correct estimates of distance. The author has had experience of how useful traverses of this kind can be during the survey of a wild district in South America. No reliable map was available, but little pueblos near the coast-line were fairly correctly marked. Inland, all was conjecture. The ground to be examined and surveyed lay some fifteen to twenty miles inland, and a broad coastal-plain desert, partly covered with cactus and gradually merging into thicker jungle, had to be traversed before the foothills were reached. Owing to the paucity of practicable paths and the difficulty of obtaining supplies, it was necessary to travel by the road near the coast and to make expeditions of a few days' duration inland from each stage, travelling with as little impedimenta as possible. The distance to the foothills and their dense vegetation rendered it impossible to obtain one's position inland by taking compass bearings, and consequently on every traverse inland from the coastal road track had to be kept.

Two methods were adopted: Mr. G. W. Halse, who was accompanying the writer, took compass bearings at intervals of five minutes, and plotted the results at the end of the march. The writer attempted to map track on the one-inch scale, checking the mileage also by time. Owing to the nature of the ground, most of the journey had to be done at a walking pace. Pocket compasses only were used, and as hardly any notes of geological importance could be taken, the strata being marine and river alluvium and gravels, these traverses were the most dreary, uninteresting and annoying that the author has ever experienced.

But the results were quite remarkable. The traverses independently plotted on the one-inch scale by two different methods so nearly coincided in every case that it was impossible that there could be any very serious error.

A pioneer geological survey of the district was being made on the scale of one in 250,000, and a very large area, some 1200 square miles, had to be examined in as short a time as possible, so that an error of half a mile in position was negligible. The final results after eight or ten such traverses proved that the work had been done with very fair accuracy, and the geological map carefully surveyed was founded upon the positions established by these traverses. Such methods are by no means easy, they are without any exaggeration a weariness to the flesh, but they have the merit of being fairly rapid, and certainly they enabled in this case a very large area to be mapped with comparative accuracy within a few weeks Military traverses of this nature are frequently made very successfully, in unexplored country, and can even be done at the trot or gallop, but the geologist is recommended, if he ever has to attempt anything of the kind, to do most of it at a walking pace.

For instruments, the first essential is a good pocket compass, one at least two inches in diameter, with a clearly marked dial, that will enable the observer to take bearings to within two degrees. This compass should be carried in a case from which it can be taken and manipulated with one hand. The saving of time, trouble and, it may even be added, temper, that is effected by carrying a compass that does not require two hands is enormous; this can be understood when bearings have to be taken once at least in every fifty yards, as is necessary when working in dense forest. It is as well to have this compass combined with a clinometer sufficiently reliable to take angles of dip without an error of more than one or two degrees.

For taking bearings from distant points a good large prismatic compass is necessary; it must be sufficiently sensitive to read correctly to half a degree, but the needle must not be too "lively." That is to say, though sensitive, the card should have a comparatively high "moment of inertia." This will enable readings to be taken by the method of oscillations, and another great saving of time will be effected. The geologist will soon learn to recognize the happy mean between too great mobility and too great sluggishness in a prismatic compass.

An Abney's level, or some similar instrument, is sometimes necessary in taking readings of the angles of pitch and dip where these have to be measured very carefully, but it need not be carried always. In producing fields and open ground it is far more likely to be required than in new and unexplored country.

Theodolites, tacheometers or omnimeters are often of great value in open ground, especially where there is no topographical map available, but it is impossible for the geologist to carry such instruments with him in rough jungle work. The young geologist should have no ambition to make himself a third-rate land-surveyor, and though it is necessary to understand the use of these instruments, and to be able, if it is required, to measure a base-line with them, he will be well advised to use them as little as possible; to give undue attention to the more or less mechanical duties of land-surveying may run away with time that may be more usefully employed in geological work. Like the Abney's level the omnimeter or tacheometer may be left at headquarters, and only taken out when some special work with it becomes necessary.

A good pair of field-glasses are often of considerable use to the geologist working in open country, particularly when a pioneer survey is being made in unexplored ground. It is always as well to look ahead and study from hilltops the country that will be traversed in the next few days, and much time may be saved by selecting the route to be traversed and noting roughly on a map the particular localities where evidence of importance seems likely to be obtained. But to use field-glasses to *obtain evidence* at a distance is dangerous and may lead to fatal mistakes—if the observer does not take the trouble to visit the localities which he has studied at long range. It is a lazy man's method to depend on such observation.

There is nothing more deceptive than apparently obvious dips and strikes of strata seen in perspective through field-glasses and if the geologist put such dips and strikes on his field map he will find that he almost invariably has to correct them when he visits the locality later. The writer has done this so often himself that he feels it necessary to warn others against it. If the observer is content with long-range observation and neglects the necessary detailed examination he is almost certain to regret it afterwards. He should leave his hammer mark on all important outcrops: even walking past them or over them will not do; there may be some important detail, that will later on prove of great importance, that will be missed unless a complete and careful examination is made. Therefore, field-glasses, unless the strata are thoroughly familiar, are all the more to be avoided except in enabling the geologist to determine his route and his tactics in advancing over unknown country.

A good protractor adapted to the scale used in mapping must be procured. This may have to be made specially, of ivory or aluminium according to the taste of the geologist. Ivory is perhaps the better material, though it warps badly in hot weather. The six-inch protractor used by the Geological Survey of Great Britain, and furnished on the back with handy tables to enable thicknesses of strata, depths and gradients to be calculated rapidly, is quite the best instrument of the kind for six-inch mapping.

A hammer may be carried if required, but in Tertiary strata it will not often be used; a cutlass, machete, dah or kukri will be as effective, and will serve other useful purposes, *e.g.* in clearing a path through thick jungle or in digging down a grass-grown section to lay bare the strata.

A stout walking-stick with a crooked handle by means of which it can be hung on the arm when using the map-case or compass is almost invariably carried by the writer. In taking the dip of a ripple-marked sandstone it may be laid upon the surface of the rock and the clinometer placed upon it. In slippery or soft ground or in rock-climbing it may also be very useful, and in tropical countries where snakes are numerous it may be necessary as a weapon. The carrying of a stick is, however, a matter upon which the individual must decide according to his inclinations.

Pencils, hard or soft, will be chosen to suit the material upon which mapping is done, and the climate, whether wet or dry. A few coloured pencils will be found of great use, and they should be carried so that the colour of each can be seen, and any one selected and brought into use with one hand. A good india-rubber is of course essential.

As to the material on which the mapping is to be done, the author, after trying many varieties from tracing linen to Whatman's boards, has come to the conclusion that oiled paper mounted on linen combines the greatest number of advantages with the fewest defects; it does not shrink or stretch appreciably, it is not rendered useless by damp, takes pencil and chalk marks clearly, and keeps a good surface even after much rough usage. It is advisable to have the paper cut accurately to fit the map-case. Thus for the ordinary six-inch map-case the mapping paper should be cut in rectangles of twelve by nine inches.

Some observers favour squared paper for field work, but if it is really to be of use it must be adapted to the scale on which the mapping is done. It must tend also to make field-work too mechanical, and does not teach the field-student to train and depend upon his eye.

A note-book is often useful, but it is not absolutely necessary; all notes of importance *must be put upon the field-map.* Descriptive notes, lists of compass bearings, or fossils collected from various horizons, and small details of mapping or sections shown on a larger scale than that employed on the map can be kept in note-books, but as a rule all these can be put in condensed form on the field-map.

Finally a strong waterproof bag or satchel, capable of holding the map-case during rainstorms, and with an extra pocket for other instruments, is an essential part of the geologist's equipment. Willesden canvas is a very suitable material for such a bag, especially when bound with leather and slung on a strong leather strap for an attendant to carry.

The geologist will do well to carry all the instruments he is constantly using himself. Hammer, Abney's level, and occasionally cutlass and prismatic compass may be carried by one of his attendants, but everything else should be disposed about his person in such a manner that it can be brought into use with the least delay and fumbling. It may be thought that these are trivial details, the neglect of which can be of no possible consequence; but if the field-student has to work in the tropics in a temperature of 100° Fahr. or more in the shade, and 160° or 170° Fahr. in the sun, he will find that even trifling details become of importance, and trifling annoyances may be magnified into trials. To have to wait while a lazy native servant comes up with the instrument required, and slowly unloads a bag in search of it, to have to hunt for a coloured pencil among several concealed in a pocket, when the required one is always the last to appear, and to repeat these performances fifty or a hundred times a day is enough to become a serious worry to the geologist struggling with climatic conditions to which he is not accustomed, and his work may really deteriorate and become less careful through lack of attention to such details. Again, the time occupied in the making of a geological survey is often a matter of great importance. Rival geologists may be in the field, other interests may be represented by other prospectors, and it may depend largely upon the speed with which the main points of a structure are elucidated that the success or failure of the company or syndicate for whom the geologist is acting will turn. Everything, therefore, that favours rapidity in field work, without decreasing efficiency, is to be cultivated.

The equipment above described cannot be called elaborate yet if the young geologist tends to rely too much upon it he may never become a really rapid mapper. It is wonderful what can be done with no equipment at all beyond a pencil and piece of paper. This was forcibly brought home to the writer when taking classes of officers of some of the units of the New Army in mapping, field-sketching and rapid reconnaissance. The eyes in a position of rest take in an arc of approximately 60 degrees, the hand spread out at arm's length before the face subtends an angle at the eye of from eighteen to twenty degrees—the angle varies slightly with each observer. Small angles can be measured by holding the fingers closed at arm's length, or the thumb and finger or thumb alone. The cardinal points can be found by means of a watch and the sun (point the hour hand to the sun, and bisect the angle between the hour hand and the figure XII on the dial; the result is approximately south in the Northern Hemisphere). Turns of a right angle to right or left can easily be made even by an observer without military training. With these methods and a pair of eyes trained in judging distances a remarkably accurate map can be made with astonishing rapidity, and can be checked and corrected by observations from other points of view. Thus, if it should happen that the geologist is without his equipment at any time, and yet requires to put on record some important geological observation requiring a map, knowing his scale he can produce a sketch-map that is sufficiently reliable for all practical purposes. It is an art well worth practising, not only by military men; facility comes very readily with practice even to those who have never attempted such rough-and-ready methods, and the observer gains great confidence from his ability to jot down rapidly on paper the essential features of a landscape or a geological structure.

Armed with the equipment set forth above, the geologist may go anywhere and map any ground in the world, provided—and on this the success or failure on his work depends—that he adapts his methods of survey to the particular variety of ground with which he is dealing. The dense forests of Central or South America cannot be attacked in the same manner as the barren hills and plains of India or Persia.

It is presumed that the aspirant to become a petroleum geologist has had some training in geological mapping on a large scale before he is called upon to attempt the survey of a new territory, and if he has had experience of mapping in Britain on the splendid six-inch maps of the Ordnance Survey, he will start with a great advantage over others who have not been so fortunate. The areas which he will have to survey in new countries where the oilfields of the future are waiting for development, have in all probability never been mapped topographically, and he will have to start with blank paper and construct his own map. In such cases everything will depend upon the methods by which the survey is conducted.

Survey in Open Ground.—If the ground be open and largely bare of vegetation, the matter is fairly simple. A base-line, or still better, two-base lines meeting at an angle, must be measured and marked clearly on low and, if possible, level ground, where their extremities can be viewed from the surrounding country. Triangulation by prismatic compass from and to the extremities of these base-lines will give a sufficient number of points to form a skeleton upon which to construct a geological map. Of course such a method is not, and cannot be, entirely accurate, as the readings of compass bearings with a hand prismatic compass cannot be vouched for within less than 30′, but a map can easily be constructed by means of numerous readings and check readings that will be quite accurate enough to ensure that no error in geological structure is possible. Should the area prove eventually to be a productive field, careful land-surveying will have to be undertaken sooner or later, and topographical maps accurate in all details constructed, but that is not a matter for the geologist.

The length of the original base-lines will depend upon the size of the area to be mapped, and the nature of the ground; a quarter of a mile will usually be sufficient. The distance must be measured carefully by chaining, or, if such instruments be available, by means of a tacheometer or omnimeter. An alluvial plain, if the area contains such, is naturally the best place for such measurements. The angle between two base-lines must be read very carefully by means of an omnimeter or by prismatic compass. The positions of prominent features, hilltops, isolated rocks, or trees, conspicuous bends in the course of streams, etc., in the immediate neighbourhood are determined by taking bearings from the extremities of the base-lines, and thus a series of points is obtained from which secondary points of importance can be fixed upon and marked on the map. As many check readings as possible should be taken in determining new points, and where discrepancies occur, and the triangle of error is large, the readings which are most nearly at right angles to each other must be taken as the most reliable. The top of the paper upon which the mapping is done should always be taken as true north, and the magnetic variation allowed for in plotting the results of the observations made: if the variation be to the eastward, it is added to the readings of the prismatic compass, and if to the westward, subtracted. Many square miles can be mapped by this method, beginning with base-lines of not more than a quarter of a mile in length, and the resulting map should be sufficiently accurate to make the working out of geological structure, and the location of wells to test the area matters of practical certainty.

Topographical details, except in the case of important cliff or river sections which must be mapped carefully, can be sketched in as the geological work proceeds, and must be regarded as of secondary importance to the purely geological mapping.

Excellent work is often done in open and hilly country by the use of a plane-table, the maps being roughly contoured at the same time. In the hilly ground in Persia very valuable work has been done by this method, and when this is combined with the following out and mapping of individual beds the resulting map leaves little to be desired. The method, however, is not rapid, and if it be followed by the geologist there is always the danger that details of stratigraphy and lateral variation may be overlooked through too great attention being paid to topography. The ideal method in such country, though unfortunately this is not always possible, is for a surveyor to make the skeleton topograpical map, and the geologist to follow him filling in the purely geological details.

Once the skeleton of the map is prepared, the mapping in fairly open ground will not be a matter of difficulty, as there will always be some point visible from which bearings can be taken. The principal section across the general strike of the strata, preferably a cliff, river, or road-section, will be mapped in detail in order that the natural subdivisions into which the strata range themselves may be ascertained, and prominent groups of beds differentiated and selected for following out through the area. Upon the selection of such groups a great deal depends, especially where variations are frequent and rapid; unless such main divisions of the geological series can be determined, the construction of an efficient geological map is impossible. To cover an area with innumerable observations of dip and strike, however carefully taken and noted on the map, is not geological mapping in any sense of the word, and may be a mere waste of time since both strike and dip faults, unconformabilities and lateral variations may never be detected by such an amateur method, and even pitches and dome structures may not be recognized if the ground be rough and much cut up by valleys.

Frequently the strata group themselves naturally, and the geological boundary lines to be followed are obvious, but in very many cases the geological series consists of rapid alternations of two or three types of strata repeated over and over again, and it becomes necessary to select a few well-marked beds neither too near nor too far from each other and to map their outcrops as far as possible. It may be necessary to map the outcrops of many beds before one is discovered that persists and maintains its characteristics over a sufficient area; a prominent sandstone or limestone bed may thin, split up, and die out, and it may be necessary to cross to a lower or higher horizon and carry on the mapping of another band, which though not so conspicuous where first observed, extends further and remains recognizable over a greater area than the bed first selected. It is better to map a thick bed or small group of beds than a thin bed, on account of the rapid changes due to lateral variation.

Where dips are steep it is not necessary to map separately horizons near to each other, as the structures will be made clear by the tracing of horizons from 500 to 1000 feet apart, but in areas where the strata are gently inclined and outcrops consequently become complicated and irregular, horizons separated by no more than 150 to 200 feet should be mapped. In an area with low dips towards the centre, and steep dips towards the margins, thin groups will be mapped in the central part, and the groups differentiated may be thicker and thicker in the outermost portions.

It is not sufficient to map a number of sections across the strike and join up the outcrops of the groups as observed, unless the ground is sufficiently bare to allow the outcrops to be seen all the way between each dip section. The selected beds or groups *must be followed and mapped* to detect any faults, changes of dip or strike, unconformabilities, or lateral variations. This method is, of course, somewhat more arduous, and takes up more time than sketching outcrops between the mapped sections in which the various groups have been identified, but it gives absolutely certain and indubitable results and brings out evidence which might be missed by making use of any less careful method. Coloured pencils will be found most useful in distinguishing the horizons followed on the field maps; in the finished map the areas between mapped horizons form the separate groups, which will be differentiated by well-contrasted colours to bring out the structure so that it can be understood at a glance. It is then of very little moment whether or no the various groups are of the same types of sediment or not, so long as they are separated by mapped horizons and are distinctly coloured.

In open and bare ground as in Egypt, Persia, Baluchistan, and parts of India and Burma, there is seldom much difficulty in selecting groups for mapping and differentiation, but when vegetation is thick or the ground obscure the geologist may have considerable trouble in subdividing the part of the series that he is dealing with into such groups as will by their outcrops bring out the geological structure most clearly; it is in easy and open ground that the experience is gained that will enable the field student to deal effectively with more obscure areas.

Eye Training.—One point is of the greatest importance to the young geologist who is undertaking the survey of new territory. He must train his eyes and learn to be as much as possible independent of his instruments. In bare and open ground, where one's position can always be ascertained accurately by taking cross-bearings upon known points, the tendency is naturally to rely upon such observations, with the result that when one is suddenly confronted with a densely-forested area, one may despair of ever making an accurate geological map of it, and may content oneself with the observation of a few dips and outcrops, the result being that a geologist of better training has eventually to go over the ground independently and do it all over again.

To begin with, the geologist must learn the scale upon which he is mapping, that is to say, he must become so familiar with it that he can judge a distance as seen on the ground before him and mark that distance upon his map, *without pausing to consider how many yards or feet it is.* To pace or chain a distance and then measure if off on the map by means of a protractor is no doubt often very useful, but there is no reason why the geologist should not train his eye by estimating the distance before he measures it; to be able to map any distance up to three hundred yards or a quarter of a mile without making any measurement is a very valuable asset to the field geologist. It is doubtful whether any one is so favoured by nature as to have a special gift for the estimation of distances, but the faculty can easily be acquired by constant practice, and distances up to half a mile have been mapped in the author's experience with errors of not more than thirty feet. It is better, however, not to attempt to map distances of more than a quarter of a mile without some checking observations. It must be remembered always that estimates of distance are apt to vary greatly according to the light. The length of a coast-section with the tropical sun beating upon it is liable to be underestimated, while the length of a shaded road-section overhung by trees or a distance in jungly ground may easily be overestimated. Consequently the field student should be constantly practising the transference of a distance as seen to his map under every condition of light or shade, afterwards pacing or chaining it and correcting any error he has made.

"Judging distance" is taught regularly in infantry training, and is of the greatest value to military men, but it is not as a rule practised sufficiently and under sufficiently varied conditions. The percentage of error allowed is five.

During the war, while the writer was acting as instructor in map-reading, rapid reconnaissance, field-mapping and sketching to the officers of a brigade of the New Army, he was astonished at two things, the almost complete lack of eye-training of the ordinary well-educated and athletic young Briton, and the wonderful rapidity with which his eyes could be trained. Guesses at distances, heights, angles and slopes were at first ludicrously inaccurate, but after a few days' practice a marvellous improvement almost invariably became apparent, and towards the end of a fortnight's course pocket-compass traverses of three miles or more over difficult country were executed sometimes with remarkable accuracy by men who had never attempted such work before.

During the sketching of panoramic views, a very useful and often necessary piece of work both for soldier and geologist, the judging of distances up to as much as three miles was attempted, and the results convinced the writer that it is quite possible to gauge long distances with fair accuracy. Errors of only fifty or one hundred yards in distances of two thousand to three thousand were perhaps the lowest recorded, and this measure of accuracy may not appear to be remarkable, but in the pioneer geological survey on a small scale—say one-quarter inch to the mile—of an unexplored country if all similar distances could be judged with a similar approximation to accuracy the geologist's task would be greatly simplified. It is not suggested that the geologist should rely upon his eye alone at such distances, but there is no harm in attempting and practising such difficult feats: it will give the observer greater confidence when judging shorter distances.

The next point in the training of the eye is learning to transfer observed angles to the map without the aid of a protractor, and with a very small margin of error, so that when bearings are taken with the pocket compass the observed angle can be sketched at once. This faculty can be acquired very quickly with a little practice; angles of 45 degrees 30 degrees, and 60 degrees are, of course, very easily drawn, and the eye soon becomes efficient in estimating smaller, greater, or intermediate angles quickly. The error should not be more than 2 degrees, and provided that bearings are not taken from points more than a quarter of a mile distant, the map will not suffer in accuracy. When bearings are taken by prismatic compass the protractor must always be used and the angle laid off as carefully as possible, but in all ordinary field mapping with a compass by means of which the observer can read a bearing within 2 degrees, and with an eye practised in the estimation of angles on the map to within 2 degrees, mapping can be done at a rapid rate, and with wonderful accuracy, provided that each observation only includes a short distance.

The estimation of dips, heights, depths and angles seen in perspective is more difficult, but is equally important. It is not always possible to reach an inclined bed to measure its dip with the clinometer, and even to get a view of it along the strike may be impossible in some cases. To measure the thickness of strata in a cliff-section may entail almost impossible feats of daring. In such cases, therefore, estimates must be made and this more advanced form of eye-training must be practised, as the view of the strata may be at any angle, from above or from below.

The field student will probably find, to begin with, that he overestimates heights, depths and dips. This is due to the fact that the human eye exaggerates vertical distances as compared with horizontal. Every fisherman knows, or ought to know, that in showing his catch to his friends it is better to hold the fish vertically; it will look bigger than if laid horizontally. Bringing the head to the horizontal position and looking at a height again will help to check the first estimate made with the head in the normal position. This applies to depths, dips and angles also, and till the eyes are thoroughly trained it is always as well to take two or more points of view if possible and two positions of the head, vertical and horizontal, before deciding on what the final estimate is to be.

Having cultivated the faculty of estimating angles and distances with fair accuracy, the geologist will be able to make traverses with pocket compass, starting from a known point and if possible finishing also at a known point. Such work, it may be objected, can never be entirely accurate, but it must be remembered that it is absolute certainty as to the geological structure that is to be aimed at rather than meticulous attention to details of topography. A traverse by means of pocket compass of a mile or a mile and a half in length should not terminate with an error of more than forty or fifty yards. Bearings should be taken when possible by prismatic compass at distances of not more than half a mile; this will prevent any error from being made. If, however, no check readings are possible till the end of the traverse, there will nearly always be an error to correct. This should not be done at once, but a "correction mark" put upon the field-map (Fig. 16), and a new start made from the correct position as determined by compass bearings. Afterwards, when the maps are being inked in, *which should be done every day*, the error can be corrected. If the traverse has been very faulty, it will

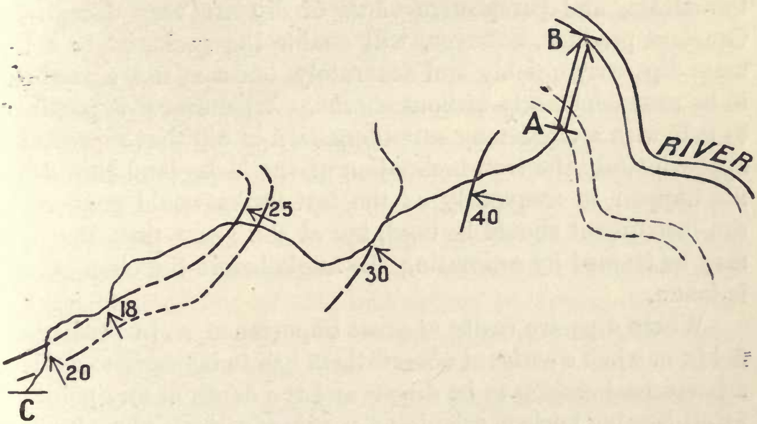


Fig. 16.—Sketch-mapping in the field. C. Start of traverse; A. Finish of traverse; B. Point actually reached. ⇛ Correction mark. Traverse starts again from B.

do no harm to make a second traverse, starting from the other end; it is better to learn thoroughly the scale on which one is mapping than to depend entirely on one's instruments. It is not recommended that pocket-compass traverses should be carried to a distance greater than three miles, and the beginner may find even that distance too long. In fairly open ground it will never be necessary to traverse any such distance without being able to check one's position by taking bearings from some point fixed by triangulation, but in forest land a traverse without check of three miles or more may frequently be necessary. It is in bare or comparatively open ground that the field-student must teach himself to map with that accuracy which will be his only support when he has to deal with dense jungle, where no check readings are possible, and where the man who depends on his instruments rather than on his eyes may feel quite unable to construct a geological map.

Another, but less important, faculty that should be cultivated is the estimation of the dip of strata without making any observation of it with a clinometer. This is a more difficult matter than the estimation of distance. When it is possible to look at a bed along the strike the matter is simple, and every geologist should be able to read the angle within 2 degrees, but it is often impossible to get such a view of the strata, and perspective views of dip are very deceptive. Constant practice, however, will enable the geologist to estimate dips very quickly and accurately, but it is not a method to be used constantly without checks. Whenever it is possible to take with a clinometer an observation of dip that represents approximately the true inclination of the beds—and this does not happen so frequently as the text-books would suggest—the instrument should be used, but at the same time the eye may be trained by estimating the angle before the observation is taken.

Where dips are really of great importance, as in producing fields, or when a series of observations has to be made to enable a horizontal section to be drawn and the depth at any point to an oil-bearing horizon calculated, readings with an Abney's level or some similar instrument up or down dip slopes are by far the most reliable method. Strange as it may seem, it is in this simple operation of observing a dip, probably the first thing in field work that the budding geologist learns, that most mistakes are made, and mistakes that may have very serious results. The tendency is *always* (and this applies to the experienced geologist as well as to the beginner) to exaggerate the angle of dip. Where bedding planes are not well bared or exposed, it is almost invariably the one dipping most steeply that is selected as offering the best surface, and unless a number of observations in the immediate neighbourhood be taken and averaged, the general inclination of the strata will be put at too high a figure in degrees.

Again, and this is especially true of Tertiary deltaic and littoral deposits, the dip of bedding planes may be at a very different angle from the general inclination of the series. Even where no false bedding can be detected, the strata probably have not been deposited in a horizontal position. Theoretically, in fact, deltaic deposits are not deposited horizontally, and amidst the rapidly varying and quickly accumulated deposits of a Tertiary delta, where much of the petroleum geologist's work will be done, it is by no means easy to make sure of the average inclination. Where folding is well marked, dips may change every few yards, and not by regular gradations, but often suddenly, so that quite apart from irregularities of original bedding the determination of the true dip at any point may be a very difficult matter. The only method in such cases is to make many observations on all sides, if there be sufficient evidence, and to take an average both as regards strike and dip, always remembering that the minimum inclination observed is more likely to be correct than the maximum. Strike is in any case more important than dip, and it is always as well to mark the strike of a bed, even when it is impossible to ascertain its true dip. It is because dips have to be averaged, and because it is inadvisable to give too much weight to a few isolated observations of the inclination of strata, that the method of estimating dips by the eye alone is frequently sufficient for all practical purposes.

In recording on the map an observation of dip, the point of the arrow should be marked as nearly as possible on the spot where the observation was taken.

Surveying in Jungles or Forest Land.—Lack of evidence is always the greatest difficulty in the way of making an intelligible and accurate map, and it is in the making of an intelligible and accurate map where evidence is meagre, that the experienced geological surveyor proves his ability. Any one can map strata that he can see exposed, but where exposures are few, or perhaps entirely wanting over miles of country, new methods have to be devised, new kinds of evidence have to be studied, and nothing may be too small and insignificant to give some hint as to the strike or dip of concealed strata. Unless evidence be studied minutely in more or less open ground—such matters, for instance, as the colour and texture of soils, the vegetation that grows on different varieties of deposit, clay, sandstone, limestone, as the case may be, outcrops of water or petroleum—the key to the structure of obscure or wooded country may be lost.

One frequently sees it stated that there are "indications of petroleum" in a certain district, but that "it is impossible to ascertain the geological structure, as the ground is too densely clothed with vegetation." In other words, the geologist has been unable either from want of time, want of sufficient care, or the lack of reliable methods of surveying, to determine the geological structure. With the single exception of alluvial flats so vast in extent that the particular area, the geological structure of which is in question, is too far from any of the margins where reliable evidence can be obtained, there is no part of the world's land surface where such an impossibility exists. An ice-sheet may be considered as an exception to this, but it is hardly to be regarded as a land surface.

Alluvium acts as a sponge, wiping out all direct evidence, though where belts of alluvium are not very large, their very presence may furnish valuable negative evidence; but no other covering, whether of glacial drift, blown sand, peat, vegetation, or coral terrace, is sufficient to prevent some details of geological structure being found somewhere. It is with the dense vegetation difficulty that the petroleum geologist has to deal in many parts of the world. Tropical forests, such as those of South and Central America, or the bamboo jungles of India, are perhaps the most disheartening areas in which to attempt geological mapping, but it can be done; geological structure can be elucidated, and maps, not in great detail or of great accuracy, but at least reliable, can be made even under such conditions. The secret, if secret it can be called, is simply the adapting of one's methods to the particular work that is in hand. A completely accurate map is perhaps an impossibility without great expenditure of time and money in trace-cutting and land surveying, for which the geologist may not be able to spare the time, nor in all probability will he have the necessary instruments, but a sketch-map of sufficient accuracy can be pieced together by careful, if at times laborious, work, just as a sketch-map may be made anywhere without triangulation. It is here that the observer who has thoroughly mastered his scale and can map accurately on pocket-compass traverses, has the advantage over those who are, so to speak, tied to their instruments.

If there be any road or coast section crossing or skirting the area to be surveyed it must be examined and mapped in detail first, copious notes being taken of the characteristics of each bed, such as the presence of pebbles or nodules and their natures. In a road, even where there is no section in side cuttings, it is possible to glean a fair amount of information. For instance, those parts underlaid by clay can always be distinguished from parts where the underlying beds are arenaceous, and a sharp and distinct line between thick masses of arenaceous and argillaceous sediments can often be drawn where no actual exposure is seen.

Then the forest or jungle must be attacked as far as possible in the same manner as in the case of more open ground. It is presumed that there is no topographical map available, that no hills, from the summit of which compass bearings can be taken, are to be seen, and that the courses of such streams and rivers as flow through the area are unknown. A coast, road, or river section may give the key to the structure at once, but should no such section be available, or should it be discontinuous or obscure, it can only serve as a base-line on which starting points for traverses may be selected.

To begin with, if any group of hard or massive beds be present, the geologist should endeavour to follow it along the strike, noting the types of vegetation it supports, the colour and texture of the soil it forms, and whether under the weathering processes peculiar to forest land it is capable of standing out as a marked feature. In all thickly forested country there must be a fairly heavy rainfall, and consequently denudation of the surface will be fairly rapid in spite of the protection afforded to the soil by the vegetation. An arenaceous group in these circumstances, however soft and loosely compacted the strata may be, will always tend to form hills and high ground as contrasted with argillaceous strata. Much of the rainfall is absorbed by the porous arenaceous rocks to be thrown out as springs at the foot of dip-slope or escarpment, whereas an argillaceous outcrop absorbs little of the rainfall, but causes it to flow over the surface, thus favouring sub-aerial denudation. Consequently the outcrop of an argillaceous group among arenaceous rocks will almost invariably be marked by a valley or belt of low ground, however tough and hard the material may be, and an arenaceous group among clays will stand out as a ridge, however loosely compacted the strata of which it is composed. In bare and open ground where the rainfall is not heavy, the relative porosities of the strata do not have such a marked effect upon the contours of the surface.

The mapping of surface features, therefore, often becomes very important and of the greatest help to the geologist, though it must not be relied upon unless confirmed by other evidence such as the nature of the soil. Where denudation is rapid it may produce a complex system of ridges and valleys that have little or no relation to the strike and dip of the strata; in a thick series of clays in which the physical characters of different bands differ very slightly, an irregular and complicated drainage system quite irrespective of geological structure may be established, and the contours of the country where they can be observed, *e.g.* in areas planted with sugar-cane, may be sufficient to show that the strata are argillaceous before the soil has even been examined.

The angle of dip has also to be considered when features are being mapped; the greater the angle, the more clearly marked will be strike features, and where the strata are practically horizontal, outcrops naturally become very irregular and the following of them in undulating forest land may be simply a waste of time.

Having selected a group of strata that seems likely to form good strike features, and that is dipping at a sufficiently high angle where it is observed in the base-line section on coast-line, road, or river, it should be followed as far as possible along the strike. Exposures may be few or entirely wanting, but by studying the soil and the vegetation it may be possible to follow a group for great distances. The occurrence here and there of loose fragments of a hard rock, *e.g.* a calcareous sandstone, along an ill-defined ridge, may enable an outcrop to be picked up and mapped for miles till a river valley cutting across the strike gives an exposure and allows an observation of dip to be made. Once an horizon has been traced through the area to be examined the following of other horizons becomes a much easier task, and a fairly complete geological map may be constructed from evidence which approached by any other method would throw very little light upon the geological structure.

As a rule it is better not to follow the courses of streams at first, at least not until their general directions are ascertained. If their courses be tortuous the mapping will be very tedious, and perhaps will result in the discovery of little evidence, while alluvial flats may be encountered to the discouragement of the observer. Where steep dips give evidence of flexuring on a considerable scale, however, the courses of streams or rivers can usually be resolved into "consequent" portions, *i.e.* across the strike, and "subsequent" portions, *i.e.* along the strike; and even where no exposures are to be seen, the evidence from the directions of drainage taken in connection with the orientation of ridges and hollows may give valuable evidence as to the strike of the series.

In following up outcrops or traversing across the strike, the geologist must map by "dead reckoning" with his pocket compass, using his map case every fifty yards or so to mark his track. Where the jungle is thick and has to be cutlassed to allow passage, if two men be kept in front of the observer at intervals of from 10 to 20 yards the mapping of track can be simplified by omitting many of the minor turns and twists inevitable when marching in forest land. It is not recommended that traverses of more than one mile be made at first, while three miles is as far as any one is likely to be able to traverse by dead reckoning with any degree of accuracy; the writer has found that a traverse by pocket compass of four or five miles in forest land is inadvisable unless it is to a known point, or to a point the position of which can be ascertained by taking compass bearings.

The time required for simple mapping of the route taken, without study of geological data, will vary greatly according to the nature of the ground. Where there is not much cutlassing to be done and slopes are not too precipitous, one mile an hour is a fair average pace. In difficult country and where many observations have to be made the pace may be much slower.

Checking a traverse can only be done by making it a "closed traverse," coming out to some point along a road, river, or coast-line where the position can be found, or by making another traverse from a different starting point to the same final point.

In any case where the geologist fails to keep his track mapped and does not know his position, he should map on a new sheet of paper or in a note-book, and either begin a fresh traverse from his unknown position to reach some point which he can fix or recognize, or take a compass direction and keep it as straight as he can out to road, river, or coast-line. It is always better, however, to follow an outcrop, if one can be recognized and followed, than to map across bedding.

It may seem that these methods are very rough and uncertain, and there is no doubt that the geologist when he first undertakes work in tropical forest will make many faulty traverses before he becomes master of the scale on which he is working and capable of traversing forest up and down hill, in and out of creeks and gullies while keeping his dead reckoning with accuracy, but there is no other method that will yield results so quickly, and at the same time develop confidence in the observer. To map with theodolite or plane-table in the forest, cutting traces and chaining distances is far too cumbrous and slow a method, and can only be justified when the area to be examined is very small or when the exact position for a test is being determined.

In jungle work where evidence is very scanty the geologist must be continually on the alert: nothing is too insignificant to be noted. Every change in the colour of the soil, every ridge that does not run parallel to the drainage channels, every occurrence of loose pebbles or nodules should be noted and the note marked clearly on the map. Similarly changes in the nature of the vegetation, if they are sudden, should be mapped. An exposed section may make clear the reason for such a change, and a very valuable piece of evidence may be added to the geologist's store of accumulated data. In Trinidad the Cretaceous formation, which lies unconformably beneath the petroliferous Tertiary Series, has frequently been recognized by the colour of the soil and the nature of the vegetation, when no exposures of the strata were to be seen. When exposed the strata are often very similiar to some of the Tertiary deposits, but the soil formed by the disintegration possesses some pecularities which distinguish it from that formed from any of the Tertiary strata. Much of the Cretaceous formation has been prospected for petroleum by observers who have not learnt to distinguish it from the overlying Tertiary rock.

In clay ground the different tints induced by weathering processes have often proved of the greatest value, and have enabled different bands to be mapped with accuracy. The black soils of a marl outcrop contrast so strikingly with the red or yellow soils derived from a clay that there need be no hesitation in mapping them separately. Again, "outcrops of water," surface springs, or damp ground marked by the occurrence of water-loving plants and trees, often enable the observer to draw a boundary-line which will be found later to coincide with the outcrop of a porous stratum.

Excavations.—The making of excavations to ascertain the nature, dip and strike of strata is sometimes, but very rarely, necessary. False evidence obtained by this method has often to the writer's knowledge led observers to make very serious and sometimes even ludicrous mistakes in their interpretation of geological structure. It must be remembered that in forest land, especially in tropical countries, disintegration of the strata extends for a great distance from the surface, often upwards of thirty feet, and in hilly ground surface-slip in partially disintegrated rock causes an astonishing amount of modification in the position of bedding planes. Root growth also disturbs the strata for a considerable distance. The result is that it is very difficult to select a spot for digging a trench where really reliable evidence will be obtained without excavating to a great depth. Small pits and trenches are liable to be dug into displaced or disintegrated beds, and it will readily be understood what confusion may arise through accepting the false evidence obtained by this method. It is only natural that the observer, having been at the expense and trouble of having a few excavations made, should attach more importance to the evidence obtained from them than to the possibly more obscure, but certainly more reliable, evidence that he has obtained by mapping outcrops or by the examination of natural exposures. And thus he may acquire an entirely incorrect idea of the geological structure.

There is something to be said for the digging of a few pits or trenches when it is done in connexion with the mapping of outcrops, but to depend on excavation alone to obtain evidence is to court disaster. In mapping some 500 square miles in the island of Trinidad the author only made use of specially dug trenches some half-dozen times, and then it was to settle some detail rather than for general purposes of mapping. Some cuttings on roads in that Colony are sufficient to prove what startling changes in strike and dip, and even inversions, in the soft Tertiary strata are due to surface dip.

If it becomes necessary to make an excavation, it is important to select a spot where evidence should be obtained without digging deep, and where such evidence is likely to prove reliable. The bottoms of valleys are naturally to be avoided

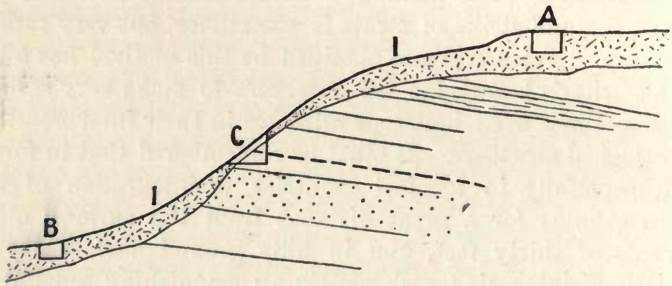


Fig. 17.—Excavation for dip evidence. 1. Disintegrated strata or surface wash.

and also the tops of hills, hillocks, or plateaux; in the first case there will probably be a great accumulation of surface wash (Fig. 17), while on the tops of hills there may be a great thickness of completely disintegrated rock. At the top of a sharp ridge or hillock, or just beneath its summit (Fig. 18), surface curvature may vitiate the accuracy of the observation although the strata may be obviously *in situ*, and at the bottom of such a ridge water may collect so rapidly as to hinder the digging. Halfway down a steep slope, especially if the slope is at a high angle to the probable line of strike, gives the best chance of a reliable exposure, while the work of making the excavation will be easier, and the trench or pit can be kept drained and the exposed rock allowed to weather if the bedding is not apparent at once. In many varieties of Tertiary strata it is easier to detect the bedding planes after a certain amount of weathering has taken place, so that the keeping of an excavation free from water is a distinct advantage. But even with such a favourable spot selected, false evidence may be obtained if the strata be largely argillaceous. It is among the alternations of arenaceous and argillaceous beds, and where bands of

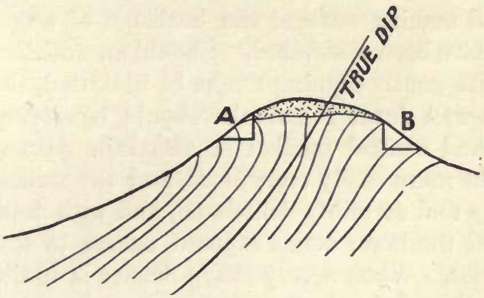


FIG. 18.—Surface curvature, giving false dips at top of ridge.

hard rock or nodular concretionary bands are present that the best results are obtained from excavations.

When flexuring has been intense, small minor folds or wrinkles may be occasionally present in a monocline far from any important anticlinal bend. This may lead to an incorrect reading of the geological structure if the observer relies upon excavations for his evidence. Fig. 19 shows a case that has

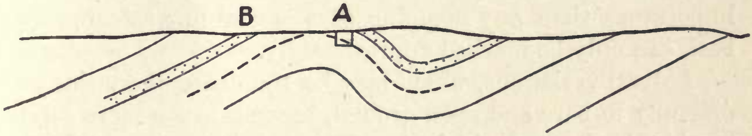


FIG. 19.—Obscure ground local flexure giving a false idea of general structure.

actually come under the writer's observation. The ground was low-lying and evidence was very scanty; only at the points A and B could evidence of dip be obtained. The minor pucker disclosed by making an excavation was taken as being the crest of a great anticline, and as the strata on both sides were entirely argillaceous, and gave no evidence at all that could be considered reliable, the error survived for a long time, till field work in neighbouring districts proved the structure to be entirely different. But for this one unfortunate excavation no mistake would have been made.

In all field work in forest ground, as soon as the general structure has been ascertained, the more detailed mapping of stream sections should be undertaken with a view to getting as accurate an estimate as possible of the thickness of strata exposed, and making sure of the horizons of any oil-bearing strata that have been discovered. Should an anticlinal or dome structure with gently dipping flanks be indicated, the following of outcrops well down the flanks should be attempted before the inner and central portion is attacked. By this means faults will be more easily recognized and the structure will be more clearly and certainly delineated, and with less chance of error than if the lower zones exposed nearer to the crest are examined first. When a very sharp flexure is indicated it will be best to follow and map the crest first, as by this means any pitches of the flexure that may be present should be detected and the relation of surface indications to the crest will be made clear. Afterwards, prominent beds on either flank can be selected and their outcrops traced, and if possible correlated on the two sides. When anticlines are sharp, it is obvious that the position of the crest is the most important matter, and its trend must be mapped as carefully as possible, while where dips are gentle and flexures broad and comparatively speaking flat, the general form, asymmetry or pitches are of much more importance than any mapping of a crestal line, which, at the best, can only be marked approximately.

Lateral variations, which may be the cause of considerable difficulty in bare and open ground, become much more serious troubles to the geologist in heavily wooded country, but if the area be examined systematically, a general idea at least of such variations should be obtained. Correlations cannot always be established with certainty, and the field student must not expect to be able to correlate the two sides of any anticline in detail. The subdivision of the series into groups may even be impossible in some cases, except locally, but the attempt to subdivide should always be made; the construction of a new road through the forest may eventually furnish excellent evidence in side cuttings, and may enable a correlation that has been commenced to be carried to completion and settled beyond doubt. The mapping of any bed locally, even if it cannot be carried far, is always advisable, but the extension of dotted lines, indicating uncertainty as to an outcrop, between the points where the mapping of outcrops has terminated, when it has not been proved that the outcrops represent the same horizon, is to be deprecated.

Generalizations on insufficient evidence are above all things to be avoided; it is better to leave points with regard to correlation unsettled, and to say so definitely when reporting, than to force evidence to support a conclusion, however brilliant, which is not absolutely certain. In cases where there is some doubt as to the meaning of such evidence as has been collected, a doubt that leaves the geological structure a matter of uncertainty, a process of elimination should be employed, and every structure possible in the particular circumstances tried and tested both by map and section. It will always be possible to reduce probable explanations to two or three, and the ground must not be quitted till sufficient evidence has been obtained to enable the geologist to decide as to which explanation is the true one. From the map, whether completed or only half finished, the various possible explanations can be deduced, but it may be necessary to return again and again to certain parts of the area to settle points which will tilt the balance towards one or other of two alternative readings of the geological structure. No mistake in structure is allowable, and none should be possible if reliable methods be employed in the survey.

Ratio of Boundary to Area.—In all mapping, whatever be the nature of the ground, it is from the number of miles of geological lines drawn that we get the clearest idea of the efficiency of the geological survey. The area of land surveyed in a given time is no test of the ability of the geologist, but the ratio of linear miles of geological boundary-lines drawn to the square mile of area mapped shows at a glance whether evidence has been scanty or not, and is the most certain criterion of the care with which the mapping has been done. This ratio may vary from fifty or sixty miles of boundary to one square mile of area, in very complicated and well-exposed country, to perhaps two to one in obscure and wooded ground. In the simple geological work of a Tertiary oilfield the ratio will seldom rise above 7 to 1. From 400 to 500 miles of geological lines represents a good year's work for any geologist, allowing time for the necessary indoor work, and it will be found that this will hold good in any country and in any kind of ground, bare or forest-grown.

To sum up, in ground thickly clothed with vegetation the geologist must often be content with a map by no means complete or accurate. Mistakes in accuracy will doubtless be made in the mapping and need never be worried over, so long as no error is made with regard to structure. Should active development work follow the geological prospecting of an area, details of mapping can always be corrected as the ground is opened up and new sections on roads and in excavations on sites for tanks and buildings are laid bare. The map can always be added to and improved in details, but if the structure be incorrectly delineated, the responsibility for the opening up of a field expensive to work and incapable of yielding results of commercial importance may lie at the door of the geologist. Thus, it is not till there is no doubt whatever about the geological structure that the geologist has any right to speak favourably or unfavourably of any new field: by advocating development work without knowing what is to be tested by the drill, or why, the geologist will class himself with the wild-cat drillers of a former generation or the company-promoting experts from whom the commercial world and the unfortunate public have suffered only too severely and too long.

It is naturally in thickly wooded country, where at the best little can be known till development work has begun, that the greatest probability of ill-advised speculation is afforded, and consequently the more obscure the geological structure and features, the more cautious the geologist must be in making up his mind on the problems before him, and the more certain must he be of the main facts before he dare venture upon writing a report.

To visit a few oil-shows, to dig a few pits in search of evidence, and to make a few observations of strike and dip may suffice for some experts, but no one whose ambition is to take rank as a geologist can afford to advise a commercial company upon the results of what are merely preliminary observations. If the area be tested and failure attend the attempts to strike oil, to shelter oneself behind the alleged capricious nature of that liquid is merely to call attention to the uncertainty of one's own field work, and the unreliability of one's own mental processes.

CHAPTER XIII

(For Beginners)

INDOOR WORK

Though it is in the field that the real work of the geologist is done, systematic and careful indoor work must follow if the full fruits of his toil are to be garnered. In the last chapter the author has endeavoured to explain the methods that he has found most effective in field-work under different conditions; it remains to indicate the lines upon which the necessary indoor work can be conducted with the greatest facility, in the hope that the field student may find in them some hints that will prove useful to him in the more irksome but no less important portion of his task.

When the field work in any district has been completed there must be a gathering together and correlation of facts, a reviewing of evidence, and a preparation of finished maps and sections, all of which can be done much more effectively in some office or headquarters, where there are greater facilities and better appliances for indoor work than the geologist will be able to carry with him in the field, however elaborate his equipment.

As a rule it will be found that two months of actual field work, during which an area of from twenty to fifty square miles, according to the nature of the ground, should have been mapped, will necessitate three weeks of indoor work. The author has found that this proportion of indoor work to field work holds good both in bare ground, where twenty or thirty linear miles of geological lines are mapped in a square mile of area, and in obscure or densely forested land where the ratio of boundary to area is 2 or 3 to 1.

Preparation of Map.—The first thing to be done is to prepare the finished map of the area on the scale upon which the field work has been undertaken. This, if there are many corrections to be made for errors in traverses by dead reckoning, will be a matter requiring considerable care, and it may be necessary in order to fit the traverses together with accuracy to make a rough copy of the map first. If the area proves to be of little importance, or if the evidence collected is insufficient to make a large-scale map, a reduction to the one-inch scale may be expedient. In all preliminary work a map on the scale of one inch to the mile is generally quite sufficient to give a clear idea of the structure and the prospects of obtaining a production of oil. Again, where a large area has been prospected on the one-inch scale in search of localities worthy of more careful examination, the smaller scale is quite sufficient. But if the area is to be exploited and active development work is to follow the geological examination, a large-scale map is necessary, even though it may not be possible to put much evidence upon it as the result of the first geological survey.

In the finished map it may be necessary to omit much detail that has occupied a considerable time in mapping. To introduce detailed work where it is not essential will have the effect of confusing those who, having little technical knowledge of geology, may yet have to study the map and master its significance. The map should be as simple and clear as possible. The strata should be grouped and coloured distinctively, so that every essential point in the geological structure is brought out. "Colour without line" is not allowable; that is to say, every group distinguished by a separate colour must have a clearly defined boundary up to which the colour is brought. Mapped lines of outcrops without special colour may be introduced locally in the midst of any group if any object is to be gained thereby, such as showing sudden changes of dip or explaining the broadening or narrowing of outcrops owing to the contours of the surface. Similarly it may be expedient to map a fossiliferous horizon in some group, without colouring it specially. When dips are gentle the groups of strata coloured must be comparatively thin, but in an area where the rocks are highly inclined it is not necessary to colour specially more than three or four groups, and they ma be of considerable thickness.

Dip arrows and the conventional geological symbols should not be distributed too thickly about the map. There must be enough to make the structure clear to any one without an intimate acquaintance with geological work, and any line of section to which special reference is to be made should have a large number of dips noted, but the map must not be overloaded with such symbols. It will be found advisable to use some characteristic and prominent symbol for surface indications of petroleum, and if the map be on a sufficiently large scale the words "gas," "oil-seepage," "asphalt," "manjak," or "ozokerite," as the case may be, can be written or printed beside the symbol. The author has always used a diagonal cross to mark surface indications, making it rather larger and more prominent than the symbols indicating the inclination of strata. A symbol indicating the direction of the pitch of a flexure is often useful.

Every map should be accompanied by a tablet showing the groups of strata with their distinctive colours and their order of deposition, and all symbols used.

True north should be shown on every map, but it is not necessary to indicate magnetic north.

Sections.—When the map has been completed it is often useful and sometimes essential to make one or more horizontal sections through the area. These cannot be made till the map is finished. They are very valuable as giving an idea of the structure to those who are not capable of reading a geological map, though they are not necessary to the experienced geologist.

It is a common mistake of the amateur or the untrained geologist to draw sections through a property or concession without making a geological map at all. Such sections, though interesting as giving evidence of the ideas of their authors as to the geological structure of the area, are generally useless, and are almost invariably misleading. Till the area has been carefully mapped the drawing of horizontal sections with any measure of accuracy is practically impossible.

Horizontal sections should always be drawn on the same scale as the map, and, except in very rare instances for special purposes, the vertical and horizontal scales should be the same; for it is obviously impossible to give the true dip and thickness of strata, or the true hade of the axis of a fold, if the vertical scale be different from the horizontal.

In making a horizontal section the contour of the surface must first be sketched from aneroid readings, topographical surveys, or any other evidence that is available. If there are no ascertained data to go upon, the surface must be sketched by guesswork. Except in very hilly ground errors will have very little effect, as the depths beneath the surface that will have to be considered will probably be very much greater than the irregularities of the surface, and will make the latter appear quite insignificant.

A base-line is then drawn at a sufficient distance below the

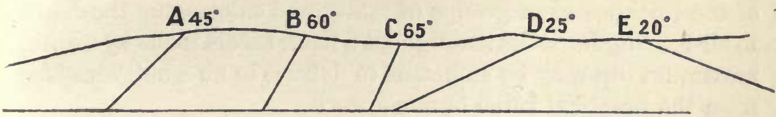


FIG. 20A.—Wrong method in section drawing.

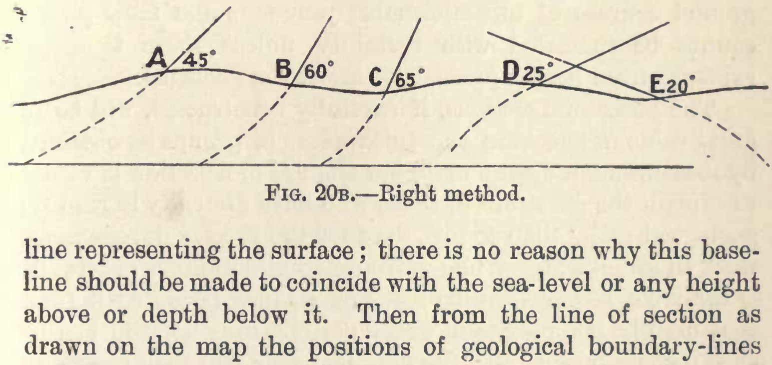


FIG. 20B.—Right method.

line representing the surface; there is no reason why this base-line should be made to coincide with the sea-level or any height above or depth below it. Then from the line of section as drawn on the map the positions of geological boundary-lines and dips of strata as noted are marked on the base-line and projected to meet the line representing the surface of the ground The angles of dip are then drawn *upwards* from the surface and not downwards (Fig. 20). The reason for this is that at the surface where the dips are noted the angles of inclination are only observed for an infinitesimal distance. The first thing that one learns in drawing horizontal sections to scale is that all inclined strata are parts of great curves, and that the dip of no bed continues for any considerable distance downwards without changing. The lines representing the bedding planes are then continued downwards, care being taken to keep the thickness of each group constant, unless variations in thickness have been actually proved to exist. It will be found at once that dips as observed are almost invariably too high to make the drawing of a section an easy matter, and that if there be no faulting and dislocation of the strata the minimum observed dips will have to be accepted. This is to some extent a concession to convention, but, that notwithstanding, it throws a striking light upon the errors into which one may fall by a blind acceptance of the dips observed at the surface as being constant for large distances downwards, and the danger of depending on a few observations of dip for the elucidation of structure. It is obvious that when it comes to the measuring of the thicknesses of groups of strata and calculating the depth to oil-bearing horizons throughout a field, errors made by noting maximum dip may be sufficient to detract in no small measure from the practical value of one's work.

There are naturally many details in a section which must be almost purely imaginary, and such points as the underground courses of unconformable junctions and fault planes cannot be indicated with certainty unless there is direc evidence from boring journals to assist the geologist.

The horizontal sections, if carefully constructed, will be of great value in checking the thicknesses of groups as obtained by measurement on the map, but the use of a section is rather to explain the structure to those who have difficulty in reading geological maps than to give data for the precise development work in an oilfield. When evidence from a number of oilwells is available, sections can be made on a much larger scale than that used in mapping, and every petroliferous horizon can be shown at its true depth; the field-manager will then be able to adapt his methods to the end in view in each well, knowing exactly at what depths water must be shut off and where oil is likely to be struck. In new untested fields such accuracy is unfortunately very seldom possible.

Vertical Section.—After the horizontal section has been completed it is often expedient to construct a vertical section of all the strata exposed in the area, leaving room below for the strata to be proved in the drilling. The vertical section must be drawn to scale, but a much larger scale should be employed than that on which the ground has been mapped. The groups of strata, coloured as on the map and in their relative thicknesses, will be marked clearly in the vertical section, and the horizons of all fossiliferous beds and oil-bearing bands observed will be noted as accurately as possible. It is advisable also to mark the initial horizòns of any wells that have been drilled, or that it is proposed to drill, so that it will at once be apparent what horizons have been or can be tested.

Palæontological Work.—Any fossil evidence that has been collected must then be gone over and compared with previous collections or books of reference in order that any organisms of importance in establishing stratigraphical horizons may be recognized. Where palæontological evidence is abundant as, for instance, in Burma, some such method as that described in Chapter VII. may be made use of, but as a rule a less elaborate system will be quite adequate; it is seldom that fossil evidence becomes of any great importance till a great mass of material has been collected.

Petrographical Work.—It is but rarely that petrographical work is of much value in an oilfield till after it has been at least partially developed, but there are often points that can be settled by the use of a microscope, and that may eventually prove of vital importance. The examination of oilsands may furnish very valuable evidence, as it is often possible to identify different sands by their mineral contents. This is especially important when an unconformability is suspected but has not been proved. Sands that appear very similar may be from formations of different ages, and may contain minerals which enable them to be distinguished at once.

The identification of heavy minerals from the oil-sands or from the strata generally is often a fruitful field of inquiry. In a thick series formed by the denudation of older strata the lithological characters of the rocks may not appear to vary very greatly, but the heavy mineral contents may show a progressive change from the base to the top of the series, and sudden changes are not unknown. From such data the direction from which the sediments have come can often be deduced, and much interesting evidence concerning lateral variation can be collected, while concealed unconformabilities that have not become apparent by mapping may be detected.

The drillings from a well are often worth examining, especially when it is not certain what horizon has been reached or what formation is being pierced: the heavy minerals such as zircon, ilmenite, apatite and ferro-magnesium often give sufficient evidence of horizon or at least enable the strata being drilled to be compared with strata examined at the surface in other areas.

The simplest method of examination is to powder the rock or débris upon a steel plate or in one of the little steel mortars specially made for the purpose, put the powder in a watch-glass and wash it with water and if necessary with dilute acid to remove calcite, and then gently van in water to remove the lighter minerals. The heavy minerals thus roughly separated can be picked up with water in a cannula and dropped on a microscope slide, excess of water removed with blotting paper and the minerals examined under a fairly low power in the film of water that remains. A study of the cleavages, refractive indices and double refraction—if the mineral is not isotropic—will in almost all cases be sufficient to identify any mineral, and after a little practice it is an easy matter to identify all the ordinary minerals that occur in the heavy residues of clays and sands.

Separation by means of one of the heavy liquids is an equally effective method, each mineral being identified by its specific gravity.

In the study of metamorphic and igneous rocks the writer has found these methods very effective, and in sedimentaries, though not so essential, such investigations often lead to important results.

The powdered minerals can be mounted in Canada balsam for comparison with material from other beds and the proportions of the different minerals determined roughly, for though the same minerals may be found throughout a series their relative proportions may alter according to horizon and so give evidence of stratigraphical value. The presence of Kaolin or decomposed felspar may be a point of great importance, as in some parts of Burma, in separating post- from pre-volcanic strata.

The determination of the extent to which a limestone has been dolomitized is another question that may be of vital importance in oilfields where the petroliferous rocks are calcareous.

All these matters can be dealt with by means of a petrographical microscope without the necessity of making any chemical tests, and though that instrument can hardly be regarded as an essential part of the petroleum geologist's equipment, it may be of very great use when other evidence fails and only petrological work can be depended on to solve some difficult problem. There is, in fact, no department of geological work that cannot in certain circumstances be brought to the aid of the geologist who is engaged in the study of oilfields.

Report writing.—With the completion of any palæontological or petrographical work that may have had to be undertaken, the geologist's task is practically over for the time being; it only remains to write a report upon the area examined. It is in the field work and the preparation of map and sections that the real work of the geologist has been accomplished, but by a very natural irony it is the report that will receive the most attention, and the young geologist may be assured that for one man who will study his maps, ten at least will read his reports and interpret them in their own fashion. Chairmen of Companies, Managing Directors, Technical Experts, Company Promoters, and even a small section of the shareholders and the speculative general public all attach value to a report rather than a geological map, and consequently it is essential that great care should be taken in the writing of it. As with most practical geologists, among whom the writer has no further ambition than to be classed, the hammer is mightier than the pen, the writing of the necessary reports may be not only difficult but irksome.

It should be the geologist's endeavour to try how short a report he can write, provided all essential matters are covered, and not how long he can make it.

In the report on a new area, a presumed but untested oilfield, brevity is the first essential. The geologist, if he has sufficient time, should write out his report three times, each time making it shorter by cutting out all that does not seem absolutely necessary. Looked at from this point of view it is wonderful how much "padding" can be detected in even a workman-like and concise report.

Perhaps one of the most fruitful sources of "padding" is in alluding to, discussing, or criticizing previous work done by others in the same area or district. This is very seldom necessary, except in the briefest possible fashion; it is wearisome to the reader, and it is occasionally dangerous. It may flatter the writer's sense of his importance and ability to hold post-mortems upon the work of previous observers, who perhaps have not had equal facilities for the survey or examination, but it serves no really useful purpose and it fills up much space that might be used more effectively. It is, however, fatally easy, and for that reason the inexperienced geologist is very apt to be led away into a very long and unprofitable discussion or criticism. The last report *must* be the best, if the observer be competent, as he begins where his predecessors left off, with many of the essential facts already marshalled for him.

Clearness is no less essential. Technical geological terms should be eschewed as far as possible, as it is probable that of those who read a report few will have more than a smattering of geological knowledge. It is not difficult to explain in simple language all that can be conveyed by sesquipedalian scientific phraseology. Again, it is not enough that the writer is clear in his own mind upon a point; he must set it down so that the reader cannot fail to be clear in *his* mind as to what is meant to be conveyed. This is not such a simple matter as it appears at first sight. In correspondence with reference to a report or the ground with which it deals, the geologist's statements will be paraphrased and unintentionally misquoted, and some day a statement which the writer considered impossible to misconstrue will come back to him distorted out of all recognition and labelled as his opinion. Therefore short, crisp sentences, without conditional clauses, should be the rule.

Graces of style and the neat turning of phrases are to be avoided; it is possible to give a literary flavour to scientific work, as many of the greatest geologists, from Hugh Miller onwards, have taught us, but it is not literature that is required from the field geologist, but facts. If in reading over the draft of a report one comes upon any sentence with which one is particularly pleased, the wisest course is to cut it out at once. Be literal rather than literary.

The point most essential of all is to stick to facts. Opinions *must not be given on any points of importance in the geology* *of the area examined.* It is, of course, impossible to avoid giving an opinion upon such a question as whether an area is sufficiently promising to warrant development work being undertaken or not, but in dealing with questions of structure, lateral variation, thickness of oil-bearing strata, depth to be drilled, etc., no mere opinion will suffice. If the certified facts cannot be given, the geologist must say so clearly. "To the best of my belief," "as far as I could ascertain," "in my opinion," "it seems to me," and the numberless similar phrases should be tabooed. Indeed, the geologist will do well to shun the use of the first personal pronoun as much as possible, and to write his report in the third person. The report will read better and will appeal more forcibly to both scientific and commercial readers if the writer does not intrude his personality, but allows the facts as ascertained by him and set forth in map, section and report to speak for themselves.

The ideal report must be partly descriptive; it must explain the map to those who may not be able to read geological maps. It must call attention to the points of greatest importance in the structure, etc., but it is quite unnecessary to describe and explain the map in detail. Geological structure can be dealt with very briefly: the map and sections should be sufficient with a few sentences of explanation. Enough must be written concerning the methods of mapping employed and the nature of the strata examined to show the care with which the survey has been conducted. The distinguishing characteristics of different groups of strata mapped must be mentioned, but long lithological descriptions are unnecessary.

Evidence of the presence of petroleum should be treated separately and at greater length, for much, and in some cases perhaps undue, importance will be attached to such evidence by those for whom the report is written. It is always necessary to prove as conclusively as possible the petroliferous nature of the series that has been studied geologically, and the conditions under which surface shows of petroleum occur afford very valuable hints to the expert or technical adviser and the field manager.

A comparison of the field with other areas as regards structure, stratigraphy, and surface indications, especially if those other areas are producing fields, may be introduced with advantage in this section of the report in order to give some idea of the significance of the evidence, but any canvassing of the probabilities of proving a valuable field is better kept for the final section.

It is always best to divide a report into clearly defined sections, and to keep each piece of evidence rigidly to its own section. These sections may again be subdivided, and the report should be headed by a page showing the divisions and subdivisions, so that any part can be referred to with the least trouble and delay. A convenient form which the writer has found to meet most cases of new and untested fields, is as follows:—

Report on Concession.

I. Introductory.
II. Formations and strata.
III. Geological Structure.
IV. Oilshows.
V. General Conclusions and Recommendations.

Fig. 1. Map of Concession and surroundings, 6 in. to the mile.
Fig. 2. Horizontal Section . . . . do.
Fig. 3. Vertical Section . . . . 2 in. to 100 feet.

In the first section the position of the property or concession is briefly described, and the nature of the ground, whether low or hilly, forested or bare. The methods of survey employed are explained and the work of any previous observers in the same area must be touched on.

In the second section the various formations exposed in the area are described shortly in their stratigraphical relations. Each group of strata mapped and coloured separately is described and its thickness estimated, and the horizons of oil-bearing strata and fossiliferous beds are given. If fossil evidence be very abundant, it is better not to give it at length in this section, but to state the general conclusions arrived at from palæontological work, and keep a detailed account of it for an appendix to the report.

In Section III. the structure as shown by the map and horizontal section is explained briefly, and the account may be subdivided into evidence of: (1) Flexuring, (2) Faulting, and (3) Unconformabilities, etc., as may be necessary.

A special section upon the indications of petroleum is only necessary when they are extensive and important enough to deserve careful description. If the "oilshows" are few and insignificant this section can be merged in Section II.

In the last section the general conclusions on scientific points must be stated very clearly and briefly: it is often advisable to number them, *e.g.*:—

(1) The strata are of the nature common to many oilfields, and give evidence of containing petroleum at intervals throughout a thickness of 3000 feet.

(2) The geological structure over the greater part of the area is unfavourable to a production of petroleum, but in the north-west corner of the concession is very favourable.

(3) The area of favourable structure is approximately acres, etc., etc.

Though the scientific reader will doubtless give full attention to the whole report, it is the last section, the "conclusions and recommendations," that will be studied most closely, and that will be quoted and canvassed by every one else; indeed, the earlier part of the report may merely be glanced through.

After the "conclusions" comes the "opinion" as to whether development work on the new field will be justified or not. If properly led up to, this opinion should appear inevitable.

Then, if a favourable opinion has been given, come the recommendations as to how the area should be developed. The sites chosen for test-wells should be described, and the reasons for selecting them given. If locations have actually been marked on the ground and on the map, it is not necessary to deal at length with their advantages and disadvantages; the initial horizon of each test-well can be shown on the vertical section, and the position of each as regards geological structure can be given on the horizontal section.

The depth to be drilled in each case should be stated, as well as the nature of the strata to be drilled through, and any difficulties likely to be encountered in the drilling through the occurrence of water-sands, loosely compacted sands, thick soft clays, or steeply dipping strata must be mentioned.

Proximity to water supply, best means of access to the well sites, and difficulties in the way of road-making incidental to the nature of the country and strata should be touched upon: though these matters are hardly within the province of the geologist, any information about them will be of value to a field manager.

Finally, if the geologist has sufficient experience in oilfield work to justify him in so doing, the method of drilling which he believes will give the most successful results in the special circumstances, and the expenditure which he considers should be sufficient to allow of the test-wells being drilled in a satisfactory manner, may be indicated. On these latter points, however, it is well to use a wise caution. Unforeseen circumstances may arise to falsify estimates of expenditure, and it is better, unless specially requested to do otherwise, to leave all such matters to those who will have to be responsible for the practical development work.

It is a very simple matter when dealing with a new oilfield to write a favourable report in somewhat indefinite terms, dealing with such evidence as has been obtained in a general way, and not stating the reasons why any particular fact is regarded as favourable. Reports of this kind are very common nowadays, and may frequently be found in a prospectus. The geologist who wishes to establish his reputation for reliability must be careful not to fall into this style, which is fatally easy to acquire. The disadvantages of a new field should be stated as clearly as its advantages, and though the expert who does not hesitate to condemn a field upon evidence which he gives, and holds to be sufficient, is never so popular as he who can write a carefully safeguarded report, which at the same time gives the reader a highly favourable impression of the prospects of a field, in the long run the man who confines himself to the stating of facts, and has the courage of his convictions, will carry the most weight. A reputation for caution and even pessimism will be of more value to the young geologist than an ill-regulated enthusiasm which may have the effect of inducing capitalists and the public to sink large sums in fruitless expenditure.

Report on a proved field.—In reporting upon a field already tested and partially developed, the geologist has a much more complicated task. An accurate topographical map in all probability will be available, and the geological data must be noted upon it with great care. A larger scale than 6 or 8 inches to the mile will probably have to be employed, and the exact position of every well, drilled or drilling, must be marked. Then after the geological map and horizontal section have been completed, logs and boring journals must be consulted and every well projected on to the horizontal section, showing its initial horizon and the depth reached. The underground geology can then be added from the logs of the wells and a correlation of the oil-bearing horizons attempted. Where many wells have been drilled it is often possible to correlate every water-sand and every oil or gas-show throughout a field, and to draw contour lines upon the map showing the depths to an oil horizon at any part of the area. In some of the American fields, notably that of Coalinga in California, this has been done with great success. When such accurate work is possible the required depth for each new well can be calculated from the elevation of its site and its position with regard to these contour lines, and the depth at which water must be shut off can be given with certainty, so that a field manager is enabled to save much expense by adapting his methods to the particular object aimed at and economizing in the matter of casing.

The report will require to be written on a different system; there must be a section dealing at length with the evidence from wells and the correlation of the underground strata. These, however, are matters not entirely geological, and can be undertaken by persons without any special technical knowledge. It is before a field has reached the producing stage that the services of a geologist are essential. After the map and horizontal sections have been completed, and the confines of the field proved, the petroleum expert may take the place of the geologist.

When working in a producing field great caution must be exercised in taking hearsay evidence about the strata in any well and the shows of water at any horizon in it. The logs of wells are not always reliable, and even when kept with care too much is often left to the personal opinion of the driller. Strata are frequently incorrectly described, and two drillers may give different names to the same type of sediment. Boring records and hearsay evidence, therefore, must not be blindly relied upon. Not that the geologist will be intentionally misled by the practical workers in an oilfield—though cases of deliberate attempts to mislead the scientific worker are not altogether unknown—but the mind untrained in scientific work may not be able to convey or express information in such a form that it can be grasped accurately. From a report hearsay evidence should be rigidly excluded; it is better to leave a point unsettled than to rely, however slightly, upon second-hand information.

One point with regard to the writing of reports remains to be touched upon. It will frequently happen that the geologist in the course of his field work will establish, or obtain evidence about, some point of general scientific interest, and he will naturally be tempted to enlarge upon it in his report. In such cases the best procedure is to consider whether the scientific point in question is of practical importance in the commercial development of any particular field, and whether other members of a scientific staff working in the same interests will be helped in their investigations by the new knowledge acquired. If so, the evidence should be described briefly and the conclusion stated. Otherwise it is better not to overload a report with matters, however interesting and important from the scientific point of view, that have no direct bearing upon the practical finding and producing of petroleum. Appendices can always be written to a report to contain such results of the geologist's investigations as are of greater scientific than practical importance.

Reports are always subject to criticism, and as a matter of course always receive it, practical or academic, pertinent or impertinent, fair or unfair, and occasionally merely ignorant. Any criticism is stimulating, or should be so, to the practical geologist, and in the majority of cases must be beneficial howsoever unfair it may be. The answer to it is in work rather than controversy. Theories may be promulgated, tested by the facts, and fall; fallacies often die very hard and may even be brought to life again unexpectedly, but the search for truth goes on, and the dealer in facts has in the end the victory over the critic steeped in theory who has not the advantage of first-hand acquaintance with all the evidence. Therefore the field-student in his writings should eschew theory and stick to facts, nor resent the spur of criticism however clumsily applied.

In these notes the author is conscious that he is setting forth, probably at undue length, a great deal of very obvious advice, which even the tyro in geological work in oilfields may stigmatize as commonplace and banal. "These matters," he may say, "are merely common sense," in which he neither requires nor desires instruction. The author does not cavil at, but rather applauds such a dictum; each man must depend on his own common sense, and to teach geology from books rather than in the field is an academic absurdity. Out of the fruits of considerable experience the author has written in the last two chapters these notes, not claiming for them any originality, nor desiring to dogmatize, but hoping that here and there among them the beginner may find something that will help him in his practical work.

It may seem that the duties of a petroleum geologist have been made to appear somewhat elaborate and complicated. They may be, and indeed often are so; the geological work in an oilfield, especially in a Tertiary oilfield, is in itself simple, but to guide the development work of a petroleum company with complete success, without causing needless expenditure, and without having to admit failure now and then, may be very difficult. Every kind of evidence must be studied, every precaution taken, and every detail examined if certainty is to be arrived at. And that in very many instances practical certainty can be attained in oil-finding is the firm belief of the author, though years of laborious field-work and research under conditions not always of the most attractive may have to be accomplished before such a result is within sight.

A great field is opening up nowadays for the prospecting geologist, the man trained in scientific processes of thought, and physically fitted to endure the hardships and discomforts of field work in those parts of the world where nature is not yet shackled by civilization. It is in tropical and sub-tropical countries that much of the earth's richest stores are to be searched for and won, and it is to him who can withstand unfavourable climatic conditions, under tropical sun, or in dark forest, on desert and barren hill, or in cane-field and plantation, that the prizes will fall.

In no branch of geological work is there a more promising field than that offered by the search for petroleum, and no commercial enterprise depends more for its success upon the geologist than the finding and winning of oil.

There must be many young men with military training but no definite profession in civil life, with an experience of far countries and a distaste for indoor occupations, to whom the work of a petroleum geologist would naturally appeal.

To those the author would like to say that the prevalent idea that geology is a difficult subject, requiring a lengthy academical course, is completely erroneous. He has had to manufacture geologists, sometimes from rather unpromising material, and he has found that a little field experience, even without previous study, is worth terms of grind at a University. A gunner, an observer in the R.A.F., or an infantry subaltern, who has learnt to think in maps, starts as a field geologist with half his difficulties already surmounted, while he may have acquired that "eye for country" to which men with the most distinguished academic careers may never attain.

There is no geological work more practical and easier than that of the petroleum geologist; it may not equip the student to deal with really abstruse and difficult geological problems, but it may make a very useful man of him in a comparatively short time, and the writer's experience is that keenness on scientific points comes imperceptibly but inevitably during the work. The student's reading can then be undertaken gradually, as it is required, for definite objects, more definite and more useful than the passing of examinations and the taking of degrees. There is room for many in the profession even among the ranks of students and beginners: there is far too much room, at present, at the top. The life of the oil-finder, with its travel in many lands, its contact with many races, and its frequent change of scene, is, taking the rough with the smooth, a thoroughly enjoyable one. To the sportsman—and every field-geologist should be somewhat of a sportsman at heart—there are moments that compensate one richly for the hardships incidental to the exploration of wild and little-known country.

If this little introduction to the great subject of oil-finding be instrumental in turning the attention of the young geologist to the fascinating subject of petroleum, and be of service, in however slight a degree, in setting his feet in the path that leads to success, the aim of the author will be accomplished and his labour rewarded.

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