CHAPTER II

SUBMARINE GEOLOGY

THE submarine geologist is concerned with the shapes of the oceanic slopes and floors, with the materials of which the sea bottom is composed, with the changes these materials undergo in the process of deposition, and with such chemical and physical features of the sea water as affect these changes, directly or indirectly. In practice it is convenient to divide this general field into (1) Submarine Topography, (2) Sedimentation, and (3) Submarine Dynamics.

Many illustrations might be given of investigations carried out, and of advances won in these fields during the past half-century. But to attempt a comprehensive account of these matters would reach far beyond the permissible limits of this discussion. We wish, therefore, to make it clear that our present aim is limited to setting forth certain of the unsolved problems, and to suggesting lines of work that now seem promising.

1. SUBMARINE TOPOGRAPHY

Knowledge of the topography of the basins that enclose the oceans is the rational introduction to the science of oceanography, because this is the factor that determines the extent, shapes, and depths of the oceans, which in turn largely control the whole gamut of thermal, circulatory, and biological phenomena in the sea. Knowledge of submarine topography is equally needed by the general geologist, for (as often stated) all advances in the specific field of submarine geology must be founded thereon, while it is equally basic to our understanding of some of the most pressing problems of terrestrial geology, as illustration of the methods and results of the earth's deformation in past ages. For example, much more sounding is needed, in submarine hollows such as the Tonga, Kermadec, and Porto Rico deeps, in connection with the problems of the strength of the earth's crust and the degree of stability of mountains and plateaus. Neither can we hope to understand the origin and history of the thousands of oceanic islands, or the geologic events that led to the formation of such archipelagoes as the Hawaiian or Samoan groups, until we know more about the exact depths and about the contours of their submerged slopes.

An exact knowledge of the topography of the bottom would go far toward establishing the possibility of great rockslides on the steeper submarine slopes, a question recently raised by puzzling rock formations in the Alps, Appalachians, and other mountain chains. To quote from Doctor David White's statement to the United States Naval Conference on Oceanography, 1926, 'the bearing of submarine mapping and its geologic interpretation on the discovery of regions of submarine volcanoes, and areas of earthquake displacements must be obvious to all.' Fuller knowledge of the shape of the bottom should, as he has emphasized, disclose the locations where many of the great earthquakes originate; it should also disclose the centers of submarine vulcanism where islands may now be building up, or the reverse.

More detailed knowledge of the depth, especially for drowned valleys, etc., would also afford data for deducing the minor changes of position of shorelines, and for estimating the amount of material removed from the land surfaces by the various processes of erosion. In this connection we need to know how deep wave-base is, and how effective waves and currents actually are, as scouring forces.

The coral reef problem — a hardy-perennial controversy — is also as much a question of submarine geology as of biology, or more so, because of the fact that the upgrowth of these peculiar lime formations depends on a complex interaction of physical and chemical factors, in which temperature, salinity, currents, the absolute depth, risings or sinkings of the sea bottom, and possible changes of sea level, all play a part. In considering the origin of any given reef, as well as in the general reef problem, the submarine topography of the island or of the continental slope in question is of first importance. This is no less essential as a basis for weighing the validity of the assumed shifts in sea level that are integral in the glacial-control theory of coral reef formation. The relation to the coral reef problems of submarine volcanoes is equally evident, and borings that have been made on Funa Futi, at Bermuda, and on the Great Barrier Reef have contributed data of great value for discussions of the problems of lime reefs. Pendulum measurements of gravity, for some distance out at sea, are also needed to combine with the geologic data above sea level as evidence whether the region in question be one of recent subsidence, of emergence, or stationary; i.e., as a test of the crustal stability of the coral reef regions in general, especially in the West-Tropical Pacific.

This matter of depth and of the local variations in crustal stability is of equal interest to the palæontologist, and to the zoögeographer, because of its bearing on possible former land connections which have been postulated to explain the distribution of terrestrial animals and plants as at present existing; no less to account for the continental separations by which different floral and faunal areas (once continuous) are now isolated from one another. Changes in the depths of epicontinental seas, and in the degree to which the great oceans have been in free communication with one another in the past, equally concern the marine biologist as factors controlling the dispersal-routes of many marine organisms, and as affecting the ocean currents that transport animal and plant species.

The changes in the ocean currents that must necessarily follow any considerable alteration in the level of the sea floor, or in the shapes of the land masses, must also be taken into account by the meteorologist, because of their influence on the evolution of climates. Of interest in this connection is the question what configuration of the old northern oceans is reflected by the fact that fossil remains of animals and plants have been found in the Arctic, belonging to groups that can now live only at much lower latitudes, suggesting a milder climate in Eocene-Miocene times.

As pointed out elsewhere (page 231), while our charts of the more frequented coasts leave little to be desired from the navigator's standpoint, the various investigators who have attempted geologic interpretation of the configuration of the sea bottom, especially near land, have constantly faced the obstacle that few existing charts are wholly satisfactory from the standpoint of the geologist. Even around the coasts of Europe only short sectors outside of the North Sea have been charted with the requisite detail: off the North American coast one limited area off California (recently surveyed through the coöperative effort of the Coast and Geodetic Survey and of the Scripps Institution) has alone been examined intensively with the needs of the submarine geologist in mind; and the situation is even more unsatisfactory for the less frequented parts of the world. Thus, to quote two specific examples, existing soundings do not allow satisfactory mapping of the shape of the bottom of the Gulf of Maine, a region not only made physiographically interesting for the glacial geologist by its submarine troughs and banks, but recently the site of much oceanographic activity. In fact, one of the main channels leading into one of its larger tributaries (Passamaquoddy Bay) has, within the past few years, been found considerably deeper than had previously been supposed. And a recent survey of the deeper parts of the Gulf of Bothnia, with echo soundings, by the Thalassographical Institute of Finland, proved that the existing contour charts were erroneous in many respects.

A multiplication of the soundings now existing in depths greater than one hundred fathoms is still more necessary if the geologist is to discover what becomes of the geologic structures as they plunge into the sea; and it is obvious that much of our philosophy regarding mountain ranges is dependent on their submarine continuations. We might call attention especially to the inadequacy of existing soundings to show the fault scarps that are believed to exist along the northern slope of South America, or to outline the undersea contours of the Caribbean volcanic arcs and of the outer Bahamas.

The difficulty in this case is not one of inaccuracy of observation — on the contrary, the soundings taken by all the important maritime nations have long been extremely exact — but of their comparative scarcity everywhere outside the fifty-fathom contour. We must remember that while the soundings marked on an ocean chart may seem frequent enough, in reality they may be many miles apart. Furthermore, as they have been taken with the needs of navigation constantly in mind, it often happens that just those regions where the geologist needs the closest survey have been the most neglected, while the approaches to harbors, etc., that have been the most carefully sounded, may be the least interesting stretches of bottom, scientifically considered.

In the ocean basins, until very recently, we owed practically all our knowledge of the depth, away from the slopes of the continents, to the occasional deep-sea exploring expeditions, to the surveys that have been made along routes thought suitable for submarine cables, and to scattering data from other sources. Of these three kinds of information, cable surveys alone, and a few lines recently surveyed with sonic depth-finders, have yielded data at all comparable, in closeness, with the surveys that have been made of shoal waters. As a result, our knowledge of the topography is still of a very generalized sort for the floors of all the oceans. And the contour lines laid down on the present bathymetric charts of the oceans are equally generalized; located on the assumption that submarine slopes are as a rule so gentle that if soundings are taken every couple of hundred miles or so they will probably reveal the existence of any important ridges or troughs. But recent soundings by the 'Meteor,' by the United States Navy, and by the vessel 'Carnegie' prove that this assumption is not as sound as was formerly supposed, but that important corrugations of the sea floor may well exist in any, or all, of the large blank spaces that remain to be studied.

The six thousand-odd soundings that had been taken in the different oceans in depths greater than 1000 fathoms up to 1912 gave an average of only one sounding for every 23,000 square miles for the troughs of all the oceans combined; one sounding for every 7000 square miles for the deep Atlantic basin. And while many deep soundings have since been obtained with sonic methods, notably in the South Atlantic by the 'Meteor,' and in the North and South Pacific by United States, Danish and Japanese vessels — most recently by the 'Carnegie' and 'Dana' — their distribution still leaves very serious gaps. This is not surprising when one remembers how laborious and time-consuming a process sounding in deep water was, so long as it was necessary to do so with wire; to take a cast in 2000 fathoms, for instance, required at least an hour after the ship had been stopped: often much longer. From this it has followed that the growth of knowledge as to the shape of the sea floor has been inversely proportional to the depth of the water, and to the distance from land; the less frequented, too, any part of the sea, the more neglected.

The North Atlantic is, naturally, the best known ocean, bathymetrically: there is no reason to suppose that even such detailed examination as is now possible by echo sounding will seriously alter the existing picture of it. Even in the North Atlantic, however, we still lack detailed knowledge about certain of the most important features, the deeps north of Porto Rico, and in the Caribbean. We have recently learned that the representation on the charts of the slopes of the Grand Banks off Newfoundland is far from satisfactory; it was only in 1928 that the bottom contour of Davis Strait was adequately explored; much detail is also to be added even near shore and on important fishing grounds: witness the fresh exploration of Georges' Bank and of the Grand Banks that the United States Coast and Geodetic Survey and the Fisheries Service of France, respectively, have found it necessary to undertake; also the recent surveys of the Gulf of Bothnia and of the Icelandic ridge. And our present ideas as to the contour of the deep Arctic basin rest on very few actual soundings.

We owe to the work of the 'Meteor,' in 1925–27, the first approximately correct picture of the longitudinal ridge, with furrows on either side, east and west, along which bottom water from the Antarctic drifts northward, that make South Atlantic topography especially interesting. And the unexpected irregularities that her sonic soundings brought to light on her several profiles of that ocean show the need of lines run much closer together there in latitude than has yet been attempted.

It is when we turn to the Pacific, however, that we most clearly appreciate the vast amount of sounding that still remains to be done, before adequate contour charts can be constructed. In this ocean it is only directly along the cable routes from California to Hawaii and to Alaska; in the general vicinity of Japan; along one profile from America to Australia; and along one from Hawaii to the East

Indies; that the topography of the floor of the open basin had been developed with any approach to completeness up to 1928. During that year the 'Carnegie' closed some of the most serious gaps with about 1100 echo soundings along several trans-oceanic profiles, in the North and South Pacific, while the 'Dana' has since run a line along the tropical belt. But between the lines that have so far been run, areas still remain, greater in extent than most European principalities, that are marked only by soundings far apart along the lines of the few earlier deep-sea expeditions; or scattered here and there. Thus a region off to the westward from Lower California, fully twice as large as the Republic of Mexico, is still to be marked by its first sounding. Another *terra incognita* extending northward from the foot of the Hawaiian slope nearly to the Aleutian chain, and southwestward toward the Japan deep — i.e., more than halfway across the Pacific (larger than the whole of the continental United States) — is crossed from east to west by only one line of soundings along which the individual measurements of depth lie hundreds of miles apart. In an area of nearly 2,000,000 square miles to the southwest of Chile only eight deep soundings had been taken up to 1928 when the 'Carnegie' reduced the size of this *terra incognita*. To the southward of the Jeffrey trough south of Australia, and right down to the Antarctic edge, we again find only odd soundings, while other vast blanks still remain to be explored in the southern part of the Indian Ocean.

It may be of interest to note, in passing, that in 1929 the pilot charts of the United States Hydrographic Office listed no less than 127 shoals in the Atlantic, 68 in the Indian Ocean, and 221 in the Pacific Ocean, the position or the existence of which was doubtful.

Within the past few years, the perfecting of sonic sounding — i.e., by timing the echo sent back by the bottom — has made it necessary to cast the preceding paragraphs in the past tense, because many ships — commercial as well as governmental — are now equipped with the necessary apparatus, with which they can take almost continuous soundings in any depth of water while running at full speed. We may, therefore, look forward to a very rapid expansion of our knowledge of the shapes of the ocean basins along the usual trade routes, and on the tracks followed by the naval ships of different nations. In this way, and by special trips to regions not ordinarily traversed (and these cover a much larger proportion of the oceans than is commonly realized), ridges, troughs, and escarpments and other irregularities of the bottom may well be brought to light, such as have actually been revealed by the Panama–Australia profile, just mentioned, by the 'Meteor' in the South Atlantic, and by the 'Carnegie' in the South Pacific, that will greatly modify prevailing notions as to the flatness and uniformity of the floors of the great oceans outside the slopes of the continents. Perhaps the major problem in this connection, which will serve as sufficient example here, is whether the bottom of the Pacific is systematically furrowed on a grand scale, as suggested by at least one bathymetric map, also by the work of the 'Carnegie,' and how it compares in this respect with the floors of the Atlantic, Indian, and Arctic Oceans.

2. Submarine Sedimentation

The study of marine sediments has three chief objects: (*a*) a knowledge of the sediments now being laid down under the sea is prerequisite for interpretation of sedimentary rocks on land; (*b*) better knowledge of the nature of the sediments, and of the rate at which they are now being laid down, will clarify our ideas as to the permanence of the ocean basins, as to the climates of the past, and as to the chemistry and physics of the sea bottom during past ages; and (*c*) it will throw light on the present cycle of matter within the sea.

From the first of these standpoints, if from no other, the study of modern marine sediments would be (as it has often been named) a geologic necessity, because the development of stratigraphy depends upon a knowledge of the environment of deposition. And this development is made essential for a correct understanding of the sequence of events in the earth's history by the fact that sedimentary rocks which were originally laid down under water (salt or fresh) now cover some seventy-five per cent of the surface of the lands, while it is also probable that areas overlaid by igneous rocks are in many places underlaid by sedimentary. In fact, there are probably no large parts of the continental areas that were not under water at some time in the geologic past. Sedimentary rocks also contain a majority of our mineral resources. They are, in short, the most important element in the earth's outer shell as they affect man's undertakings.

Neither the study of modern sediments alone nor of their ancient prototypes now represented by the sandstones, chalks, and limestones can tell the whole story: only if the two be examined hand in hand can geologists hope to understand how the different classes of sediments, now solidified into rock, were originally accumulated; still more important, what chemical changes they have undergone since that time. And since sediments of different sorts are laid down in sequence, changing as the determining conditions change (e.g., if the sea floor rises or sinks; if the sea warms or cools; if the circulation undergoes any major alterations), study of the old sediments should also give us the sequences of the changes that have taken place in the seas of old.

The task of the sedimentary geologist, therefore, includes not only an examination of the composition, texture, chemistry, etc., of existing sediments, but, equally, the restoration from these characters, and from the factors in the environment that compel the deposition of one kind of sediment and not another, of the conditions as to depth of water, temperature, activity of circulation, distance from land, topography of bottom, and so forth, under which the old sands and muds accumulated. For this he needs especially to know which classes of sediments are deposited only under special combinations of environmental factors, and which are either less sensitive or are limited by only a single factor; e.g., by the control that temperature has on the distribution of the organisms whose skeletons have been the source of marine oozes. The rocks derived from the first group have a limited, those from the second a much more general, distribution.

An understanding of these factors would make interpretation possible of the sedimentary rocks in terms of the physical and chemical state of the sea when they were deposited. This inevitably makes the submarine geologist trespass on the realms of the oceanic biologist and of the palæontologist, because it is on a knowledge of conditions of life of the modern representatives of the sand, ooze, and reef-building animals and plants of the past that such understanding must be based, so far as the organic sediments are concerned: the chalks, for instance, the radiolarian-bearing strata, the diatomaceous earths, and those limestones in the East Indies to which an abyssal origin is usually ascribed. Conversely, the palæontologist's best clue to the conditions as to depth, etc., under which ancient marine animals lived is the nature of the rocks (i.e., sediments) in which their remains are found.

The chemical changes that the impregnating water may have caused in the nature of the limy sediments on the floors of the oceans deserve particular attention, because we know that while the old sedimentary limestone and shale rocks were laid down under water, and under conditions comparable to those existing today, they differ greatly from the modern muds and oozes. In this connection new studies on the hardening (diagenesis) of marine sediments are urgently needed to explain the origin of the old unstratified rocks of the earth's crust.

Interpreting 'sedimentation' broadly, we may here mention the assistance that a detailed charting of the regional and bathymetric distribution of the more monotonous communities of animals and plants of skeleton-building types, now living on the sea bottom (e.g., coral or Halimeda reefs, mussel, or other shell beds, forests of deep-sea crinoids), would give to the geologist in his attempts to interpret the age relationships of strata that contain, in close association, fossil communities that differ equally widely in character.

Lime rocks have certainly been the most widely discussed of marine sedimentary formations, and in some cases, as with an oyster bed, or a reef of corals, or a swarm of Globigerinæ, the progress of the event by which lime is added to the sea floor may be easily observed. But great quantities of limy mud are also being laid down in tropical seas, the minute amorphous particles of which seem not to be the simple fragments of shells of defunct animals. Whether bacteria are responsible for the formation of these muds, as formerly supposed (page 181), or whether they result from chemical or mechanical precipitation quite independent of bacteria, or whether, after all, they are simply the end product of the breakdown of exposed limestones, beach sand, etc., as has recently been maintained, is still a moot question. This question, however, is of great theoretic interest, not only for its bearing on events now taking place in the sea, but in connection with the formation of oölitic limestones, and in relation to the relative importance of salt and fresh-water situations as sites for the formation of limestones, now and in the past.

The question to what extent the formation of limestones or other sedimentary rocks has taken place in the past at great depths under characteristically abyssal conditions, or is taking place there today, is still an open one. It is suggestive in this connection that the few short cores of the bottom (up to eighty centimeters or so long) that have been taken in deep water in the North and South Atlantic basins, with their poleward extensions, by the Nordske Nordhaus, German South Polar, 'Michael Sars,' and 'Meteor' expeditions, as well as by the recent 'Atlantis' cruise sent out by the Museum of Comparative Zoölogy, show, as a rule, rather a noticeable stratification even in the thin superficial stratum, in many cases with less and less lime from the upper surface of the ooze downward.

At first thought it might seem that this decrease in the percentage of lime, as one penetrates into the sea bottom, reflects the solvent action of the entrapped water — i.e., the age of the sediment — raising the question whether solution of this sort may, in places and at certain times, actually limit the thickness to which lime deposits can accumulate on the ocean floors of today, by dissolving calcium carbonate from the deeper layers as fast as it accumulates on top. But the fact that some North Atlantic cores have been found to contain shells of Foraminifera still in good condition, though buried some sixty centimeters deep below the upper surface of the ooze, suggests quite a different explanation for the stratification, namely, that changes in the temperature of the sea have caused corresponding changes in the kinds of sediments deposited. How does all this bear on the failure of geologists to find existing sedimentary rocks to which abyssal origin can safely be credited except in limited areas, such as those of Barbados and of the East Indies, and on the view that the accumulation of thick beds of calcareous sediments has for the most part been confined to shoal waters, or has taken place at great depths only under special circumstances? To learn whether lime sediments, once buried, remain intact, or, if they are subsequently dissolved, the rate at which this happens relative to their rate of deposition, a knowledge of the chemical composition (especially of the degree of alkalinity) and amount of the water that is trapped within the modern sediments of different sorts is as necessary as it is for an understanding of the changes that sediments undergo in their alteration into rock: also of the nature of the water that lies directly upon the sea floor.

Problems equally broad arise in connection with the siliceous deposits, for with silica constantly contributed by the rivers to the sea, and with no return loss either to the atmosphere or to the land (except in regions of elevation), it seems that the silica of the earth is now tending to accumulate on the sea floor. The geologist is, therefore, as deeply interested as is the biologist in the factors that cause such accumulation of silica to take place most rapidly in cold water, and at great depths, as signboards to the conditions under which similar events occurred in the seas in past geologic ages. Among these siliceous deposits the radiolarian-bearing sediments demand special attention, both in relation to the depth at which they were deposited, as just mentioned, and because knowledge of the conditions under which they were laid down is vital to our understanding of the geosynclinal rocks, hence of the world's mountain chains.

The formation of phosphatic concretions and of glauconite on the sea bottom of today also needs fresh examination for its bearing on the origin of phosphatic and potash rocks: it is in the sea, too, that the key to the riddle of the source and mode of formation of dolomite is most hopefully to be sought (page 117).

In like manner, a study of the blue muds around the continental shoals and on the shelves is important because of the probability that many of the shales, laid down under the seas of old, were deposited in the same way. We think especially of the genesis of the Paleozoic black shales of vast extent, as to whose origin there are nearly as many theories as students. The fact that the ordinary black shales, of marine origin, grade into the algal coals, oil shales, and kerosene shales naturally introduces us to the general question of organic matter in the sea bottom, which has direct geological bearing from many angles. The conditions of growth and the environmental factors controlling the deposition and the burial in the sea of the remains of the algæ that make up a large part of the long-buried carbonaceous shales are still an open question. Is the color of the ordinary black shales due to vegetable or to animal derivatives, or, if to both, in what proportion? And by what chemical alterations have these shales been derived from the ordinary black marine muds?

Modern industry gives economic import to the problem of the accumulation of the carbonaceous and bituminous substances on the sea floor, from which petroleum, natural gases, and other hydrocarbons are believed to have been derived. Geologists, generally, are agreed that petroleum and so forth are end-products of the natural distillation, under geologic processes, of organic material accumulating whether in the sea, in fresh water, or on land. It seems certain that in such alterations of marine sediments more organic material is involved than the oil of the copepods, diatoms, and so forth; similar though the latter be to petroleum in chemical composition. But it is still an open question whether it is the vegetable matter or the animal fats that are the chief source for the geophysical and geochemical transformation in question. It is, therefore, important to learn to what extent the soft parts of animals are actually buried, and so preserved in the marine muds and oozes, and how they are transformed there by bacterial action. Cores, in particular, are needed to tell us the relative abundance of organic matter in the mud, from its upper surface downward, a question that bears on many of the chemical reactions that tend to alter the raw material sifting down in the bottom.

The problem of iron in modern marine deposits is important because of its bearing on the question, what part of the iron ores now being mined in sedimentary rocks were originally laid down with the latter, or in what part they entered subsequently, as secondary intrusions? Are deposits of this sort being laid down anywhere today? What, if anything, have bacteria to do with the segregation of iron in the sea? How does the common association of iron with manganese in modern deep-sea deposits bear on this problem? How sound are the chemical reactions that have been proposed to account for the deposition of either of these minerals, and what conclusion must we draw, as to the depths of the Paleozoic seas, from the distribution of iron, in deep and in shoal water, in the modern sediments?

In the interpretation of geologic time, the rate at which marine sediments accumulate is a matter of prime importance, regarding which present knowledge is practically *nil*. Our only direct evidence as to how fast the limy deep-sea oozes are actually building up in thickness on the ocean beds, or even whether they are so building up at all, is the rapidity with which Globigerina ooze has been found to protect (i.e., to bury) submarine telegraph cables. But it is certain that the sea floor generally, over all the vast area occupied by the Globigerina oozes, is not rising at as rapid a rate (an inch in ten years, or a fathom in every 720 years) as this experience with cables would suggest if accepted at face value. How do the processes of solidification, of solution within the sediments as suggested by the stratification of lime just mentioned, and of the sinkings of the earth's crust as weight increases (compensated by uplifts elsewhere), balance the tendency toward accumulation?

We commonly think of the terrigenous detritus around the continents as accumulating faster than do any of the oceanic oozes. How, then, are we to interpret the fact that glacial pebbles have often been dredged, and over a wide range of depths (p. 37)? Is the depth to which these stones are buried a measure of the thickness of deposition since glacial times?

The probability that cores will throw light on the actual rate of deposition in given circumstances, if some time-marker can be established to start from, gives special importance to such work off coasts, the character of which was determined in the last glacial period. Circumscribed basins, scoured out so deeply by the ice sheet that mud is now being entrapped within them, are especially attractive subjects for time-studies of this sort. Projects are, in fact, under way for obtaining cores in bowls of this sort.

The degree of alteration undergone by the particles that make up the abyssal red clay in its different layers would also show something of the age of this material relative to other geologic processes, even if it cannot be measured in years.

Allied to this problem of rate of deposition is that of the size of the particles that are deposited in different regions and depths under different conditions of oceanic circulation, combined with the transport of sedimentary material over the sea floor, by waves and currents. This bears directly on the theoretic profile of equilibrium that has been supposed to represent the balance between submarine processes of transference and terrigenous contributions. Analysis of the depths at which coarse sediments are now accumulating, and of the rôle played in this connection by the scouring action of waves, tides, and currents as a governing factor, is especially desirable from the geologic point of view, because the conglomerates and breccias that were formed in the old seas have their equivalent in the gravels and sands that are being deposited around the shores of the oceans today.

The failure of sediments to accumulate, even in deep water, in regions where the scouring action of currents or waves is strong (e.g., the Pourtales Plateau off Florida and the Wyville Thomson Ridge in the northeastern Atlantic) is also geologically suggestive. Can the fact that Devonian strata have been found lying direct upon Cambrian in certain places, with nothing between — long a geologic puzzle — be credited to similar local scourings in the Paleozoic sea?

On the steep slopes into the abyss special watch should be kept for rock masses that have broken away from the shelf and slipped down the slope. Modern deposits on the submarine slopes of the oceanic islands also bear on the sedimentary effects of landslides as pointed out on page 14.

The presence of glacial pebbles, even boulders, embedded in the bottom on the offshore banks, such as have been found far out from the land at various localities on both sides of the North Atlantic, where their presence cannot be credited to transport either by the ordinary agencies by which marine sediments are distributed over the sea floors, or by floating ice under present conditions, emphasizes the importance of relicts of this sort as evidence of the distances to which the ice sheets of the last glacial period extended out beyond the edges of the modern continents. The information so far gathered on this point is only enough to whet our appetite for more. All this is bound up with the problem of climatic changes in the sea during past ages, already mentioned in connection with shifts in submarine topography (page 17) and in the discussion of stratification in the deep-sea oozes (page 40).

The thermal relationships of the various species of Foraminifera, shells of which have been identified at different depths below the uppermost layer of ooze, may prove highly significant as indices to changes in the temperature of the ocean, as already suggested. Similarly, the alternating strata of shell-bearing and shell-less clays on the bottom of the Norwegian seas emphasize the geologic fertility of studies in this field. The urgent need for more detailed information as to the temperature and other vital optima of the various pelagic shell-builders here unites the biologist with the geologist.

The regional and vertical distribution of marine sediments of different classes (when we learn the correct interpretation) also opens one promising avenue to the solution of the recurrent problem of the permanence of the ocean basins, on the answer to which so much of our interpretation of the modern physiography of the earth depends. Is it, for example, safe to assume that where a basin is now floored with red clay (the most typical abyssal sediment), it has continued deep for geologic ages past, and that the presence of the teeth of sharks of species long since extinct, and earbones of whales that our dredges often bring up from red clay bottom, means that not enough sediment has sifted down, since Tertiary times, to bury them deeper than the instruments scrape? Or may this old stratum have been repeatedly covered by lime ooze and as repeatedly freed from the latter by the solvent action of the water, with successive uplifts and sinkings of the sea floor?

Improvement in the methods of obtaining cores of the sea bottom, at great depths, would offer new lines of attack here, for we have an index to the depth of water at which particular classes of sediments have been laid down in the fact that the limy oozes (as a class) accumulate only in depths less than about 2500 fathoms (shoaler still in the Pacific), while it is only at greater depths than those in which calcareous sediments accumulate that the red clay, or the radiolarian and diatom oozes, are found little contaminated by limy shells. Some cores suggestive in this respect have already been obtained. The presence of abyssal red clay overlying Globigerina ooze has been used as an argument for a very considerable recent sinking of the sea floor in the mid-equatorial Atlantic, seven such cases having already been recorded from the 'Meteor' expedition. But stratifications of the opposite sort — i.e., with Globigerina ooze or diatom ooze overlying blue mud, such as even the short cores taken by the 'Meteor' revealed over a considerable area off West Africa, between 13° north latitude and the equator or of red clay beneath Globigerina (found by the 'Gauss') — do not necessarily point to a shift in the level of the sea floor. They may, on the contrary, give evidence of a change in the Pelagic fauna and flora of the overlying water, caused by a change in its temperature, or of a different dispersal of clastic material from the land. The layers of volcanic ash found in some of the 'Meteor' sediments also open interesting problems. Similar cores, and if possible, longer ones, are desiderata for all the deep submarine troughs, especially for those that fringe the continents, as possible clues to the ages of these depressions relative to the stability of the ocean floor as a whole, and relative to the ages of neighboring mountain chains on land. In the same way, the discovery of shoal-water shells in dredgings from considerable depths illustrates the importance of submarine evidence of that sort for its bearing on the possible existence of former land bridges.

As final examples of the importance of submarine geology in the household of geophysics, new work on the radio-activity of deep-sea sediments would add much-needed data on the origin and distribution of radio-activity in the earth, hence of its internal heat.

Hopefully to attack problems such as these mentioned in the preceding pages, geologists need a much more detailed knowledge of the distribution of different classes of modern sediments on the sea floor, as well as of their nature, than it has yet been possible to attain: this is especially true for the shelves of the continents, where all sorts of débris from the land overshadow the contributions made to the bottom by local shell-builders. In part, the wide regional variations in this zone are associated with differences in the nature of the source-rocks on land from which much of the material comes; this applied equally in the past. But regional differences in the turbulence of the water, and in the scouring action of tides and currents are also important in this connection, because they govern the degree of coarseness or fineness of the detritus that can be held in suspension, thus sorting the sand or mud regionally as it is laid down.

No shoal-water survey can be adequate, from the geological point of view, unless samples of the sediment be taken close together (many more per hundred square miles than would suffice in the abyss), and throughout the entire depth range of the region in question; they must then be subjected to detailed analysis in the laboratory. Though this last requirement may seem self-evident, it has been met for very few shoal localities, because our present knowledge of shoal-water sediments is based chiefly on the data given on the navigational charts, which, in turn, are drawn from wholly inadequate samples or (as when the bottom is described as 'hard') simply from the failure of the sounding lead to bring back any sample at all. Geologically speaking, 'hard' or 'rocky' is a meaningless term, unless we know whether it was some rock fragment that the lead struck, perhaps brought from afar by glacial action ages ago, or solid ledge *in situ*, or unless at least a fragment of the material is obtained. To quote a specific example, the nature of the bottom as noted on the charts of the Gulf of Maine (one of the better-sounded seas), is of very little service to the geologist, and even when samples were collected and analyzed for this very purpose, from two hundred stations there, it proved that serious gaps still remained.

The obvious importance in the formation of sedimentary rocks of accumulations of calcium carbonate in shoal water has, it is true, stimulated intensive examination of several shoal areas in tropical and sub-tropical regions; of the reefs of Murray Island, Australia, for instance; of restricted localities around

Samoa; and of the Floridian and Bahaman Banks. Much attention has also been directed, of late, to possible precipitations of calcium carbonate from the sea water in the tropics, whether by bacterial or by direct chemical action (page 115). Similar studies of sedimentation in restricted areas are also in progress in more northern seas; around Great Britain, for example, in the Bay of Fundy, off the coast of California, and elsewhere. But these isolated projects must be greatly multiplied and extended out to the mud line at the edges of the continents, before we can hope even to sketch in the very complex mosaic picture presented by the processes of deposition in shoal water.

Samples of the sediments need not be taken at such close intervals to meet the geologic requirements in the deeps of the ocean basins, because (within certain ranges of depth, and at certain distances out from the submarine slopes), the deep-sea mud or ooze that superficially clothes the ocean floor is comparatively uniform. Consequently data from points scattered as widely as are most of the deep-sea soundings have usually been assumed to suffice for the intervening stretches, except where more detailed examination may reveal unexpected shoals or troughs dissecting the abyssal plain. This assumption, in general, is justified by the direct relationship that the types of deep-sea deposits bear to the depth, to the distance from land, and to the plankton of the overlying waters. For as a rule the sediments of the ocean basins, far out from the land, are 'oceanic' in origin, consisting of the shells of pelagic plants and animals that rain down from above under the regions where the plankton is abundant, of the skeletons of bottom dwellers, or of the so-called 'red clay' that gradually accumulates from the disintegration of the pumice from volcanic eruptions, from cosmic dust, and from the precipitation of manganese and other less common minerals out of the sea water.

So much information has already been gathered from the bottom samples that have been collected by the various deep-sea expeditions, that further exploration is not likely seriously to alter our general conception of the character of the materials that floor the ocean basins, at depths greater than, say, five hundred fathoms; either as to the structural or chemical composition of the several classes of deep-sea sediments or as to their regional distribution.

Much, it is true, remains to be done in the abyss, to fill in the extensive blanks that still mar our charts, especially for the Pacific and for the Indian Ocean, while recent work shows that important modifications of present charts of Antarctic deposits are needed. But a much more pressing need is that of examining the vertical distribution of the sediments, by probing the underlying mass to a far greater depth than has yet been possible. Here, as in so many submarine problems, we face a practical obstacle. With deposition proceeding almost everywhere in the sea (except right along the coastline, and in certain restricted localities where currents scour the bottom), there is no opportunity for a direct examination of submerged geologic sections, because no transversely dissected sedimentary layers are left exposed under the sea, or are accessible for examination if exposed. The collection of additional cores with the primitive instruments so far devised for the purpose would be of great assistance in the study of sedimentation. But while it is easy enough to gather mud in any desired amount from the uppermost stratum, in any depth of water, no method has yet been devised for obtaining vertical cores of the bottom more than about three to four meters long, nor have any corings of more than about eighty centimeters yet been obtained from deep water in the great oceans. The perfection of apparatus for taking longer cores is therefore an urgent need.

No further discussion is needed to make clear that the sedimentary geology of the sea is still in an elementary stage, even if judged as a descriptive science. Compared with soil science on shore, our knowledge of the muds of the ocean deeps corresponds in a way to that of some steppe or prairie region, where the soil is so uniform over great areas that scattered tests will give a representative picture of the whole. But we know hardly more of the bottom in shoal regions than examination of a garden plot, here and there, would tell us of the agricultural possibilities of a land with widely diversified soil. Picture, too, how far geology would have progressed on land had there been no way of studying anything but the top soil!

3. Submarine Dynamic Geology

The study of dynamic and structural geology has been greatly handicapped in the past by the fact that two thirds or more of the earth's surface is put out of reach by its covering of water. While it is possible to survey the topography of the bottom and to gather samples of the sediments, these are only two of the factors involved in the problem of the cause of basins and continents, or of the existence of troughs, submarine ridges, and oceanic islands.

We still lack any means of obtaining samples of the rocks that underlie the oceanic sediments. But studies of earthquakes and of the volcanic rocks of oceanic islands suggest that the regional grouping of these may throw light on the constitution of the crustal material below the oceans. And the recent development of a means for measuring the force of gravity at sea (as geophysicists have for many years been able to do on land) opens a wholly new field of oceanic research, for previously there had been no way of determining whether the high values of gravity that prevail on oceanic islands do or do not indicate an excess of material in the crust under the oceans as a whole. An answer to this question is prerequisite for any general conclusion as to whether the state of hydrostatic equilibrium or 'isostasy' that has been proved to be the normal condition of the emergent portion of the earth's surface is equally characteristic of the ocean beds. In other words, do these depressions represent the heavy sectors of the crust, just as the masses above sea level are compensated for by a deficiency of material (i.e., lightness of the crust) beneath the continents? This is one of the major problems of geophysics, because rational interpretation of the irregularities of the earth's surface must depend largely on determining the relative densities of the material underlying oceans of different depths, compared with lands elevated to different heights above the mean level of the earth's crust.

Gravity measurements at sea supplemented by analyses of the igneous rocks found on oceanic islands may, therefore, be expected to throw much light on the causes of ocean basins and continents, of the sinkings and risings of oceanic islands, and of volcanic activity, past or present, on the latter. Such measurements may also be expected to show whether the processes that caused broad uplifts in the past are now working under the oceans to make uplifts that may appear above the sea in geologic ages to come.

Other questions are also involved. For instance, is there any support for the theory that the ocean beds have tended to sink under their own weight with the lighter margins of the continents tending to buckle up in compensation? In areas, on the contrary, where the sea bottom is rising (if any such be found), might lightness compared to the surrounding lands be responsible? How is all this related to the weight of the sediments that accumulate on the sea floor, and this, in turn, to the new hypothesis (raising one of the insistent problems in modern science) that the blocks of the earth's crust that form the existing continents have not only moved horizontally to their present locations, but may so shift position again?

For such reasons a net of gravity measurements is needed over the oceans. A beginning has already been made in this direction by determinations carried out by the Dutch Geodetic Commission and by the United States Navy from submarines, on voyages from Europe to the East Indies *via* the Mediterranean and Suez Canal, and in the West Indian-Caribbean region, while a gravimetric marine survey of the East Indies from a Dutch submarine has recently been completed. These observations have already opened interesting vistas, for while the flatter parts of the sea floor (along the lines so far run) have given values roughly in accord with the isostatic principle, decided differences have been found between the observed and the theoretic values of gravity over and near some of the deeper submarine troughs, near oceanic islands and close to the margins of the continental shelves. It may be premature to conclude that abnormalities of gravity of this sort, plus the fact that the grouping of submarine earthquakes is similar (the deep troughs seem, in particular, to be the seats of the strongest earthquakes), necessarily reflect a lack of stability in the parts of the earth's crust in question, for other explanations may be possible.

Solution of dynamic questions of this category calls for studies of the ocean deeps, of the regions around the oceanic islands, and of the margins of the continental shelves far more intensive than have yet been attempted. The discovery, for example, of a long arc of negative anomalies of gravity in the East Indies by the Dutch expedition mentioned above has already thrown new light on submarine foldings of the earth's crust.