YALE UNIVERSITY

MRS. HEPSA ELY SILLIMAN

MEMORIAL LECTURES

Hans Pettersson

THE OCEAN FLOOR

New Haven: Yale University Press, 1954

London: Geoffrey Cumberlege, Oxford University Press

Printed in the United States of America by
Vail-Ballou Press, Inc., Binghamton, New York.

Library of Congress catalog card number 54-9521

To My Collaborators on the “Albatross”

The Silliman Foundation

In the year 1883 a legacy of eighty thousand dollars was left to the President and Fellows of Yale College in the city of New Haven, to be held in trust, as a gift from her children, in memory of their beloved and honored mother, Mrs. Hepsa Ely Silliman.

On this foundation Yale College was requested and directed to establish an annual course of lectures designed to illustrate the presence and providence, the wisdom and goodness of God, as manifested in the natural and moral world. These were to be designated as the Mrs. Hepsa Ely Silliman Memorial Lectures. It was the belief of the testator that any orderly presentation of the facts of nature or history contributed to the end of this foundation more effectively than any attempt to emphasize the elements of doctrine or of creed; and he therefore provided that lectures on dogmatic or polemical theology should be excluded from the scope of this foundation, and that the subjects should be selected rather from the domains of natural science and history, giving special prominence to astronomy, chemistry, geology, and anatomy.

It was further directed that each annual course should be made the basis of a volume to form part of a series constituting a memorial to Mrs. Silliman. The memorial fund came into the possession of the Corporation of Yale University in the year 1901; and the present work constitutes the thirty-third volume published on this foundation.

Preface

By the terms laid down for the lectures given in memory of Mrs. Hepsa Ely Silliman, these are "designed to illustrate the presence and providence, the wisdom and goodness of God, as manifested in the natural and moral world."

I believe it is true to say that nowhere on our planet's surface is there less interference by men with the acts of providence than in great ocean depths, where natural laws have reigned supreme for untold millions of years, in fact since the birth of the ocean itself. It therefore seems to me that the subject discussed in the following pages fits well within the frame of the Act of Foundation.

It is for me a great privilege and honor to have been invited to give the Silliman Lectures of 1952 on "The Floor of the Ocean." The deep ocean has recently come to the foreground of geophysical and geochemical investigations, thanks largely to new instruments and new methods of research which were used for the first time by the Swedish Deep-Sea Expedition of 1947–48. About one-half of the planet's total surface, considerably exceeding in area all the five continents taken together, is covered by water masses from one to six miles thick. Only the uppermost surface of this enormous lowland has so far been accessible to investigation, and a relatively small number of sediment samples have been raised from great depths. It seems likely that the new science of submarine geology will be much advanced during the latter half of this century. Many problems concerning the deep-sea deposits —their structure, their composition, and their origin—will be elucidated through future international efforts in deep-sea research.

I owe a debt of gratitude to David H. Horne for clarifying the English of the manuscript, making the index, and helping to see the book through press.

HANS PETTERSSON

Göteborg, 1954

Table of Contents

Illustrations

1. The Oceans and Their History

For thousands of years men have been scanning the ceiling of our universe, the vaults of Heaven. The stars in their courses have stimulated the imagination and fostered belief in ultimate things. Today, thanks to the magnificent resources of modern astronomical observatories, especially in America, we are able to probe the remotest spaces of our universe and study galaxies separated from our own small world by hundreds of millions of light-years. Modern physics has shown us how to interpret the faint light signals transmitted to us across enormous gulfs in space.

On the other hand, the oceans around us were long neglected. Five centuries ago explorers began to steer their frail ships across the unknown ocean, discovering new continents, but for obvious reasons their interest was limited to the ocean surface, and the great depths beneath remained unknown and unexplored until less than a century ago. True, pioneers of the new science of oceanography had made some earlier attempts to learn how deep the ocean is, the temperature of the water at great depths, and the character of the sediments which carpet the ocean floor, but their tools of research were altogether inadequate for measuring very far below the surface.

To our ancestors it was a source of astonishment, not to say dismay, that the Creator in dividing our planet between land and sea should have given an unfairly large share to the barren ocean, as compared to the fruitful continents on which we, his specially favored children, have been allowed to dwell. This apparent disproportion gave rise to hopes of discovering a vast new continent in the southern hemisphere, a *Terra Australis* (Figure 1), redressing the balance between land and sea. A famous attempt to make this discovery was the expedition to the Pacific Ocean sent out (1768–71) by the British Admiralty under the command of Captain James Cook, the greatest of all marine explorers.[1] (In setting Cook first, I pass over that remote countryman of mine who during an inland voyage into North America may have become responsible for the celebrated Kensington Stone, as well as that still remoter one Erik Raude, who two centuries earlier happened to discover "Vineland the Good.")

Not even Captain Cook succeeded in finding the vast *Terra Australis* in the South Seas, for the excellent reason that it is not there; and geographers had to accept the painful fact that the field of work reserved for oceanographers is more than twice as large as their own occupying over 70 per cent of the planet's total surface.

Viewed through a supertelescope by an extramundane astronomer inhabiting, say, one of the outer

Fig. 1. *Terra Australis*, at bottom, outlined in black

planets, our earth with its glittering oceans would no doubt be an object of admiration and envy, and would probably be called "the water planet." It certainly forms a striking contrast to its next neighbors in space. Venus, "the cloud planet," coyly hides her charms behind an impenetrable veil of dazzling white clouds. (Spectroscopic analyses indicate these clouds do not contain water but are largely built up from carbon dioxide.) Her old admirer Mars, "the desert planet," is also deficient in water. Venus is possibly still in a pre-oceanic stage, but Mars is strongly suspected of having consumed his original supply, either drinking it into his crust or perhaps squandering it into interplanetary space. This contrast inevitably suggests that our present oceanic splendor represents a transient stage in the development of earth, which may be on its way toward the Martian state of complete desiccation. According to some pessimists, in another few thousand million years or so oceanographers will have to learn a new profession.

Let us, for a moment, anticipate such a future development of ocean shrinkage and assume our earth to have become half dry, so that the sea surface has fallen below its present level by 4,000 meters, that is, some 13,000 feet. Figure 2 gives an idea of how the Atlantic Ocean will then look. The present continents are gray, the remaining ocean is black, and the parts of the sea bottom uncovered by the retreating ocean are white.

One easily recognizes the characteristic S-shape of

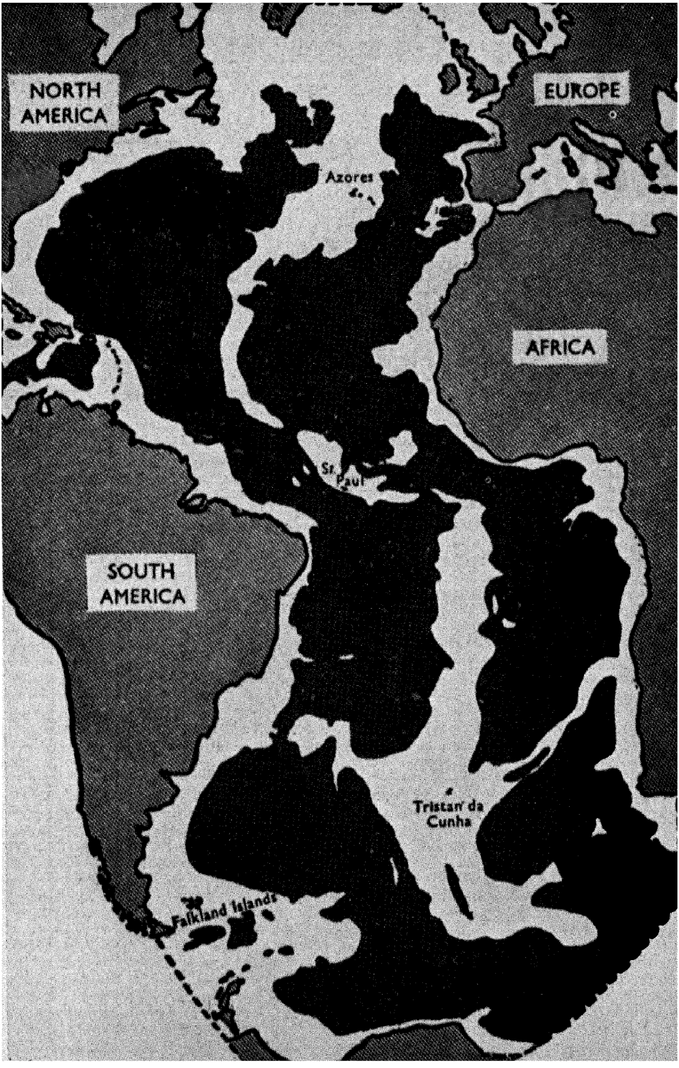

Fig. 2. The Atlantic Ocean on a half-desiccated earth

the Atlantic, but he also notices that a new Atlantean continent has risen out of the sea, dividing the remaining ocean into two parts. This "New Atlantis" is the present gigantic submarine Mid-Atlantic Ridge, with its crest at an average depth of about 10,000 feet. We have special reasons to be grateful that this strange sea change is not likely to occur in our politically unsettled times. One shudders at the international complications which might ensue from the rivalry between East and West for the possession of such a seaborn continent.

The remaining black surface on the map is divided between *two* parallel Atlantic Oceans, the present eastern and western Atlantic Valleys, with their lowlands spread 5,000 to 10,000 feet below the level of the ridge between them. Closer inspection shows one, possibly even two, sounds or channels cutting through the Mid-Atlantic continent. The northern one is more hypothetical, whereas there is little doubt regarding the existence of the southern channel, situated just under the Equator. This is the famous Romanche Channel, which runs quite close to the equally famous Romanche Deep, a curious cavity in the sea bottom accidentally discovered in 1883 by the French survey ship "La Romanche." We further notice a transverse ridge, the Walvish Ridge, which runs northeast from the South Atlantic island of Tristan da Cunha toward Walvish Bay on the west coast of Africa. It acts as a submarine barrier or water divide, holding back the ice-cold bottom water from the Antarctic and preventing its entering from the south into the eastern Atlantic Valley. Since there is a corresponding submarine barrier, the Rio Grande Ridge, running westward from the Mid-Atlantic Ridge but broken through by a wide submarine channel, the Antarctic bottom current is free to enter from the south into the western Atlantic Valley, where its cooling effect on the bottom temperature is apparent as far north as the vicinity of the Bermudas. South of the equator a narrow branch from this westerly Antarctic bottom current runs toward the northeast, entering the eastern Atlantic Valley through the Romanche Channel. (Figure 3 is a rough representation of the Antarctic bottom current.)

Figure 4 shows what the Pacific and Indian Oceans would look like after the same fall of ocean surface by 13,000 feet. In the Pacific a vast submarine ridge or plateau, laid bare by the retreating ocean water, would stretch northeast and north in a mighty curve from the Antarctic continent, reaching the west coast of Central America. This ridge now supports the very few East Pacific islands.

In contrast to these few in the east there is an abundance of islands in the central and western parts of the ocean, especially south of the equator. They are mainly of magmatic origin—volcanic cones rising steeply from great depths, a few crowned by lofty peaks towering thousands of feet above the ocean surface. The great majority have summits a few hundred feet below the surface but carry above it white diadems of living coral. They are the lovely atolls of the South Seas.

In the northern part of the Pacific Ocean we find the vastest lowlands of the earth's crust, with enormous areas lying at depths of more than 15,000 feet. It is a

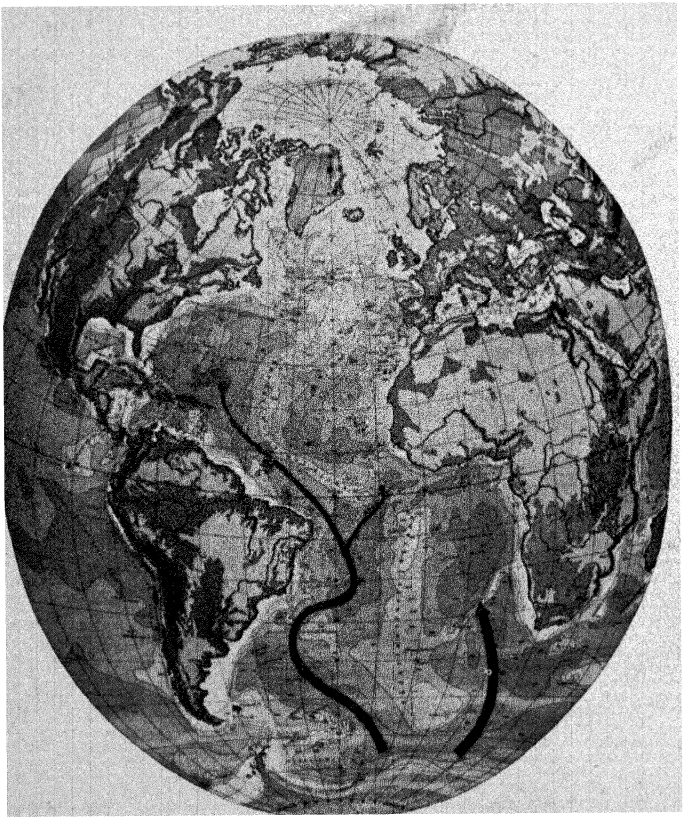

Fig. 3. The Antarctic bottom current in the Atlantic

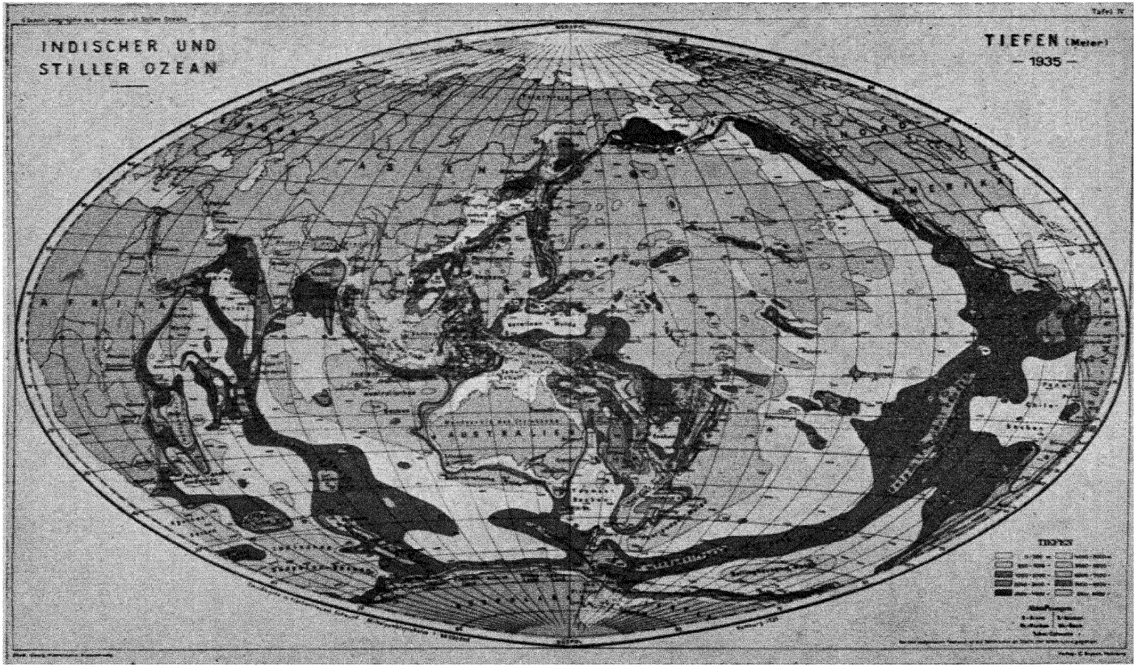

Fig. 4. The Pacific and Indian Oceans on a half-desiccated earth

remarkable fact that the very greatest depths are not found in the central parts of the oceans but are concentrated within curiously formed furrows or trenches which run close to and parallel with continental coasts or island festoons. In these trenches are found record deeps like the Emden Deep and the Johnson Deep in the Philippine Trench off the west coast of Mindanao, with soundings of very nearly 35,000 feet, and the still greater Challenger Deep southeast of Guam, with a maximum depth of 36,000 feet. This is considerably more than the height above sea level of the world's highest mountain peak, Mount Everest.

Turning to the Indian Ocean, we find in the western part, where most of the banks and islands are located, a great submarine ridge running south to north from the Antarctic Continent. The eastern part of the Indian Ocean is in general of a greater and more uniform depth and has only one deep trench, the great Sunda Double Trench, running along the south coast of Java with a maximum depth of about 25,000 feet.

Such are, in brief, the main features of the great cavities in the earth's crust which are at present filled with ocean water. The question naturally arises whether this has always been so. In other words, what is the history of the oceans in relation to the continents?

Here oceanographers must confess their ignorance. What little we believe we know is largely conjecture—theories put forward by students of geophysics, geology, zoogeography, and phytogeography (the last two from

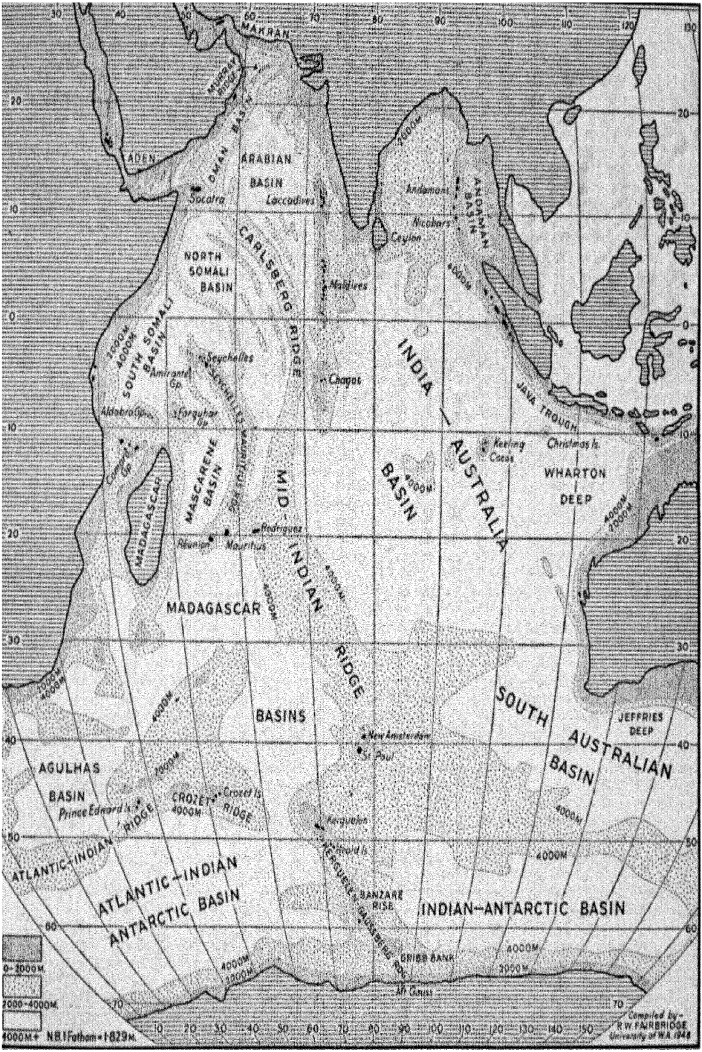

Fig. 5. Depths in the Indian Ocean

the viewpoint of both the present and the remote past, that is, paleontology). Specific hypotheses have been advanced to account for the distribution of plants and animals and their past migrations from continent to continent. It will be necessary to consider these hypotheses briefly, since they have played an important part in discussions of the problem before us, the ocean floor.

The evidence is overwhelming that large parts of the present continental surface have in earlier phases of the evolution of our planet been submerged and formed the bottom of relatively shallow epicontinental seas. Thus, the material from which sedimentary rocks such as chalk, shists, and sandstones were built is ancient sediment deposited on the bottom of vanished seas which were laid bare at the regressions of the shore line and gradually hardened into rocks. Our loftiest mountains, the Rockies, the Andes, the European Alps, and the Himalayas, are built up largely from such ancient sea beds, which by enormous horizontal forces have been folded and crinkled into mountain chains. On the other hand, very few if any deposits from great ocean depths are found in the continents. This fact, among others, has led to the theory of the "permanence of the ocean basins," propounded 90 years ago by the great American geologist James Dwight Dana and his school. The strongest opposition to this view came from the biologists and paleontologists, who claimed to find evidence for "land bridges," now out of sight below the sea surface but which in a remote past afforded roads for the migration of nonaquatic organisms across the wide gulfs separating one continent from another.

In general, it has been assumed that the Pacific Ocean is the most ancient of all the seas, possibly a primary feature of the earth's crust. Some theoreticians have even gone so far as to suppose its basin to be the "birth scar" left behind when our satellite, the moon, was torn out of the earth's body by enormous tidal forces. Those who had the privilege of listening to Harold Urey's masterly exposition of the origin of the planets, and especially of the earth and its moon, in the Silliman Lectures of 1951 will remember on how slight a foundation this hypothesis is based.[2] Nonetheless, the demand for a reconstruction of the Pacific basin which would satisfy paleontologists and biogeographers has found support among eminent geologists like the late J. W. Gregory. The need to postulate an ancient path of migration from northeast Asia over the Hawaiian Islands to Central America has led to the reconstruction of a hypothetical ancient land bridge called Archigalenis. A similar bridge, called Archinotis, has been suggested as a link between the Antarctic Continent and South America.

These and similar tamperings with the map of the Pacific Ocean are not much favored by present-day geologists. However, the evidence for an intercontinental land bridge in the far North appears to be much better founded. Behring Strait, which separates northeast Siberia from northwest Alaska, is fairly narrow and has a maximum saddle depth of less than 200 feet. During the great glaciations of Quaternary time, when enormous masses of water were transferred from the oceans to the inland ice, the ocean surface is generally admitted to have sunk about 250 feet, some authorities claiming a still greater lowering. This would imply that unless there was a corresponding sinking of the bottom of Behring Strait one might have walked across dryshod a few hundred thousand years ago. It is generally assumed that an invasion from Asia into North America, both of animals and of men, took place over this subarctic land bridge, so that the ancestors of the Indian population of the New World may have crossed thus from one continent to the other.

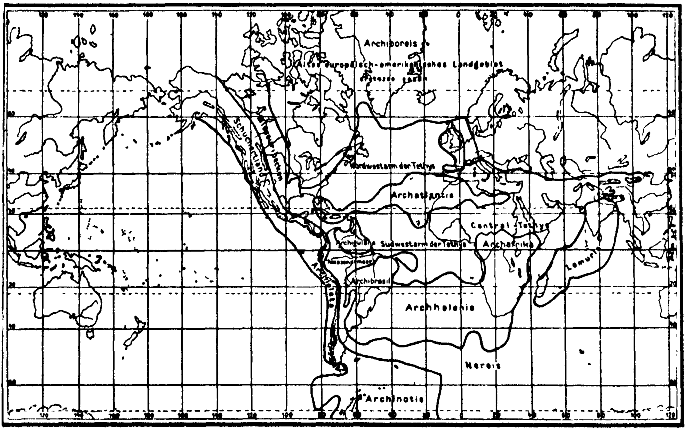

Fig. 6. Distribution of ocean and land in Mesozoikum

As for the Indian Ocean, very radical attempts at a reconstruction have been made, one of the most recent being propounded by the Australian geologist Fairbridge.[3] In late Paleozoic time a large part of what is now the bottom of the Indian Ocean is assumed to have been above sea level: the famous Gondwana Land, which united Australia and the Antarctic with southeastern Asia. Lemuria, a last remnant of this ancient continent, hypothetically linked East Africa and Madagascar with the Indian Peninsula. Because of a break in the earlier parallelism existing between the paleontological series found on the two continents, the Lemurian land bridge is assumed to have foundered in Mid-Tertiary time. According to Fairbridge the Indian Ocean in its present shape is the youngest of the three oceans. Its northwestern part he assumes to have been formed "only" 10 to 20 million years before our time.

However, it is our own ocean, the Atlantic, which has given rise to the most fantastic attempts at reconstruction. Here the paleontologists insist there were three transverse land bridges, separated by the two arms of the ancient sea of Thetys, as shown by Figure 7.[4] Far to the north the Archiboreis linked northern Europe and the Arctic islands with North America. Farther south, Archatlantis ran across the present Atlantic Ocean from the West Indies to northern Africa. Finally, Archhelenis spanned the southern Atlantic Ocean from Brazil to South Africa.

Much fiercer than the discussion over land bridges was that provoked by the famous theory of "continental drift" propounded and worked out in great detail by the Austrian scientist Alfred Wegener,[5] although the fundamental idea had been launched a few years earlier by the American Frank B. Taylor.[6] According to this theory the present continents are mere fragments of the outermost shell of the earth's crust, supported by being partly immersed in a deeper layer of higher specific weight and greater plasticity. To these continental blocks Wegener ascribed movements in both vertical and horizontal directions. This idea of drifting continents, worked out in great detail by Wegener and his followers, is supposed to explain the striking parallelism between the continental borders on both sides of the Atlantic Ocean, first emphasized by Taylor. Thus, the Atlantic Ocean was taken to be a kind of rift between the

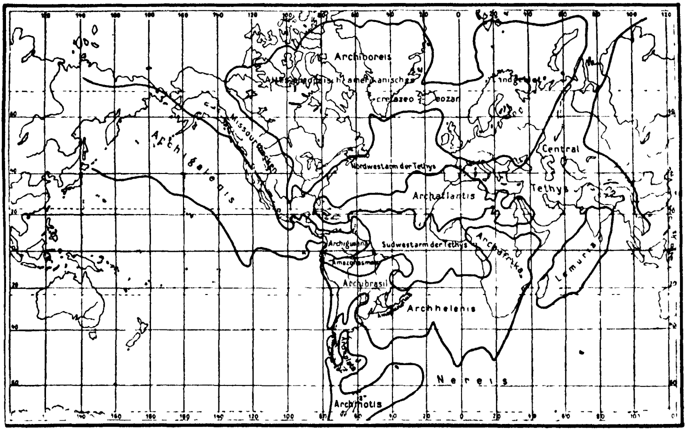

Fig. 7. Map of the Oceans in the Eocene

two continental blocks, Europe-Africa and the two Americas, which began to open up in Cretaceous time and is still widening through a progressive westward drift of the two Americas. The Atlantic Ocean would thus have a maximum age in its central parts of less than 100 million years, perhaps only 70 million years.

A great variety of arguments geographical, geological, biological, paleontological, etc. have been brought forward in support of this ingenious theory. Since its vogue in the twenties, adverse criticism has been overwhelming and very few leading scientists of our skeptical age have remained faithful "Wegenerians." One main objection to the theory is that enormous energy would be required to move the vast continental

Fig. 8. Birth of the Atlantic Ocean

blocks through a highly resistant substratum, an energy for which no adequate source was suggested, only subcrustal convection currents set up in the substratum at the escape of radioactive heat from the continental blocks through the ocean floor. On the other hand, movements of continents or parts of continents in a *vertical* direction are generally admitted to have occurred. They have been invoked in order to explain the so-called regressions and transgressions of the shore line, and have been attributed to a varying load of inland ice on accumulated sedimentary layers. But *horizontal* displacements of great magnitude are in general discredited.

Thus there still remains considerable uncertainty regarding the early history of the ocean basins, and many problems concerning their origin and that of the water masses filling them remain unsolved. Highly interesting contributions to the discussion of these problems have recently been offered by American authorities like Harold Urey and William Rubey. Although the theme is too vast to be further dealt with here, certain aspects of it will be considered later.

2. Envisaging the Past and Future

Few things are more fascinating than speculation about happenings in the remote future—or in an equally remote past. For instance, what did the earth look like two billion or 500 million or even a paltry 100 million years ago? We have strong reasons to believe that our Tellus really did exist as long ago as two billion years. Assuming that the radioactive transformations known to us proceeded then at the same rate as today, we can ascribe an age of over two billion years to the oldest rocks hitherto submitted to radioactive analysis.

However, we know next to nothing about the division between land and sea then prevailing, and whether water in large quantities existed on the primeval earth is subject to discussion. Arguments have been advanced to prove that the total volume of ocean water was at the beginning only a fraction of the present total.

In a recent brilliant paper William W. Rubey has attempted to show that the water masses of the oceans were derived largely from the earth's crust rather than, as has been assumed, from a cataclysmic condensation of water vapor present in a very dense primitive atmosphere.[1] For representatives of the two opposing schools of thought on these theories Rubey has coined the expressive terms "the quick soaks," who prefer to believe that all the water was present from the very beginning, and "the slow soaks," who think that it increased by small increments over a much longer period of time. The "excess volatiles," which the slow soaks assume were released gradually from the earth's crust, are supposed to have been retained within the interior of the earth in quantities amounting to a fraction of 1% of the total weight of the solid matter.

Starting from known geochemical data Rubey finds the total quantity of water present in the primitive atmosphere and ocean to have been not more than one-sixth, probably a still smaller fraction, of the present-day total, the rest having been gradually released from the crust during the crystallization of complex silicate melts. A large part of this magmatic water Rubey assumes to have been released as "juvenile water" through hot springs.* Even if the water which existing hot springs are delivering to the surface consisted of only .8% of juvenile water, in the course of two billion years they could account for the entire volume of present ocean water, without counting contributions of water from volcanic eruptions!

---

* Professor Eugen Wegmann has called my attention to the fact that as defined by E. Suess the term "juvenile" should be used for matter which has not participated in supracrustal cycles, so that the excess volatiles released from the crust should properly be called "juvenile" instead of "magmatic."

A question Rubey does not consider in his exposition concerns the *rate* at which these contributions from below to the ocean water masses have been delivered. Dividing the total volume of water in the oceans—1.3×10^{18} cubic meters through two billion years (a conservative estimate for the age of the oceans)—one finds the annual increment to have been on an average $.65 \times 10^{9}$ cubic meters, a small fraction of the present annual rainfall over the planet's surface. There are, however, strong reasons for assuming that this contribution from juvenile water may have varied considerably in the course of geological ages and that it has reached higher values than the average during epochs of intensified volcanic and magmatic activity.

More recently Roger Revelle, director of Scripps Institution of Oceanography, has taken up the problem of the origin of ocean water.[2] Revelle believes a large part of the magmatic volatiles—water vapor, carbon dioxide, and mineral acids—has been released from the ocean floor itself through a process of recrystallization of the underlying substratum. In the last 100 million years of earth history a water layer over 3,000 feet deep, according to Revelle, has been produced "from below." With this release the ocean floor has sunk considerably, so that no very great change in the water level has occurred. Such a subsidence of the ocean floor would explain the gradual sinking of the volcanic islands and the present great depth of the mysterious *guyots,* the truncated, flat-topped volcanic cones with wave-planed summits which are at present lying in the Pacific Ocean at depths of between 2,500 and 6,000 feet. The carbon dioxide simultaneously released, amounting to about 5% in weight of the water, has given rise to the thick layers of calcareous sediments covering parts of the ocean bed.*

It seems reasonable to assume that the effusion of magma over the ocean floor, as well as the release of magmatic volatiles, has varied greatly in intensity during the earth's history. If the origin of the Mid-Atlantic Ridge is placed in the early and late Tertiary, as Ivan Tolstoy and others assume, a great release of crustal water and other volatiles must in fact have taken place in the course of the last 100 million years, and only a

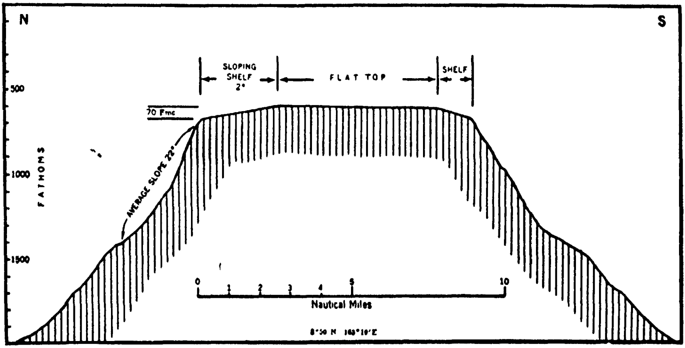

Fig. 9. Vertical section of a guyot

---

* Another possible source of water which seems to have been overlooked by American authors is that contained in the clay minerals.[3]

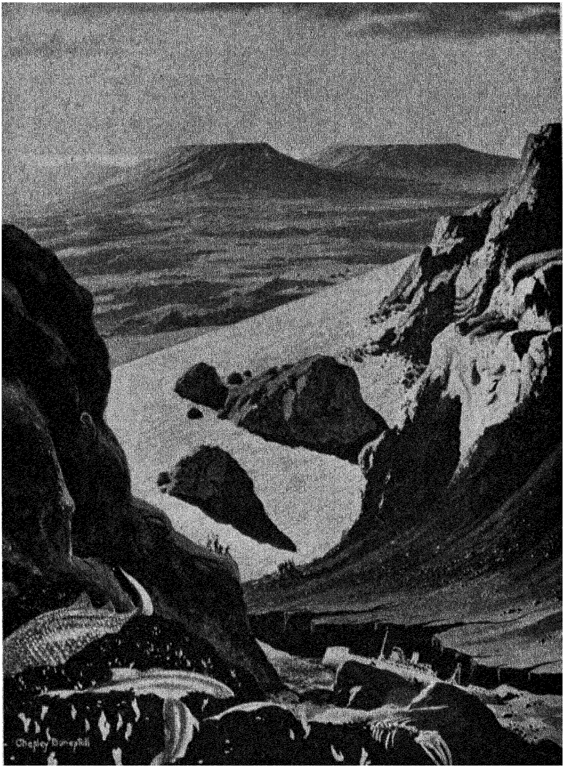

Fig. 10. Seascape of a half-desiccated earth (by permission of the artist, Chesley Bonestell)

deepening of the floors of the Atlantic valleys on both sides of the ridge could have accommodated the water masses thus discharged. The same probably applies to the ridges running from south to north in the western Indian Ocean, and the bottom in the eastern part of that ocean has presumably subsided, like that of the central Pacific, at the release of water from the underlying substratum.

This view of the interplay between the ocean floor and the water masses above it must naturally be considered a hypothesis, to be tested by future work undertaken by new expeditions like those recently sent out with such signal success from Scripps Institution.

It appears very probable that the adherents of the slow-soak principle are in the ascendant and that a continued discharge of further masses of crustal water in coming ages is likely to occur.

However, the reverse process, the disappearance of water into the earth's crust, is also possible. Perhaps, as Revelle has intimated, a cyclic process of water discharge and absorption by the substratum beneath the ocean will be operating in the future to shape and reshape incessantly the bottom profile. In any event, the prospect of our planet ultimately becoming desiccated and its oceans vanishing appears very remote—a comfort, at least, to oceanographers.

3. Exploring the Ocean Floor

At what time man's present interest in the ocean floor first arose is unknown. One of the many legends spun around Alexander the Great, according to the old script called "Pseudo-Kallisthenes," is that he and two companions made a descent into the ocean depths in a "case"—or, as we would say, a diving bell—made from transparent material and the skin of asses, and remained there for 96 days and nights watching the wonders of the deep, among other things a monstrous fish so long it required four days to pass the king's hiding place.[1] Whether the material of this royal diving bell, the asses' skins, was a sly dig at early oceanographers is unknown.

The first historical evidence of interest displayed in great ocean depths is a note in the log book from Magellan's voyage around the earth in 1519–21, from which only one ship returned, though not with the intrepid commander, who was killed in a skirmish on the Philippine Island of Mactan. According to that note Magellan made an attempt to sound the depth of the Pacific Ocean between the islands of St. Paul and Tiburones with six ordinary sounding lines tied together. Their combined length has been estimated at about

Fig. 11. Alexander the Great in his diving bell

2,500 feet. No bottom was reached. From this negative result the great seafarer, rather rashly, concluded that he had chanced upon the greatest of all ocean depths. Modern soundings have proved the depth in the vicinity to be about 15,000 feet or six times the length of the composite sounding line. However, on this slender evidence many authorities in the following centuries declared the ocean to be "immeasurably deep." *

Toward the end of the eighteenth century serious attempts were made to investigate the deeper layers of the ocean. During the expedition of Captain Phipps (later Lord Mulgrave) to the Arctic in 1773 a record sounding of over 4,000 feet was taken. It brought up a sample of blue mud. Dependable soundings in great depths were first made by Sir James Clark Ross during the British Antarctic Expedition of 1839–43, when the first abyssal sounding on record was taken in the southeast Atlantic, showing a depth of nearly 15,000 feet or 2,425 fathoms, a figure which in the light of modern research is considered quite probable. The great stimulus to early deep-ocean research came, however, from biologists. In the early 1840's Edward Forbes, the leading marine biologist of his day, repeated Aristotle's study of the marine organisms in the Ægean Sea, made over 20 centuries earlier.[3] From the fact that the deeper he went the more rapidly the marine organisms decreased, Forbes inferred that there is a lower limit, a "zero line," of organic life at about 1,800 feet, which he believed due to lack of light and a prevailing high pressure. This would mean that only a relatively thin surface layer of ocean is populated, the deeper and

---

* Rational views regarding the deep sea and its investigation were first expounded by Conte Luigi Ferdinando Marsigli (1735),[2] who objected to the idea of immeasurability of the ocean and indicated methods of measurement.

much vaster water masses being "azoic," that is, a region of death. However, in the following decades the dredging of northern waters, especially by British and Scandinavian biologists, proved Forbes wrong. In fact, an abundant life rich in new, unknown species was found to exist at great depths. The death blow to the idea of a zero line at 1,800 feet was dealt by the discovery—made in 1862 when a telegraph cable laid along the bed of the Mediterranean was raised for repair—that corals had attached themselves to it at a depth of more than 7,000 feet.

The laying of submarine cables over great ocean depths, which had been started about the middle of the nineteenth century, afforded a practical purpose for deep-ocean research quite apart from the growing interest of scientists in the problems of the ocean floor and its inhabitants. The laying of such cables requires a very careful bathymetric survey along the proposed line of communication, not only with reliable depth soundings but also with samplings of the kind of sediment on which the cable will be resting. This explains the conspicuously linear arrangement, with closely interspaced depth figures, of the mechanical soundings taken for this purpose. Over the rest of the ocean bottom only a sparse network of soundings was made, as shown by the well-known bathymetric chart of the North Atlantic, the "Monaco chart," inspired by the late Prince of Monaco, Albert I.

Several important discoveries of abyssal morphology we owe to the cable-laying engineers. For example, repeated breaks of the cable between Funchal, Madeira, and Lisbon, Portugal, necessitated a closer study of the ocean bottom there.[4] The result was the discovery in 1882 and the following years of a number of "banks"—

Fig. 12. Prince Albert I of Monaco

steep cones, probably of volcanic origin—which rise from depths of between 6,000 and 12,000 or more feet, with their crests only a few hundred feet below the ocean surface. To the practical requirements of the cable companies we also owe the rapid development of the gear used for accurate depth soundings, a development which led among other things to the substitution of a thin metal wire, later a piano string, for the unwieldy hemp line, an innovation first used from the United States survey ship, "Tuscarora" in 1874 and later introduced by Lord Kelvin in his automatic sounding machine.

The increased interest in the configuration of the ocean bottom and the fauna inhabiting great depths led to the circumnavigating British deep-sea expedition with the "Challenger," sent out in 1872 by the British Admiralty and the Royal Society of London conjointly. During three and a half years the "Challenger" cruised the three oceans, almost as far south as the Antarctic Continent and as far north as Newfoundland, collecting a wealth of information out of depths ranging from the surface down to over 3,500 fathoms, and including water samples and temperatures, deep-sea sediments, and an abundance of deep-sea organisms, both invertebrates and fishes. The zero line of Forbes was thus pushed down to depths of at least 15,000 feet. Samples from totally unknown types of sediment carpeting the ocean floor, especially the mysterious red clay, were brought up and subsequently studied in the laboratories. The results from this great expedition were published in a series of over 40 quarto volumes, the Challenger Reports, which, not without reason, has been called "the Holy Writ of Deep-Sea Oceanography."

In the following decades a number of other expeditions were sent out from different countries, among which those led by Prince Albert I of Monaco, the great

American biologist Alexander Agassiz, and the German biologist Carl Chun were the most noteworthy.

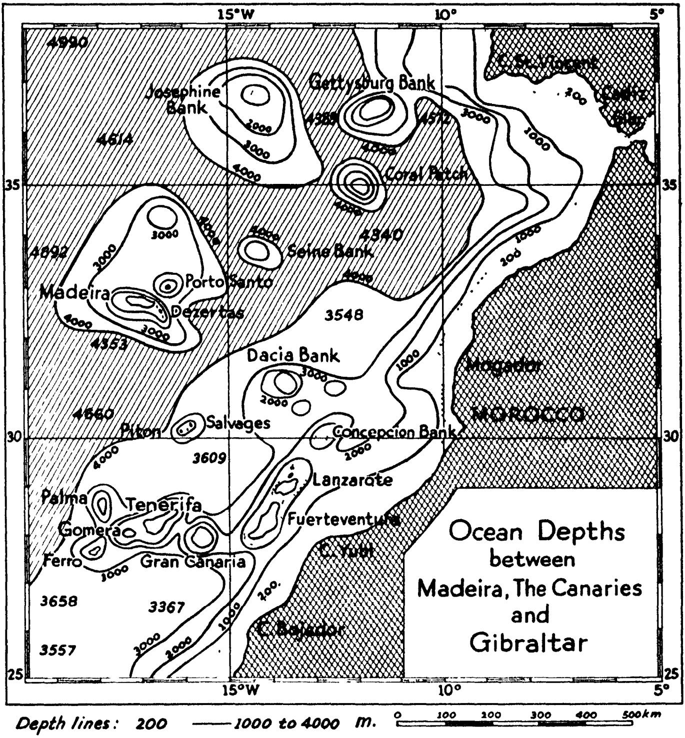

Fig. 13. Ocean depths between Madeira, the Canaries, and Gibraltar

In our century deep-sea research has taken large strides forward in spite of great technical difficulties. The International Council for Sea Investigations, started by Otto Pettersson in the early years of this century, although limited in scope to seas of moderate depths worked out a number of exact methods of research and analysis, from which deep-sea research has also profited. These new methods were put to practical use in 1910 by the "Michael Sars" Expedition in the North Atlantic, led by Sir John Murray and the Norwegian biologist Johan Hjort.[5]

The methods were also employed by a number of Antarctic expeditions. The culmination was the magnificent effort made by the Germans on board the "Meteor."[6] This cruise, originally planned by the Austrian oceanographer A. Merz for the Pacific Ocean, for want of a ship with a sufficiently large radius of action had to be limited to the Atlantic. The results gained there were, however, extremely important and revealed unknown features of both the ocean floor and the structure and movements of the ocean water masses. The expedition made excellent use of the technique of acoustic echo soundings then available, but their resources for studying the ocean sediments were not adequate and did not show any marked improvement over those of the "Challenger" cruise half a century earlier. The ordinary core-sampler, which was used rarely produced cores as much as three feet long, that is, reaching back about 50,000 to 100,000 years in time. Still, even these relatively short cores revealed a significant stratification of the sediment and indicated the possibilities of climatological studies of late Quaternary time, based on an analysis of the surface plankton shells from *Foraminifera* found in different levels of the core.

After the "Meteor" cruise the Dutch cruise with the "Willibrord Snellius" (1929–30) to the Sunda Archipelago and adjacent waters marked an extended use of the same technique, which in one case resulted in a core nearly six feet long. An explosive core-sampler invented by C. Piggot of the Carnegie Institute of Washington and used in the middle and late thirties made possible a penetration to somewhat greater depths, with a maximum in one core from the northwest Atlantic of 10 feet. Although the increase in obtainable core length was moderate, it proved to be most fruitful for deep-sea stratigraphy.

The idea of improving the coring technique so as to penetrate further back into the records of the deep has been one of the guiding motives of Swedish oceanographers. The second World War, which made investigations impossible in the open sea around our coasts, created an opportunity to concentrate on these problems. The new Oceanographic Institute in Göteborg, inaugurated in 1939 as a gift to our Royal Society from the late banker K. A. Wallenberg, facilitated construction. The chief obstacle to increasing the core length was the friction between the wall of the coring tube and the sediment column rising inside it. This friction not only limited the length of the core obtained to a fraction of the depth of penetration but distorted the stratification *in situ,* so that the core was not truly representative of the undisturbed layers.

In order to counteract this friction Börje Kullenberg and the author used a pressure-tight spherical container, evacuated before immersion, into which the water in the long coring tube was admitted through a valve, released at the moment of impact on the bottom.[7] In 1942 with this "vacuum corer" an undistorted core nearly 50 feet long was raised from the depths of the Gullmar Fjord, on the west coast of Sweden. Shortly afterward Kullenberg, who also utilized high water pressure but with a simpler and more effective contrivance without any vacuum container, obtained a core of 65 feet from the same fjord.[8] Where great length of core is essential, this "piston core-sampler" (Figure 14) has become the standard tool of deep-sea coring, not only in Sweden but also in other countries. Figure 15 shows the development which coring apparatus has undergone.

At the same time the foremost Swedish authority on explosives, Waloddi Weibull of the Bofors armament works, at the author's suggestion developed a new method for measuring the totally unknown thickness of the sediment carpet in great ocean depths. Utilizing depth charges, so constructed that they could be detonated at any desired depth between 1,500 and 20,000 feet, and recording by means of an oscillograph the echoes thrown back against the bottom and from the "bottom below the bottom," Weibull got a measure of the thickness of the sediment, traversed twice by the fainter and deeper echoes.

In the spring of 1946, in order to test these and other new tools of deep-sea research, the Swedish research

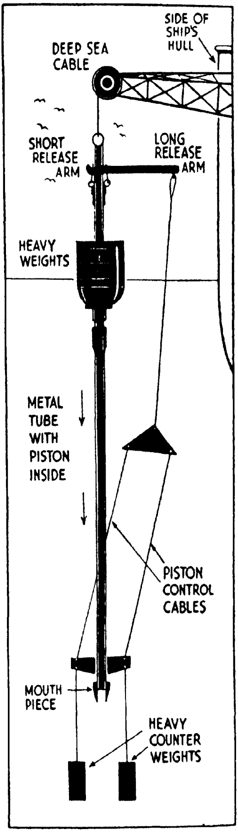

Fig. 14. Kullenberg's piston corer

vessel "Skagerak" was put at the disposal of the Oceanographic Institute for a two months' cruise in the western Mediterranean. In these waters, where the weather is generally fine in the spring, we found within easy reach

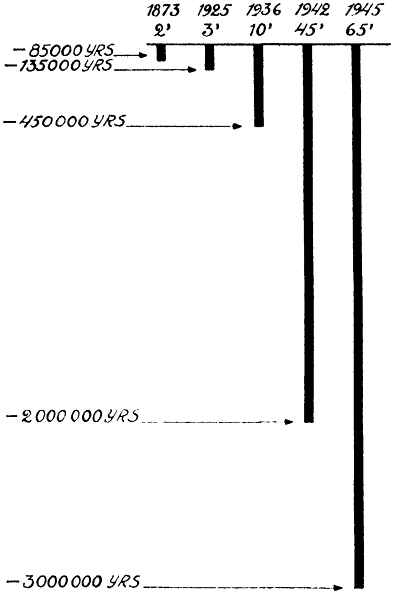

Fig. 15. Progress in length of sediment cores

of good harbors depths five to ten times greater than those accessible in Scandinavian waters. Moreover, we had chances of meeting there with layers of volcanic ash, interfoliating the records of the sea god Neptune with leaves inserted by his colleague and rival, Vulcanus. These and other coarse-grained layers frequently met with in Mediterranean waters incidentally offered by their absence of curvature or obliquity in the interspaced layers a criterion for the correct working of the core-sampler which would have been absent in unstratified, homogeneous sediments.

The results from this cruise were so promising that they encouraged us to the much bigger venture of applying the same technique to great ocean depths by a circumnavigating cruise under the Swedish flag.[9] To find a ship large enough and equipped with a powerful winch and the long steel cables required for handling the very heavy coring tubes at great depths was a difficult problem. It was overcome, thanks to the generosity of men of wealth and vision in Sweden, especially in Göteborg, by the loan from the great Broström shipping combine of their new training ship, the 1,450-ton motor schooner "Albatross," and by the wholehearted cooperation of various leading firms in Swedish industry which manufactured our gear at a merely nominal price and with the highest priority. Thanks to large donations given the Royal Society of Göteborg, which was sponsoring the undertaking, the cruise was financed without support from the Swedish government. Invaluable help in the form of advice, information, and instruments was given by foreign institutions like the British Admiralty, the Hydrographic Office of Washington, and the Woods Hole Oceanographic Institution.

By July 4, 1947, everything was ready. With a scientific staff of ten, including Kullenberg, who handled the coring operations masterfully, and Weibull (for the first part of the cruise), the "Albatross" set out from the harbor of Göteborg for an expedition scheduled to last fifteen months.[9] In fact we were back one day before the expiration of this time limit, on October 3, 1948. The ship was ably commanded by Captain N. Krafft and among the crew there were twelve young apprentice seamen, who had eagerly seized the opportunity of getting their training on a scientific expedition and who carried out their share of the work with a will.

The course followed is shown on the rough map in Figure 17. Although the "Albatross" was excellent for seaworthiness and afforded ample space for all our laboratories and storerooms, air conditioned for work in the tropics, its engine power was rather low. Only in a very smooth sea and with fair weather did it attain a speed of eight to nine knots. Partly for this reason, partly because our very heavy, long coring tubes required fair weather, we laid the course mainly within or near the regions of the equatorial calms, where the chances of favorable working conditions were optimal. We had, in fact, great luck with the weather, meeting only one heavy gale, at the entrance to the Indian Ocean; and the average speed could be kept at the precalculated seven knots.

Owing to the strict limits of time, money, and number of scientists accompanying the cruise, our program of work also had to be restricted. Several projects we were obliged with great reluctance to forego, such as measuring the bottom currents and studying deep-sea

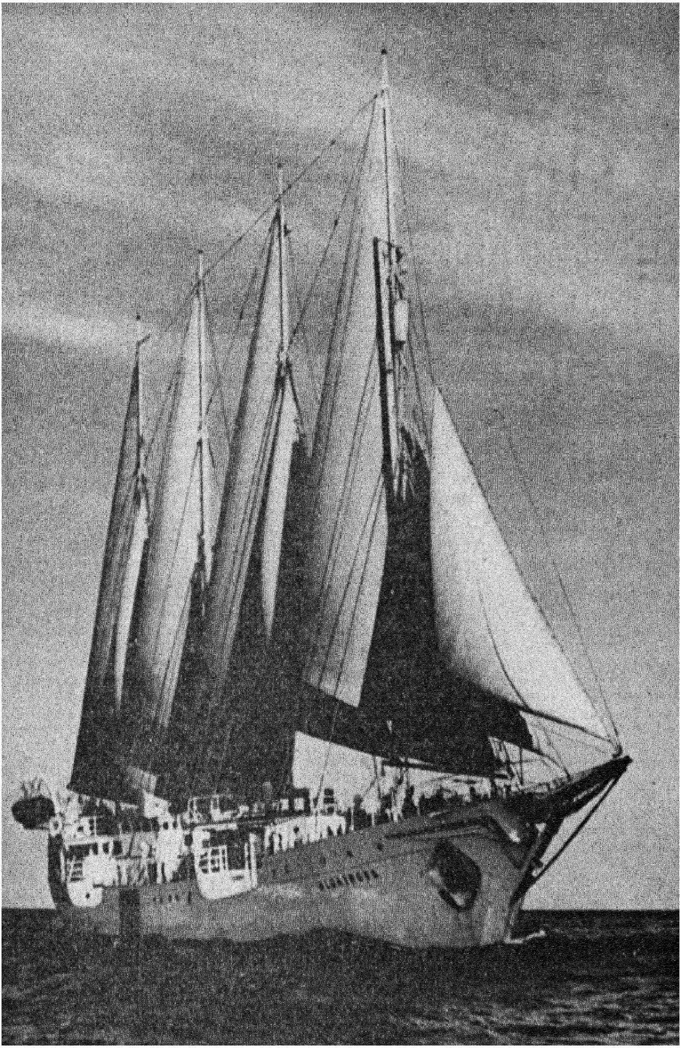

Fig. 16. The "Albatross" under sail

mounds and ridges, and bacteria in great depths. Biological work with deep-sea trawls and dredges had to be limited to the North Atlantic Ocean during the last three months of the cruise. We also had to exclude aerological work and the study of aerial "plankton," that is, organic life in the higher strata of the atmosphere. It was necessary to concentrate on the sea bottom and especially on its sediment carpet, which until then was practically unknown below a depth of three feet.

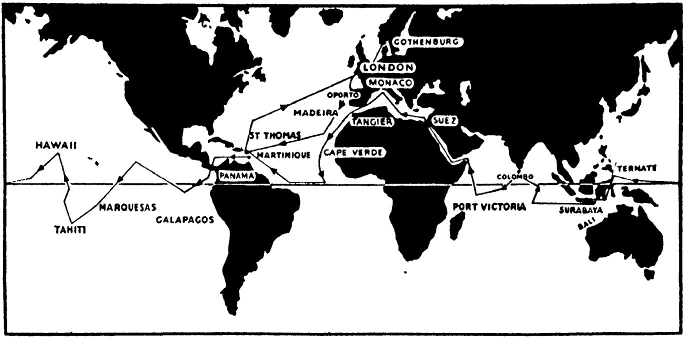

Fig. 17. The course of the "Albatross"

Most of the results to be reported in this book have been obtained from the material gathered during this cruise. Much remains unpublished and many points are not definitely settled, pending investigations now proceeding. I shall try to indicate the unsettled points and state when the views expressed are my own and at variance with those of my distinguished colleagues.

While our expedition was under way, a series of remarkable deep-sea cruises was undertaken by American oceanographers, several from the famous center of oceanographic research at Woods Hole with its ship the "Atlantis"—cruises inspired and directed by Maurice Ewing of Columbia University and his team of workers. We were first made aware of this work through an article in the *National Geographic Magazine* in the fall of 1948.[10] Ewing, who had already made his name known through his seismic investigations of the sediment layers and the rocky substratum on the shelf of the eastern coast of the United States, found means of extending that work to great ocean depths, with highly interesting and important results. Moreover, a certain amount of coring work was carried out from the "Atlantis" by means of a corer resembling the one Kullenberg had described but without any lining tubes.[8] So far very few of the results obtained from the study of these cores have been published, although extensive studies of the bottom topography of the northwest Atlantic Ocean, investigated by means of a recording fathometer, have been published by Tolstoy, one of Ewing's collaborators.[11]

From another well-known oceanographic research center, Scripps Institution of Oceanography in La Jolla, a number of deep-sea research cruises have been sent out in the course of the last few years, the results of which so far have been published only in part. Especially remarkable are the discoveries made on these cruises concerning the geothermal gradient existing in deep-sea sediments.* This subject was also on the program of the "Albatross" cruise but for technical reasons only three trustworthy measurements could be obtained. Scripps Institution enjoys the unique position of being on the verge of the most interesting part of the deep ocean floor, that of the eastern and central Pacific. I am sure its future work will be of the very first importance to the new science of submarine geology, in which an eminent representative of Scripps, Francis Shepard, has for years been active. Another member of that staff and one of the world's foremost authorities on the *Foraminifera* in sea sediments, Fred Phleger, accompanied the "Albatross" from Martinique to Cristobal, making investigations on the planktonic forams and sampling one of our longest cores, taken from the Caribbean Sea. The results of this analysis Phleger published while the expedition was still under way.[12] Together with Frances Parker and Jean Peirson, he has generously shouldered the heavy burden of studying the *Foraminifera* in our cores from the North Atlantic Ocean. Also, through his visit on board the "Albatross" and through a later visit to Sweden he has done much to clear up certain misunderstandings regarding the extent and quality of the work we were carrying out. The

---

* A paper on this subject is at present being written by Roger Revelle of Scripps Institution of Oceanography for publication in the new journal *Deep-Sea Research* (Pergamon Press, London).

results are being published in the Reports of the Swedish Deep-Sea Expedition, the first volumes of which have already been issued by the Royal Society of Göteborg.

A great Danish circumnavigating deep-sea expedition with the "Galathea," commenced in the fall of 1950 and concluded in the fall of 1952, obtained very important information, especially in the southern and western parts of the Pacific Ocean. Its main purpose was to study the abyssal fauna, in which it has achieved remarkable success. The "Galathea" took over some of the equipment used by the "Albatross," especially the unique electric winch for use in their trawling and dredging experiments. Also, a limited amount of coring work has been undertaken from the "Galathea."

From Great Britain the research ship "Discovery II" has continued its well-known work in Antarctic waters, concentrating in oceanographic studies.[13] Some of the corings have been made with the piston corer of Kullenberg, who accompanied the cruise from England to Port Said. The circumnavigating cruise of H.M.S. "Challenger" has also brought remarkable results, to which reference will be made in a following chapter.

Finally, a most interesting circumnavigating cruise began in 1954 from Toulon, headed by Commandant Y. Cousteau. His ship, the "Calypso," is expected to complete her cruise in the course of the next few years. Although not equipped for work in great depths, the expedition will investigate the upper layers by means of optical methods of unparalleled efficiency. If successful, this will benefit deep-sea stratigraphy by increasing our knowledge of the very little known ecology and distribution of surface plankton organisms, which contribute such a large part of the material deposited on the ocean floor.

The exploring of the ocean floor—a new science—has become of great interest to workers in many allied fields: oceanography, general geophysics and geochemistry, deep-sea biology and paleontology, as well as astronomy, archaeology, and paleoclimatology. The vast operation, extending over an area greatly exceeding that of all five continents together, tends in this second half of the twentieth century to become a focus of international cooperation. Its study requires a highly specialized technique and fairly large ships, as well as very powerful equipment. The experience gained by the "Albatross" cruise shows that the ideal ship for deep-sea research should be at least 1,200, and preferably 1,500, dead-weight tons, and should have a cruising speed of at least 12 knots, and a radius of action without refueling of at least 8,000 nautical miles (that of the "Albatross" was 20,000). It should be provided with a winch powerful enough to raise a load of 1,500 kilograms at a speed of three to four feet a second. It should have two independent recording echographs giving a detailed bottom profile from the greatest depths encountered, and it must afford laboratories and accommodation, preferably air-conditioned, for a scientific and technical staff of at least 12. It should have nothing to do with fishery investigations, which, according to my experience of the last 40 years, are incompatible with basic oceanographic research. At present such a ship would probably cost in building and equipping 2 to 2½ million dollars. However, it would be a unique tool of research, well worth the outlay.

Evaluation of the results of operating such a ship eight to nine months annually would require the co-operation of many well-equipped laboratories and specialists, of which there is certainly no lack in the United States. (It would, I believe, exceed the resources of any single existing oceanographic institution.) The project would furnish unique opportunities for training young students in physical and chemical oceanography and in biology. They might compose a large part of the crew, as they did on the "Albatross," where 50% of the crew consisted of young apprentices for the merchant fleet. This way of manning the ship would materially reduce running costs.

Such a ship would certainly exceed the resources of the small Scandinavian nations, which are therefore trying to set up an Inter-Scandinavian organization, planning the chartering, and eventually the building, of a deep-sea research ship run conjointly by Denmark, Finland, Norway, and Sweden. Such a ship, whose working field should mainly be the great depths of the Atlantic Ocean, would afford material for scientific studies to a number of Scandinavian institutes and would materially increase our knowledge of that ocean which is immediately before our door. The new methods developed and tested by the cruises of the "Albatross" and the "Galathea," to mention only two, could be utilized, and the methods of analysis developed for the new material of the last three and a half years could be put to use.

However, the field of work offered by the ocean floor all over the world is so vast that its exploration demands organized cooperation on a large scale from all seafaring nations. With the help of UNESCO efforts are now being made to set up a nucleus for an international organization which could serve as a center for information and exchange of plans and experiences. This would eliminate the undesirable wait of up to several years which workers must frequently endure until the results of deep-sea research are made available through publication. Such a nucleus would be especially useful in planning and equipping new expeditions.

A step in the right direction is the so-called "Joint Commission of Oceanography," in which physical and chemical oceanography, deep-sea biology, and submarine geology are represented. It was set up in September, 1951, at the last meeting of the International Union of Geodesy and Geophysics in Brussels and met for the first time in the fall of 1952 in Monaco. A second meeting was held in September, 1953, at Liverpool.

In this new international work on great depths, where free cooperation, unhampered by military and utilitarian views, is essential, the United States seems predestined to take a leading place. Situated between the two greatest oceans and with institutions capable of handling the rich harvests brought in from the ocean floor, this country has unrivaled opportunities for deep-sea research. When, a few years ago, I visited the observatory at Palomar and examined its wonderful equipment for sounding the depths of the universe, it struck me that a fraction of the capital expended on that institution would suffice for building, equipping, and manning an interstate deep-sea research ship capable of revealing the secrets of the ocean floor and obtaining abstracts from the records of the deep, a field in which Sweden and Denmark, in spite of their size, have made pioneer efforts.

4. The Sediment Carpet and the Substratum

For millions upon millions of years an incessant snowfall of tiny particles has been settling over the ocean floor. The origin of these particles has varied. There is among them exceedingly fine-grained dust from the continents, carried seaward by strong winds, especially from the great deserts. There is volcanic ash, blown high up into the stratosphere at explosive eruptions, which has settled slowly from great heights down to the ocean surface. There are, especially in the vicinity of the continents, minute particles of clay or sand carried into the sea by the rivers. There is even—most interesting of components—cosmic dust from interplanetary space and fragments of meteors heated to incandescence during their fiery flight through the upper layers of air.

In addition to these inorganic particles there are abundant contributions from innumerable marine organisms, mostly of microscopic size, which pass their life in the sunlit surface layers, building up their tiny skeletons or shells from the silica or lime present in the water. After death these remnants, freed from organic matter through bacterial action, sink to the bottom and build up sediments rich in lime or silica. The lime component dominates in the lower latitudes, while siliceous organisms, like diatoms, are largely cold-water algae and form layers of diatom ooze in the far North and South, especially around the icebound Antarctic Continent. Enormous areas of the ocean floor are carpeted with calcareous ooze, the dominant forms being tests or shells from *Foraminifera,* with the species *Globigerina* the most typical component. Nearly 50 million square miles of the deep-sea bottom are estimated to be covered by calcareous ooze, whereas diatom ooze lags far behind with only 12 million square miles.

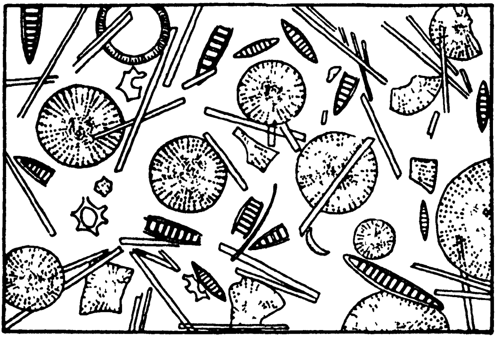

Fig. 18. Diatom ooze

In great depths, however, there is a pronounced reduction in the lime content, generally setting in at 15,000 feet and progressing downward, so that below 18,000 feet carbonate of lime is comparatively rare. In these great depths, therefore, the whitish calcareous ooze is replaced by the so-called red clay, a sediment generally poor in lime but relatively rich in ferric hydroxide and manganese peroxide, which give it a color varying from whitish red to dark chocolate brown. The red clay is estimated to cover not much less than 40 million square miles of the deeper and deepest ocean floor. The origin of red clay still offers unsolved problems to submarine geology. Normal components are volcanic material—ash, mineral grains, and waterlogged pumice—which has been carried over great distances by surface currents. An admixture of siliceous skeletons from diatoms or radiolarians is not uncommon, the latter especially in the equatorial region, where

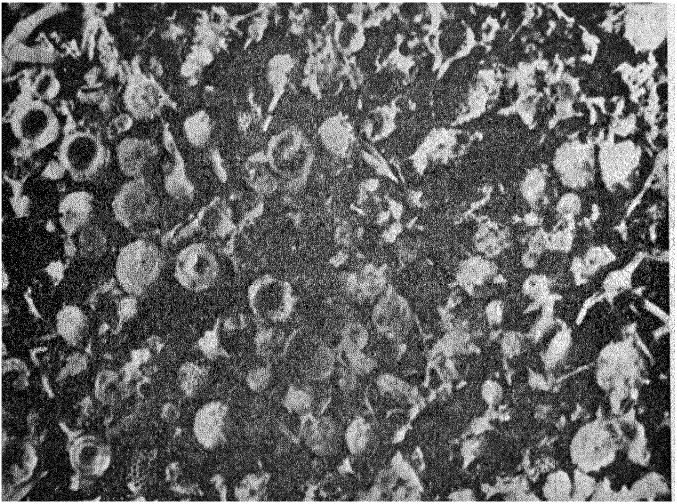

Fig. 19. Radiolarian ooze (radiolarit)

the red clay sometimes takes on the character of radiolarian ooze. Calcareous remains of larger marine organisms, like sharks' teeth and ear bones of whales, frequently occur in the red clay. Highly curious products of the chemistry of great depths are the so-called "manganese nodules"—concretions built up by accumulation or accretion of ferric hydroxide and manganese peroxide around a nucleus, say a shark's tooth or fragment of pumice. These manganese nodules are products of immensely slow growth, the rate of which it has been possible to measure by radioactive methods.

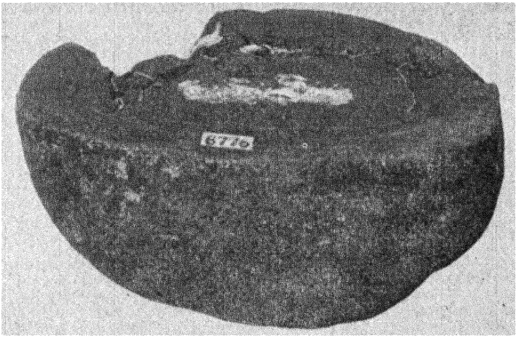

Fig. 20. Manganese nodule halved

Two of the most difficult problems of deep-sea research are determining the rate of sedimentation and explaining the stratification often found in cylindrical cores raised from deep-sea deposits. The methods used for studying and dating such records of the deep and what conclusions deep-sea chronology has contributed will be described below. Here, as an introduction, I shall summarize what we know about the total thickness of the sediment carpet and its substratum, the rock bed of the ocean floor.

By theoretical reasoning various authors have tried to estimate the amount of sediment accumulated on the deep-sea floor since the birth of the oceans, assumed to have taken place between two and three billion years ago. As a basis for these speculations general geochemical considerations have served, notably the quantities of debris carried oceanward from rocks which have eroded on the continents. Out of such debris certain components have remained in solution, whereas others have reached the sediments on the ocean floor. The conclusions drawn from these calculations have been variable, ranging from a few hundred feet to over 70,000 feet. As a result of most painstaking work, Philipp Kuenen of Groningen in Holland, one of the leading European authorities on submarine geology, has worked out theoretical average thicknesses of pelagic ocean sediments. According to Kuenen the average thickness of deep-sea sediments should be about 3 kilometers. For red clay, which has the lowest rate of sedimentation, he found 2.2 kilometers, or over 7,000 feet, to be the most probable average thickness.[1]

If we ascribe to the time of accumulation a total length of two billion years, Kuenen's figures would necessitate an average rate of sedimentation for red

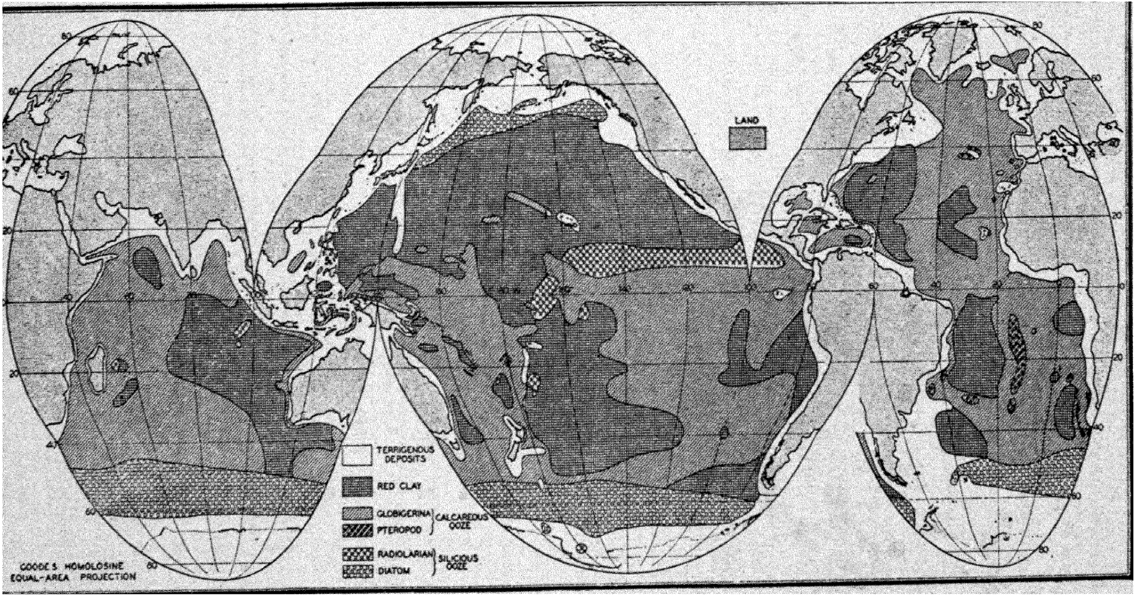

Fig. 21. Distribution of pelagic sediments

clay of roughly one millimeter, or not quite .04 inches, in 1,000 years. For the *Globigerina* ooze the corresponding figure is .4 inches in 1,000 years. Obviously, these calculations require a huge extrapolation from known figures. The rate of denudation of the continental rocks and the rate of productivity of plankton organisms in the sea are bound to have varied greatly with both climatic changes and alterations in the orography of continents. Furthermore, it is evident that the actual thickness of the sediment carpet in a given locality is likely to show considerable deviation from the average for the whole ocean floor. In general the very lowest rates of sedimentation are found in the central parts of the oceans, especially in that of the Pacific Ocean, where the distance from the surrounding continents reduces contributions from terrigenous components and where the accumulation of biogenetic matter has been largely counterbalanced by chemical action from the bottom water, acting especially on calcareous components.

Direct measurements of the thickness of the sediment carpet in great depths down to the underlying bedrock or, to be more exact, to transition surfaces within the sediment which are capable of reflecting acoustic signals have become possible only in the last decade. The method used may be called "seismic," since it is analogous to that used by seismologists for studying the internal structure of the earth and its crust by observing the elastic vibrations emanating from earthquakes. However, when studying the sediment layers in the ocean, the experimenter has to produce his own local earthquakes by means of explosives.

The first successful attempts to measure the thickness of the sediment layers in great depths were made by Weibull. After experimenting for some years in Swedish coastal waters, he brought his equipment on board the Swedish government research ship the "Skagerak" for its experimental cruise to the western Mediterranean in the spring of 1946. Weibull used the "reflection method," because it was the quickest and required a minimum outlay of time and money. A depth charge is made to explode by means of an ignitor released through hydrostatic pressure in depths varying from 1,500 to 20,000 feet under the water surface but well above the bottom. The arrival at the surface of the sound waves set up by the explosion is registered by hydrophones of special construction hung out over the sides of the ship, the electrical impulses from which are transmitted to an oscillograph in the laboratory. On the oscillograms obtained one recognizes signals set up by the direct sound waves of the explosion, followed by repeated echoes from the water surface and the bottom, which can easily be identified. But there are also much weaker and more retarded echoes, due to sound waves which have penetrated through the sediment layer twice and become reflected against transition surfaces within it, or from the underlying rock bed. Experience gained during this experimental cruise was encouraging but called for further improvements in the equipment, which was then installed on the "Albatross," Weibull himself supervising the work during the first transatlantic crossing.[2] Since then the method has been much improved by introducing the wire recorder for the immediate registering of the echoes, a transfer to oscillograms being made later in the laboratory on shore. A highly simplified explanation of how the method works is given in Figure 22, while 23 is a reproduction of one of Weibull's most interesting oscillograms, obtained in the central Atlantic Ocean between Madeira and the Mid-Atlantic Ridge. We can see three breaks in the record, due to deep echoes thrown back by three different reflecting layers in the bottom, the uppermost at a sediment depth of 5,150 feet and the

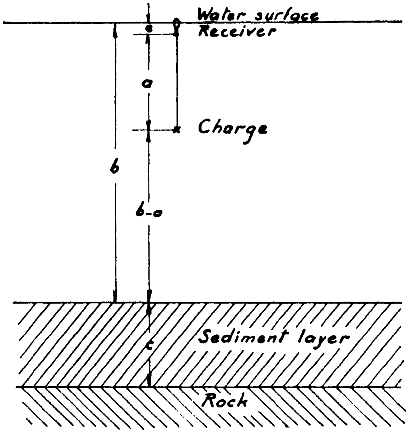

Fig. 22. Weibull's scheme for reflection measurements

middle one at 7,350 feet. The deepest, which is presumably reflected from the bedrock beneath the sediment carpet, indicates a total thickness of the latter of no less than 11,600 feet, which is a record for the cruise.

These figures, quoted from Weibull's paper now being published in the Reports of the Swedish Deep-Sea Expedition, are liable to certain final corrections. One of them concerns the comparative difference in the velocities of sound in sediment and water, the latter figure, some 4,900 feet a second, having been used in translating the time lag into sediment thickness. According to American authors who have been working with a method to be described below, the velocity of sound in sediments from the coastal shelf is 15% to 20% greater than in water. Weibull, who is at present in-

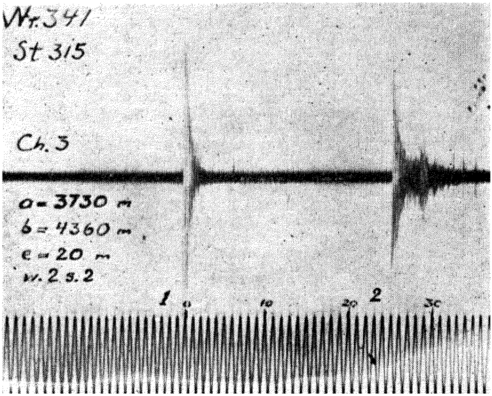

Fig. 23. Diagram from Weibull's measurement

vestigating this point in the laboratory with original sediments from the "Albatross" cruise submitted to high pressures, has found considerable variation in the figures for different kinds of sediments, some of which give a velocity distinctly *less* than that of water! Until more data of this kind have been obtained, it seems best to accept provisionally the velocity for sea water as a basis for calculations.

Figure 24 is a diagram of information on thickness gained from other parts of the ocean. This shows the figures just quoted to be distinctly greater than any found elsewhere. It is especially noteworthy that in both the Pacific and Indian Oceans the sedimentary thicknesses found were only a fraction of the record thickness from the Atlantic. I shall return to this surprising result below.

A few words might be added concerning the two advantages of Weibull's method, namely its quickness and cheapness. For recording the echoes from depth charges exploding in depths as great as 20,000 feet it is not necessary to keep the ship hove to for more than half an hour. Generally, two or even three charges, exploding at different depths, are used simultaneously. The cost of the whole equipment, including hydrophones and wire recorder, is very moderate, not exceeding $1,000. Moreover, by changing the time scale and amplification at will in the transfer to the oscillograph afterward, and by using electric "timeband-pass" filters, one has facilities for examining the fine structure of the

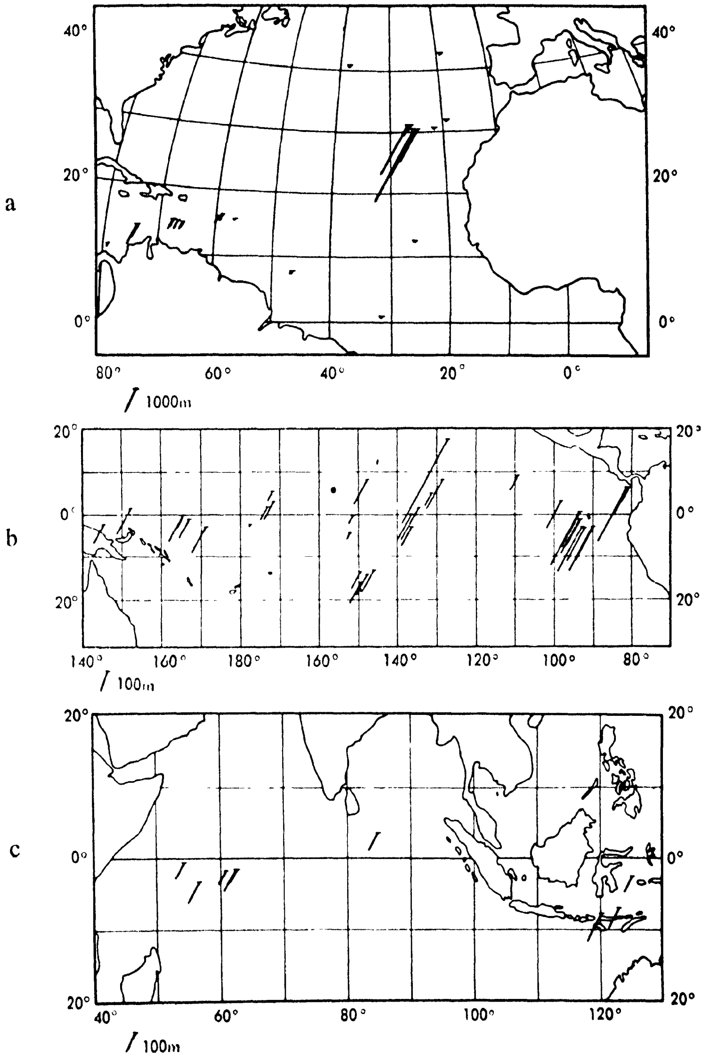

Fig. 24. Sediment thicknesses found by Weibull: *a,* Atlantic; *b*, Pacific; *c*, Indian

returning sound waves in great detail. Weibull claims that with the latest modifications in his equipment he is able to distinguish between two reflecting layers situated at levels only about 30 feet apart, a much greater separation than that achieved by other methods. One decided improvement is in the use of depth charges exploding *in the sediment itself* instead of above the bottom. In this manner the complications due to spurious echoes from hills and hummocks—in which the deep-sea bottom unfortunately abounds—can be minimized or even avoided, giving distinct and clear records where an ordinary depth charge will give a protracted series of echoes overlapping those from deeper layers.

Returning to the results so far gained, one may say that if we accept Weibull's maximum sediment thickness in the central Atlantic of about 12,000 feet, and if we further assume that the whole of this sediment is of the same type as its surface layer, namely Atlantic red clay, we can make an approximate estimate of the time required for accumulating a layer of this thickness. Taking .3 inches in 1,000 years as a reasonable value for the rate of sedimentation of Atlantic red clay, we arrive at a time span of nearly 500 million years. There are, however, two circumstances which tend to make this estimate too low. One is the so-called "compaction" of the lower layers of the sediment, due to the fact that the pressure from the superposed layers of sediment tends to squeeze the water out of the deposit and may thus easily reduce its total thickness by 40% or even more. The second factor is possible variations in the rate of sedimentation which may have occurred during the enormous span of time involved. For several reasons it is highly probable that our present epoch is one of abnormally intense continental erosion and rapid submarine sedimentation, or in other words that the growth in thickness of the sediment carpet in bygone ages went on at a considerably slower rate than at present. These two circumstances may well increase the time required for accumulating the sediment layer measured by Weibull by a factor of 2 or 3, if not even more.

At any rate, it is evident that the age of the particular part of the Atlantic Ocean where these great thicknesses were found must be counted in many millions of years. This appears to knock the bottom out of the famous "continental drift" theory of Wegener, according to which the Atlantic Ocean should have begun to open up in Cretaceous time, that is, 60 to 80 million years ago.

The explanation for the much lower figures found in the other oceans is even more far-fetched. They cannot well indicate a *lesser* age of the oceans in question, but may instead be due to a much lower rate of sedimentation. In fact there are certain indications that at least in the central parts of the Pacific Ocean the accumulation of red clay proceeds at a rate about ten times slower than in the central Atlantic.

There is, however, another circumstance which may possibly explain our failure to obtain echoes from greater sediment depths than a few hundred feet. Experience has shown that lava crusts due to submarine volcanism are not uncommon in the Pacific and Indian Oceans, crusts which occasionally have worked havoc with our long piston-corers. If the sediment is interfoliated with a number of such layers of sediment-covered lava, it is quite possible that the explosion waves are partly reflected back from their upper surfaces and so much attenuated in penetrating through the lava crust that the echo returning from a still deeper separation surface is too faint to be recognized on the oscillograms. Here the use of powerful "sediment bombs," exploding below the bottom surface, may increase the range of penetration.

One disadvantage of Weibull's reflection method is that it fails to give any information regarding the nature of the substratum. For this purpose the so-called refraction method can be used. It is much more complicated and expensive, but it does allow studies of the unknown substratum beneath the sediment carpet. It was first used successfully by Ewing and co-workers off the Atlantic coast of the United States, where a wedge-shaped sediment layer was found, increasing in thickness to about 13,000 feet at the beginning of the continental slope.[3] Similar results were obtained later from the west coast of the British Isles by E. C. Bullard and others.[4] In later years Ewing has been able to extend his refraction measurements to great ocean depths. The results he has obtained, largely from the northwest Atlantic Ocean, as well as those more recently found by the English investigator M. N. Hill working from one of the weather ships in the northeast Atlantic, are truly remarkable and must be briefly summarized.

What lies beneath the sediment carpet, the rocky basement of the ocean floor? This problem has for generations puzzled geologists and geophysicists. Seventy years ago Eduard Suess, the great Austrian geologist, put forward the hypothesis that the ocean floor is built of a material different from that of continental rocks and representative of a deeper shell of the earth's crust. This material he called "sima." It was assumed to have a more basic chemical composition than the continental surface rocks, which are largely granitic and have aluminum silicate as their dominating component, whereas in the lower, less acid rocks silicates of magnesium are dominant. Hence the abbreviations "sial" and "sima," which have been adopted by most authors dealing with the subject.* This differentiation between the two upper layers of the crust was further elaborated by another Austrian, Alfred Wegener, who assumed the continents to be blocks largely made up of sial floating on a substratum of sima, which because of a higher specific weight and a greater

---

* Quite recently Benno Gutenberg has adopted a somewhat modified nomenclature. See p. 65.

degree of plasticity allows the floating blocks of sial a certain freedom of movement in both vertical and horizontal directions (see page 17 above). Where rocks of deep origin have been thrust above the surface, as in most oceanic islands, the material is generally of the composition ascribed to sima. The very rare fragments of rocks obtained from great ocean depths by means of dredges and trawls have also, in general, this basaltic composition. Such samples, however, are very scarce and therefore vast stretches of the solid ocean floor are not accessible to direct observation.

Fortunately there are other methods. As a skilled doctor can investigate the health of certain internal organs by the percussion method, listening to the sound reflected from cavities, so the seismologist can utilize the tremors set up in the interior of the earth by earthquakes, and by means of seismographs study the propagation of the seismic waves, even down to the innermost core of the earth. The character of these vibrations from distant epicenters and their rate of propagation in different layers of the earth yield information on the structural status and elastic properties of these layers.

However, as already mentioned, science has not been content with utilizing the natural tremors of earthquakes. It has also produced tremors *artificially* through exploding charges, as described above (p. 34). Studies of this kind have been a valuable aid in attempts to locate on the continents underground mineral ores, rock salt, and especially oil—an application recently extended to the bottom of shallow coastal seas, where oil is in fact being found.

The first definite results regarding the propagation of earthquake waves through the upper parts of the continental crust were given by Mohorovic over forty years ago. He found that the longitudinal waves travel at a velocity of 5.6 km/sec through the uppermost, so-called granitic, layer, a velocity which increases to 7.8 km/sec at a depth of about 50 kilometers. More recent studies of waves propagated by great explosions have revealed the rather startling fact that there exists in the earth's crust a low-velocity layer, within which the velocity decreases instead of increasing, as would be expected with increased depth, a curious analogy to the SOFAR layer of minimum velocity found in the sea. The existence of such a layer within the uppermost crust of the earth would, according to Gutenberg, explain certain apparently contradictory results obtained from the study of seismic wave propagation. This view would also lead to a reduced thickness of the uppermost granitic layer: from over 20 kilometers to only half that amount.

As for the structure of the ocean bottom, it differs materially from that of the continents. But there are also marked differences between the different oceans. Adopting with Gutenberg the following terminology: sialic rocks with velocities of up to 6¼ km/sec, simatic rocks with velocities in excess of this limit but less than 8 km/sec, and ultra-simatic rocks with between 8 and

8¼ km/sec, we may locate the Mohorovicic Discontinuity at the upper boundary of the last-mentioned rocks.

One then finds an area in the eastern part of the Pacific Basin where the ultra-simatic layer begins at a depth of only a few kilometers, whereas in the northwest Atlantic Ocean material with a velocity of 7½ km/sec seems to exist at the corresponding depth. In the eastern Atlantic Basin the velocities found by Hill, working from a weather ship, may even indicate the presence there of a sialic layer beneath the sediment.

There are, if we return to the Pacific Ocean, clear indications of a boundary between the deep ocean basin and the continents. On the ocean side of this boundary one finds great deeps, negative gravity anomalies, and shallow earthquake centers. Nearer land comes a narrow belt of earthquake centers, starting from depths of 70 to 150 kilometers, and lines of active volcanoes. Still farther landward is the region from which emanate the shocks of very deep earthquakes, down to 700 kilometers. Within the Pacific Ocean proper, with the exception of the Hawaiian area, no earthquakes are known to have occurred.

No similar earthquake belts surround the whole or part of the Atlantic or Indian Oceans. In both, active belts of shallow earthquakes follow submarine ridges within the oceans, similarly to continental earthquake epicenters along mountain ranges. Gutenberg, from whose recent paper on crustal layers of the continents and oceans most of the preceding data have been taken, summarizes his view by asserting that for the present study of major tectonic and geophysical processes the boundary of the Pacific Basin, the so-called Marshall Line, seems to have more importance than any other crustal boundary and to be frequently marked by a sharp, deep-reaching discontinuity, whereas transitions of the Atlantic types usually seem rather gradual.[5]

In the same volume of the *Bulletin of the Geological Society of America* there is an excellent paper on submarine topography in the North Atlantic by Tolstoy, giving a résumé of the results of work done by the Lamont Observatory of Columbia University and the Woods Hole Oceanographic Institution.[6] I shall briefly summarize some of the most important conclusions from this paper, insofar as they refer to the Mid-Atlantic Ridge.

During the German cruises in the mid-twenties and early thirties considerable light was thrown on the nature of the Mid-Atlantic Ridge, thanks to echo soundings. Especially in its northern parts, north of the Azores, it was found to have a structure resembling that of folded mountains, with more or less parallel ridges running from north to south and separated by deep, almost Alpine valleys. One of the foremost specialists in geotectonics of West Germany, Hans Cloos, who died in 1951, made successful attempts to imitate the shape of the ridge and the Azores Plateau by squeezing a plastic material through a narrow fissure.

Regarding the past history of the Mid-Atlantic Ridge, Tolstoy and others believe that there have been two major periods of activity in the history of both the Azores and Iceland, one during early or middle Tertiary and the other during late Tertiary to Recent. This suggests that the origin of the ridge may be associated with the Alpine orogenies. Gutenberg and Richter in 1949 even suggested that the Mid-Atlantic Ridge may be a belt of Tertiary folds, the high degree of seismicity characterizing it being due to block faulting, following a redistribution of tectonic forces. This view of active tectonic forces in great ocean depths I shall discuss further in Chapter 6.

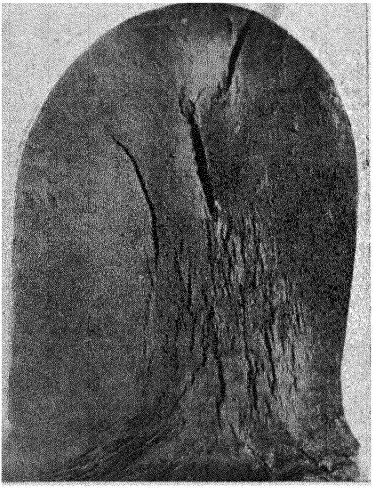

Fig. 25. Model from Cloos' experiment

5. Recent Developments in the Investigation of the Deep Ocean Floor

Since the conclusion of the Swedish Deep-Sea Expedition, considerable progress has been made in investigating the ocean floor by seismic and other methods. A brief summary of these investigations, insofar as they have been published, is given in this chapter.

As stated above, the method generally used in the seismic investigations has been that of refraction shooting, in which sound waves from depth charges exploding at distances of several miles from the ship are recorded by means of hydrophones suspended near the water surface. This method affords an advantage over the reflection method by revealing not only the thickness of the unconsolidated sediment carpet but also the velocity of sound waves through the underlying substratum.

The results of recent investigations in the Pacific Ocean by British and American expeditions have in general confirmed earlier results from the "Albatross" concerning thickness of the sediment carpet, namely that this thickness is much less than has been inferred from theoretical calculations based on geochemical data. Thus, in the Pacific depths a sediment thickness of a few hundred meters is the rule, with the figure occasionally rising as high as half a kilometer, compared to the two to three kilometers calculated by Kuenen as average for the thickness of deep-sea sediments. How this startling discrepancy is to be explained remains at present an open question.

In the North Atlantic Ocean, where Weibull found the greatest sediment thickness, between Madeira and the Atlantic Ridge, measurements by the refraction method made by Ewing and others have given lower figures than the maximum found by Weibull, but on the other hand higher than those from the Pacific depths, namely one-half to one kilometer of unconsolidated sediment. Only in the Puerto Rico Trench, where the greatest known depth in the Atlantic Ocean is situated, has a sediment thickness exceeding nine kilometers been reported by Ewing. In the northeast part of the Atlantic Ocean M. N. Hill and A. S. Laughton have reported a variable thickness of the sediment carpet, from very low in areas of rugged bottom topography to as much as two and a half kilometers over parts of the sea floor with a less rugged structure, the average thickness being about one kilometer. This is higher than the findings of Ewing in the northwest Atlantic, but the difference can be attributed in part to different assumptions concerning the velocity of compressional waves in the sedimentary layer.

Important contributions to this problem have been obtained from the recent "Capricorn" Expedition to the equatorial and southern Pacific Ocean, planned and directed by R. Revelle, director of Scripps Institution of Oceanography. This expedition, which was excellently equipped and carried a picked staff of scientists—among others Arrhenius, Riedel, and Rotschi—had the advantage of being composed of two ships which worked together, especially at refraction shootings. The results have been incorporated in a preliminary report, which may be briefly summarized.

The seismic refraction work carried out during the "Capricorn" Expedition and earlier expeditions in the Pacific Ocean indicates that the thickness of unmetamorphosed sediments over a large part of the deep Pacific Basin is at most a few hundred meters. Geochemical considerations require that the total thickness of deep-sea deposits laid down throughout the geologic past should be five to ten times this figure. From the estimated rate of deposition during and since the Tertiary we find that the observed thickness of sediments corresponds at most to a deposition over one or two billion years. We are thus almost forced to the conclusion that if deposition of sediments was taking place in the deep sea prior to the late Mesozoic, these earlier deposits are not now present in unmetamorphosed form.

The seismic work on the Mid-Pacific and "Capricorn" Expeditions has shown quantitatively how remarkably thin the crust beneath the Pacific really is. Typical thicknesses are five to nine kilometers, compared to a thickness of 30 to 40 kilometers beneath the continents.

The Nature of the Substratum Underlying the Sediment Carpet

Investigations from H.M.S. "Challenger" in the Pacific made by T. F. Gaskell and J. C. Swallow are of particular interest. These authors state that they have found three different types of suboceanic crustal structure. The first, typical of the deep ocean floor, consists of less than half a kilometer of sediment lying on a substratum, in which the velocity of sound is only slightly less than in basaltic layers. The second type is similar to that of the deep ocean, except that intermediate between the sediments and the basement rock there lies a layer in which the velocity of sound is that which would be expected for volcanic material, having a thickness of 1½ to 2½ kilometers. This interpretation is supported by the occurrence in the same region of volcanic islands and sea mounts. The third type, characteristic of stations in the western Pacific on the landward side of the "andesite line," shows basement velocities less than those found in the other types and similar to those in the continental surface layers. The results from the Atlantic part of the cruise were mostly obtained in the region of Bermuda and show the second type of structure, that is, with a layer of volcanic material interposed between the sediments and the basement rock.

During the "Albatross" cruise the extensive lava beds in great ocean depths were forcibly brought to our notice through lost or bent coring tubes (Figure 26). The interference of such sediment-covered lava beds with the echoes from Weibull's exploding depth charges was at first suggested as a possible explanation for the missing echoes from still deeper reflecting surfaces. The influence of submarine volcanic action on the composition of the sediments and especially on the solution

Fig. 26. Corer bent against lava bed

of lime is probably an important factor in deep-sea geochemistry.

Below the volcanic layer, where it exists, there are, according to Ewing, crystalline rocks four to five kilometers thick, which are probably basaltic. At the base of this basaltic layer there is the so-called Mohorovicic Discontinuity, which under the deep ocean lies at a depth of only ten to twelve kilometers, whereas under the continents this discontinuity lies at a depth of between 30 and 40 kilometers. Below the discontinuity the earth's mantle extends to great depths and is probably of the type of ultramafic rock called peridotite. It seems probable that the peridotites found on St. Paul's Rocks in the equatorial Atlantic Ocean are representative of the layers below the Mohorovicic Discontinuity. Our knowledge of these deeper parts of the earth's mantle is still very imperfect, and the velocity of the compressional earthquake waves passing through them has not been determined with any high degree of accuracy, the highest figure so far reported being about 7½ km/sec.

The Transportation of Sediments along the Ocean Floor

Kuenen has devoted extensive studies on the laboratory scale to the so-called turbidity currents. He ascribes to them a great importance not only over the continental slopes but also on the deep ocean floor, where they have been held responsible for the transportation of deep-sea sand over several hundred nautical miles from the nearest coast line. On the other hand other scientists, both geologists and oceanographers, are skeptical of the hypothesis advanced by Ewing and Bruce C. Heezen that successive cable breaks on the continental slope and in the deep water off the Grand Bank following an earthquake in 1929 could have been caused by turbidity currents running at a computed velocity of up to 55 knots.[1] To most students of dynamic oceanography and especially to students of bottom currents so high a velocity for a submarine current appears excessive.* Ewing also asserts that turbidity currents, far from being confined to regions of steep slope, can be sustained along slopes as moderate as 1:500. As regards the power of turbidity currents to cause submarine erosion and, more especially, to have eroded the famous submarine canyons along both the Atlantic and Pacific coasts of North America, a specialist on these canyons, Shepard, considers that whereas turbidity currents may be active in sweeping the submarine canyons already eroded free from fresh sediment layers, they cannot be held responsible for the origin of the canyons, since, being already loaded with sediment, their power of erosion is inadequate.[2]

* W. Ekman, the great authority on ocean currents, in a letter to the author dated August, 1953, expressed strong skepticism that bottom currents even approaching these velocities can occur in nature.

One characteristic ascribed by Kuenen to turbidity currents is their capacity of leaving behind so-called graded bedding, in which the size of the particles regularly decreases upward, owing to the settling of coarser particles at a quicker rate. Cases of graded bedding have in fact been found by mineralogists working on cores from the "Albatross," especially in a long core from the center of the Tyrrhenian Sea studied by E. Norin of Uppsala. On the other hand Otto Mellis of Stockholm, who has made an extensive study of other cores from the Mediterranean, has declared graded bedding there to be rather the exception than the rule.

Leaving an open question the prevalence of turbidity currents in particular areas of the sea, one seems justified in asserting that the theory that they are the dominant, still less the only, cause of bottom currents in great ocean depths is not borne out by our present knowledge of deep-sea sediments. Still less does it appear well founded to state that all cases of extensive flat bottom in great depths are due to turbidity currents. According to this view it would be useless to collect and investigate long sediment cores, since one would suspect their layers of having been reshuffled by turbidity currents.

6. The Deep-Sea Deposits and Their Stratigraphy

In Chapter 4 a survey was given of the different sources of the sediment carpet covering the basement of our planet, the deep ocean floor. Of the two main sources the continents provide the warp, of inorganic origin: airborne or waterborne particles, microscopic or even submicroscopic in size, which form the deep-sea clay. The ocean itself contributes a woof of biogenetic origin: particles extracted from the sea by a multitude of living organisms, mostly plankton, drifting in the upper layers of water, from which they accumulate either silica or carbonate of lime in the shape of tests or skeletons, which are ultimately deposited on the bottom. A much smaller contribution comes from the bottom-living organisms, the *benthos,* which are always animals, since daylight, the *sine qua non* of plant life, is absent in depths exceeding a few hundred feet.

A third major contributor to the deposits is volcanism. After great explosive outbreaks of volcanoes on the continents or on volcanic islands, ash particles, thrown high into the air, settle down to the sea surface over thousands of square miles, ultimately reaching the ocean bed and sometimes in quantities sufficient to form layers of volcanic ash. Submarine volcanism is also a contributor, on a scale probably much vaster than we have hitherto been inclined to assume.

The relative amounts of these different components vary all over the ocean according to latitude, distance from continents and islands, water depth, water movements, etc. The quantity of dust and clay particles from the continents varies also according to the great cycles of mountain building (orogenesis) and erosion (vastage), processes which are themselves dependent on climatic variations. These climatic changes, moreover, directly affect the quantity of planktonic and benthonic remains which, to a considerable extent, depend on the temperature of the surrounding sea water. It is only

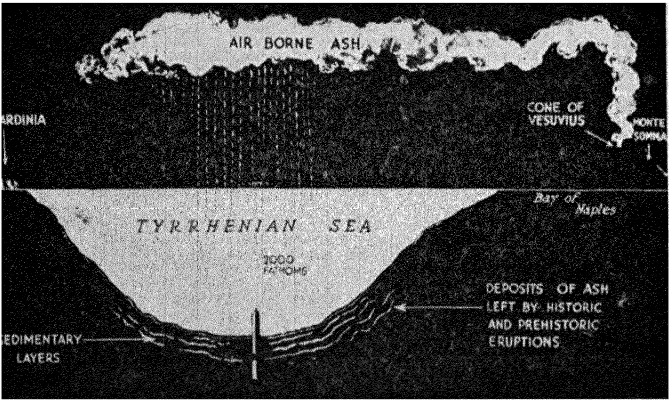

Fig. 27. Ash rain over the Tyrrhenian Sea

natural, therefore, that deep-sea sediments should display differences in composition, not only from one locality to another but also with their depth below the sediment surface. Granting that deposition has proceeded undisturbed through millions of years, one would expect a core of sediment stamped out of the sea bottom to display in its different layers effects of the changes which have taken place during the time required for deposition, in other words to represent an abstract of what one might call "records of the deep," just as geologists working on the continents are wont to regard their profiles of sedimentary material on land as "records of the rocks."

However, these latter records have in most cases been exposed to attacks from temperature changes, wind, frost, and running water, giving rise to erosion which has sometimes eliminated chapters or even whole volumes of the sequence. The "records of the deep," on the other hand, protected under thousands of feet of sea water, should represent, one would expect, unbroken sequences with no parts missing.

These expectations have been largely fulfilled by scrutiny of the hundreds of long sediment cores raised by Swedish expeditions, first from the "Skagerak" and later from the "Albatross." In relatively few cases—mostly in cores from great depths, containing red clay—does such a long core present to the eye a homogeneous appearance. Usually the cores display a stratification, with differences in structure and color; and the inter-

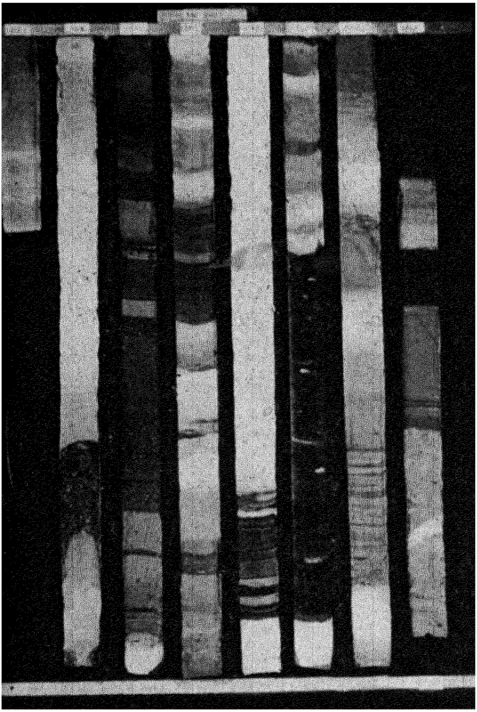

Fig. 28. Deep-sea core from near Cyprus

faces between successive layers are often quite distinct. Such stratified cores were frequently raised from the equatorial zone, where most of our work was carried out.

However, even in great depths there may have been interfering forces. On steep slopes and immediately below them there is always the possibility of submarine landslides, set into motion by seaquakes or volcanic eruptions. Related factors are the much discussed "turbidity currents" referred to above. Moreover, in certain localities there exist, even in great depths, burrowing animals like mud-eaters which delve into the uppermost sediment layers, where they may disturb, in certain cases even efface, boundaries between the different strata. Finally, bottom currents of various origins have a tendency to stir up sediment particles already settled and prevent fresh particles from coming to rest, especially where such bottom currents are intensified by passing over a submarine mound or ridge. When one is reading the records of the deep, the possible effects of all these disturbing elements on the sequence and structure of the strata must be considered.

Let us for a moment assume that the dismal fate intimated in Chapter 1 has actually overtaken our earth, namely that all the water masses of its oceans have disappeared. A trip by caterpillar jeep over the ancient sea bottom would be fairly rough going. Hills and hummocks would jut up through the sediment, and we might find ourselves negotiating steep slopes. In certain regions, as in the central Atlantic Ocean, mighty mountain chains equaling in length the Andes and Rockies together would rise before us. If we were to knock off fragments from these submarine mountains, we would find them composed of a material different from that of the continents. Mafic and ultramafic rocks from deep layers of the earth's crust would predominate.

However, the most interesting material to be met with would be the sediment carpet coating the slopes of mountains and surfaces of valleys. From the blueish clay lining the continental slope, down which we would make our entry into the abyssal region, we would come to whitish or yellowish calcareous ooze spread over the medium depths. Examining it through a magnifying glass, we would find it consists of myriads of small rounded-off tests or shells of dead plankton from the surface of the sea—the *Foraminifera* which pullulate especially in the tropical regions of our present oceans and which for untold millions of years have been settling to that great churchyard of marine creatures, the ocean floor. In certain regions, especially in high southern latitudes, a look through the microscope would reveal the presence of tiny silica skeletons from marine algae which thrive in the nearly ice-cold arctic and antarctic water, forming a siliceous deposit of diatom ooze on the bottom. Around the Scandinavian coasts their annual flowering in early spring fills the larder of the sea with materialized sunshine, transformed into potential foodstuff in the form of this microscopic grass on the meadows of the sea (Figure 29).

Proceeding to still greater depths, we would find the hue of the sediment carpet changing to red or deep chocolate brown. We would then have reached the very basement of our planet, covered with the mysterious red clay which carpets over 40 million square miles of the deepest ocean floor. From it the tiny calcareous shells would have mysteriously disappeared or else have grown very thin and frayed. Since they are as numerous in the surface layer of water above red clay as they are above calcareous ooze, it is believed that the lime-dissolving power of cold bottom water is responsible for this transformation of calcareous ooze into red clay.

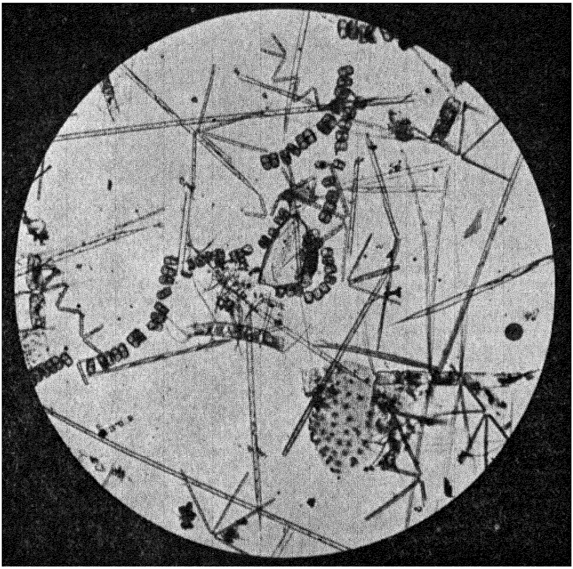

Fig. 29. Diatoms from the spring flowering

If we should examine this reddish sediment carefully, we would find here and there, especially near the equator in the Pacific Ocean, that the foram shells had been replaced by exquisitely shaped silica skeletons of radiolarians—the miniature jewelry of the abyss, as the great German biologist Haeckel called them.

In certain regions of the red clay area we might find curious potato-like or cauliflower-shaped brown to black "mushrooms," the so-called manganese nodules, slow growths of the abyssal field which may have required tens of thousands of years to attain the size of a golf ball. Very rarely the tooth of a giant shark or the ear bone of a whale is also to be found there, covered with a thin crust of the all-pervading manganese peroxide, the sugar coating of deep-sea confectionery. If we were to bring with us a sensitive Geiger counter, we would be surprised by the volley of radioactive particles

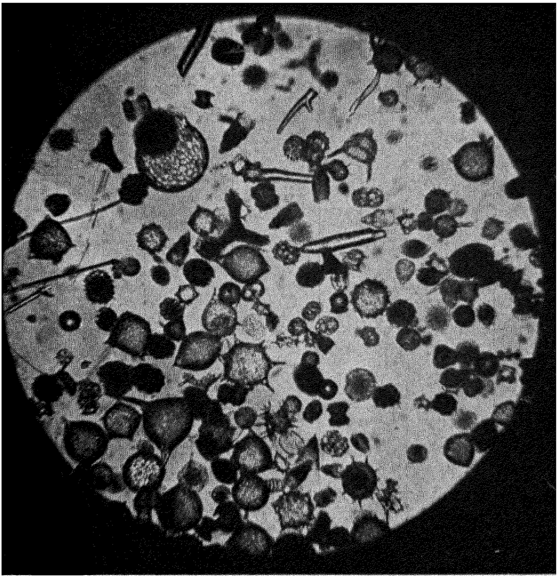

Fig. 30. Radiolarians from Pacific depths

coming from the surface of the red clay, proving that it is relatively rich in radium.

Oceanographers of the present are unfortunately not able to make such excursions over the ocean floor. Instead, we have to send into the depths our instruments, trawls, dredges, and coring devices for sampling the sediment carpet and bringing the catch up to the surface for examination and analysis in the laboratory. In Chapter 3 I tried to describe how this is achieved and how, thanks to new techniques and instruments, we are now able to measure the thickness of the sediment carpet by seismic methods and extract cores from its upper layers exceeding 60 feet in length, that is, at least six times longer than was possible only ten years ago.

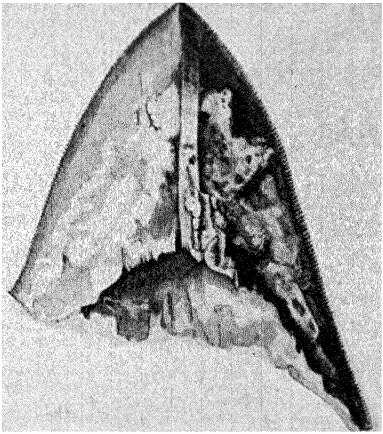

Fig. 31. Tooth from giant shark

What information has been obtained from these unique extracts of the records of the deep? Since the Swedish Deep-Sea Expedition returned to Göteborg in the beginning of October, 1948, a score of specialists in different sciences have been engaged on the archaeological task of unraveling the past. The work, which has been coordinated by the Oceanographic Institute of Göteborg, has met with generous support and collaboration from eminent scientists, not only in Sweden and on the European continent, but also in Great Britain and the United States. Some of these investigations have already been concluded and their results are being published as the Reports of the Swedish Deep-Sea Expedition. Others are still under way. It has not been possible to realize our hopes of having the whole work finished and ready for publication within a five-year period, but in the course of another few years one may expect the last volumes of the Reports to be printed or printing. Obviously the usefulness of our results to colleagues in other countries depends largely on how soon they can be made available. Thanks to generous support from the National Research Council of Sweden, from the Geological Society of America, and from various private donors, the high costs of working up the vast material and publishing the main results are being met.

In the meantime we have had the satisfaction of seeing the work planned for the "Albatross" cruise taken up by other countries. Several deep-sea expeditions, the most famous being that of the Danish ship

"Galathea," have been active since our return. From some of them striking confirmation of our own results has been reported (See Chapters 5 and 7).

The unique deep-sea electric winch constructed for the "Albatross" was taken over by the Danish expedition and did excellent service during their record trawlings and dredgings. We may claim, I think, that the Swedish Deep-Sea Expedition has acted as a catalyst on active interest in deep-sea research in various countries.

It is not an easy task to give even a highly condensed summary of the main results so far obtained from the material collected by the "Albatross." The rest of this chapter will be primarily devoted to the finds concerning deep-sea deposits and their stratigraphy, and the results of investigations of the long cores raised from great depths in the Atlantic, Pacific, and Indian Oceans.

Because of the energy and foresight of Kullenberg, who himself raised the cores from the ocean floor and supervised the packing and storing of long cores, the material suffered very little change and could be sampled in a most efficient manner. On an average, samples were taken from each ten-centimeter length of the core, leaving half of the cylindrical core intact as an "archive half" for future supplementary and confirmatory measurements.

The chemical analyses of four of the most important components, calcium carbonate, humus-carbon, phosphorous, and nitrogen, were carried out in the private laboratory of Olof Arrhenius at Kagghamra, Sweden, where his son Gustaf Arrhenius worked upon the core material from the eastern Pacific Ocean. Gustaf Arrhenius' work will be specially dealt with in the next chapter.

The analysis of the iron-group elements, the ferrides iron, manganese, nickel, and titanium, which are of special interest in the composition of the deep-sea sediments, was largely carried out in Göteborg by H. Rotschi and R. Berrit of the Département de Recherches Outre Mer in Paris, with the aid of microchemical methods. In addition, certain cores were analyzed by spectrographical methods in Stockholm by S. Landergren. A mineralogical study of a number of cores was carried out in Sweden by Otto Mellis of Stockholm, E. Norin of Uppsala, and more recently by K. Fredriksson in Göteborg; in Paris by A. Cailleux and S. Duplaix; and in Göttingen by students under that master of sedimentology, C. Correns. A special interest adheres to the radioactive elements in the sediments. Measurements of radium were carried out in Göteborg, largely by Viktor Kröll, formerly of the Institut für Radiumforschung of Vienna; uranium determinations were made by F. Hecht of Vienna; and ionium and thorium measurements by E. Picciotto and his staff in Brussels.

The very important microbiological work on the forams present in the samples was undertaken by W. Schott of Hannover, Phleger and his co-workers in Scripps Institution of Oceanography in La Jolla, Wiseman and C. Ovey of the British Museum in London, and F. Brotzen in Stockholm. The radiolarians were investigated in Göteborg and later in Scripps Institution by Riedel of Adelaide, Australia; and the work on diatoms was done by R. Kolbe of Stockholm. Fortunately, the Oceanographic Institute of Göteborg could serve as a coordinating center for these investigations.

From this very brief summary it will be obvious that the work carried out on the material of the "Albatross" cruise has been truly international—specialists from many countries having generously shouldered the burden of investigations. To all these workers my sincerest thanks are due. Without their participation in the extensive studies on our precious cores the work would have had to be severely curtailed. The Swedish Research Council generously supported the work and added to the government grant for the heavy printing expenses.

The most significant chemical component in the sediments is calcium carbonate, mainly in the form of calcareous tests or shells derived from plankton in the surface layers. The most important contributors to biogenetic sediments are the *Foraminifera,* protozoans varying in diameter from .01 to 1 millimeter. Their shells may amount to 90% of the total weight of the sediment. Other contributors are the *Coccolithophorides,* with shells built up from plates of lime of a size varying between 1½ and 12 microns.

The lime content of the sediment is of importance also for classification. A content of $CaCO_3$ exceeding

30% of the total is characteristic of calcareous oozes. Since among the contributors to the calcareous shells the genus *Globigerina* plays a predominant part, oozes rich in forams are very often called *Globigerina* ooze, although the number of shells from other genera may play a considerable part in the composition. The composition of the foram shells from thermophile or from more hardy species may vary considerably from one layer to another in a long core. An analysis of the composition affords indications of climatic variations. Layers in which the species characteristic of a high water temperature are rare or missing are generally assumed to have been deposited when the temperature of the surface water, even on the equator, was reduced, as during glacial periods. A careful foram analysis, therefore, affords signs of paleoclimatological variations. In general, a high water temperature favors the extraction of lime, so that John Wiseman, analyzing an "Albatross" core from the equatorial Atlantic, has from the lime content drawn inferences concerning minor climatic variations during the last 14,000 years. However, another factor influences the secretion of lime from the water, namely the varying content of phytoplankton, which, in its turn, depends on the abundance or scarcity of nutrient salts required for an intense vegetation—that is, on nitrates, phosphates, etc. which are carried upward by upwelling deep water in the so-called "regions of divergence." The localization as well as the intensity of such divergences can be assumed to have varied considerably with the general oceanic circulation, the strength and extension of the trade winds, and so forth. Apart from the accruement of calcareous tests from the surface layers, there is a reverse process going on in the sea, namely the resolution of lime by the water through which the shells are sinking and especially by the bottom water, where they come to rest.

Now, the lime-dissolving power of the bottom water has been ascribed partly to its low temperature plus a high content of carbon dioxide set free by the decomposition of organic matter, and partly to its movement with the Arctic and, especially, Antarctic bottom currents. A third such factor, the importance of which, in my opinion, has hitherto been underestimated, is the action of magmatic volatiles, that is, carbon dioxide and mineral acids—like hydrochloric acid, sulphuric acid, etc.—which are set free during submarine volcanic eruptions.

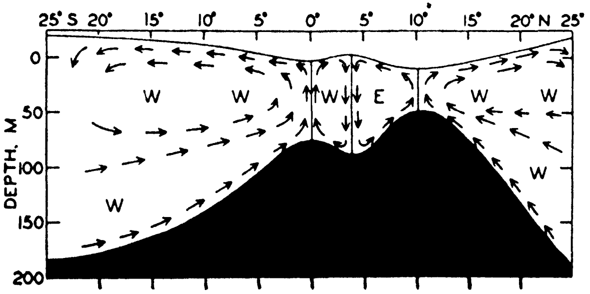

Fig. 32. Vertical circulation near the Equator

If we assume the first of the three factors mentioned above as dominant, then during the Tertiary Age—when the bottom water was much warmer than at present and no driving power for the bottom currents in the shape of melting ice existed—no extensive layers of red clay of Pre-Quaternary age should have been formed. The "Albatross" Expedition negatived this conclusion by raising long red clay cores both in the Atlantic and the Pacific, to the lower layers of which a Tertiary age must be ascribed. It seems reasonable, therefore, to assume that magmatic volatiles set free by submarine volcanic activity, together with the intense local bottom currents which it must have produced, were the main agents for converting calcareous ooze into red clay in the Tertiary Age.

Near the equator especially, cores were raised in which the lime content showed abrupt variations, so that red clay alternated with calcareous ooze. The causes of this stratification are at present being investigated.

The other biogenetic component of primary importance is silica, in the shape of shells or skeletons from siliceous algae (diatoms) or protozoans (radiolarians). The former, which are in general cold-water organisms, are encountered chiefly in polar and subpolar regions. The latter, on the contrary, are found at low latitudes. When the content of organic silica exceeds 20% we speak of diatom ooze or radiolarian ooze. Like the calcareous remains in the bottom deposits, the siliceous remains are influenced by the solvent action of the bottom water, although to a lesser extent. The silica set free as colloidal silica has a tendency to migrate vertically and reappear as a cementation with autochthonous silica. Neither the radiolarian nor the diatom skeletons lend themselves to such climatological inferences as do the forams.

Of considerable interest as an element of sediment is humus-carbon, which, like nitrogen, serves as a measure of the accruement of organic matter in the deposit. It was long assumed that there is a linear relationship between carbon and nitrogen, but the work of Wiseman and Bennett [1] revealed that there are—especially in deposits from the Arabian Sea—great variations in the carbon-nitrogen ratio, so that nitrogen cannot safely be taken as an adequate measure of the organic matter.

The phosphorus content in sediments is of considerable importance, since phosphorous compounds are essential to the flourishing of phytoplankton. Correns' study of material from the "Meteor" Expedition proved that the phosphorus associated with calcium carbonate, deposited as skeletons of planktonic organisms, is largely retained in the sediment if the carbonate is dissolved. Several investigators have pointed out that sea water below the euphotic zone, where phosphates are consumed by the phytoplankton, is rich in phosphates. This makes the upwelling of water from the deep of ecological importance, since it acts as a kind of manure on the surface layers, giving rise to an abundance of phytoplankton, and hence of zooplankton.

Of great interest also is the mechanical structure of the sediment, whether it consists mainly of clay with very minute inorganic particles or larger mineral fragments bordering on sand, of biogenetic remains like calcareous tests and siliceous skeletons, or of volcanic debris. An exhaustive mineralogical examination of representative samples from all our cores would have been a very heavy task, and the time and expense involved prohibitive. A granulometric study, in which components of different grain size are separated through a fractionated sedimentation process, was therefore carried out only with certain samples of special importance.

Of very great interest is the deep-sea sand, that is, coarse particles occurring as separate layers in cores from great depths. For instance, a core nearly fifty feet long was raised from that most interesting pit in the equatorial Atlantic Ocean, the Romanche Deep, 7,500 meters at that point. Although the sediment in the upper levels was largely fine grained and intercalated with thin dark streaks rich in organic remains, in the lower levels calcareous ooze predominated; but there were in certain levels very peculiar layers of sand. They consisted of angular fragments of mafic rocks which must have come from the substratum, that is, from the nearby Mid-Atlantic Ridge. Judging from the echograms obtained in the vicinity, this region of the equatorial Atlantic must be especially prone to tectonic changes, in which differential movements of the mafic or ultramafic rocks have led to a crushing of the material into fragments, with a subsequent sliding down the steep incline from the ridge into the cavity of the Romanche Deep (See Figure 33, a microphotograph of a typical sample of the Romanche Deep sand).

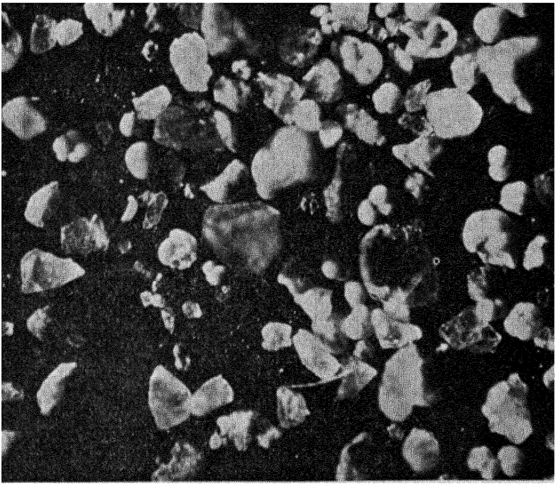

Fig. 33. Sand from the Romanche Deep

A very different type of deep-sea sand is found about 1,500 nautical miles farther west, slightly north of the equator. Here, from a depth of about 4,400 meters, the core-sampler brought up a core nearly nine meters long, the uppermost parts of which consisted of fairly homogeneous, fine-grained, deep-sea clay. In the lower part several layers of sand were found which mineralogical examination showed to be not mafic but of continental origin, that is, derived from a coastal shelf of some continent or large island. Most surprising of all, in the lowest stratum of this sand were found vegetable remains—twigs, nuts, and bark fragments of dicotyle-

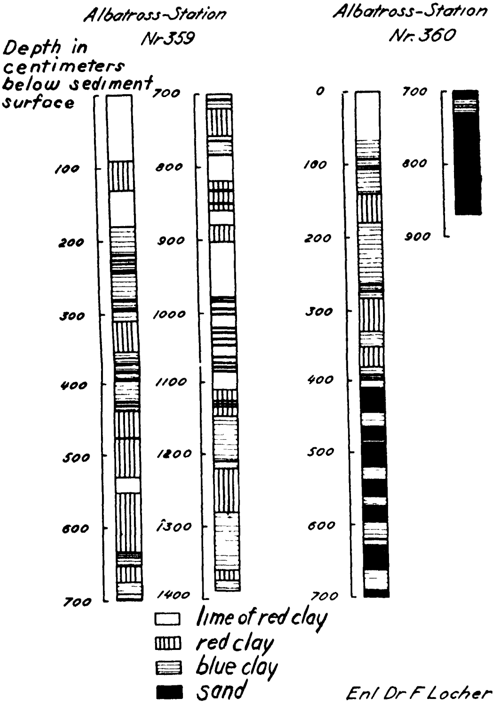

Fig. 34. Stratified cores from the equatorial Atlantic

donous bushes or trees, bespeaking still more emphatically a continental or island origin. Finally, in the uppermost part of the same core Phleger and his coworkers found a "displaced fauna" consisting of benthonic shallow-water foram shells which apparently had lived in depths of 100 to 200 meters.

One is at a loss to explain how these products of a coastal shelf and supramarine vegetation could have been carried to the position of the find at lat. 7° 29′ N., long. 45° 1′ W. The nearest part of the coast of South America is the Amazon Estuary situated at a distance of about 500 nautical miles. F. Locher, a collaborator of Correns who has studied these and other "Albatross" cores from the equatorial Atlantic, has failed to find any close resemblance between the heavy mineral components in the deep-sea sand at this locality and the heavy minerals in cores taken by the "Meteor" near the Amazon Estuary.[2] Moreover, Locher has found similar (although not so thick) sand horizons occurring in cores taken from a stretch of the equatorial Atlantic bottom running northwest to southeast from the position given above. Altogether, the sand in these cores was neither so profuse nor so coarse grained as in the first, most northwesterly, core mentioned. In the event that a large island harboring vegetation and with a fairly extensive shelf crowned the Mid-Atlantic Ridge north northwest of St. Paul's Rocks and became submerged during a catastrophe of seismic-volcanic character a few hundred thousand years ago, material like that found in the "Albatross" cores might have become distributed over the adjacent sea bottom. However, apart from the general improbability of this explanation, the prevailing surface currents at present run from southeast to northwest, that is, in a direction opposite that in which the transportation of sand, foram shells, and vegetable remains might have been supposed to occur. In this dilemma both Locher and Phleger have accepted the explanation of transportation by turbidity currents. This would mean that some very considerable submarine landslides occurring on the shelf off or near the Amazon Estuary produced a sediment-laden bottom current of great intensity, extending far enough to transport coarse and unsorted material over a distance of several hundred miles along a slope which cannot on an average have been greater than 1:200, an explanation which is difficult to accept.

The mystery of the deep-sea sand in this part of the equatorial Atlantic Ocean cannot be considered solved. We may only hope that future expeditions to this region, taking long cores and multiple echogram lines between the locality indicated and the Amazon Estuary, will throw light on this fascinating problem.

A most interesting mineralogical study was made by O. Mellis of Stockholm on stones found in a core taken at lat. 29° 21′ N., long. 58° 59′ W., southeast of Bermuda in a depth of 5,450 meters.[3] The weathering crust on these stones proved beyond doubt that a transformation of plagioclase into orthoclase has occurred through the substitution of sodium for potassium. Another find of Mellis and Norin of Uppsala concerns layers of volcanic ash in cores from the eastern Mediterranean and the Tyrrhenian Sea.[4] Thus, Mellis found in cores taken southwest of Cyprus and south and southeast of Crete layers of volcanic glass which had probably become deposited after the cataclysmic outbreak of the island volcano Santorin in the sixteenth century B.C. Norin, in a core taken in the center of the Tyrrhenian Sea, found a layer of ash which he was able to identify with ash from old Mt. Somma, which

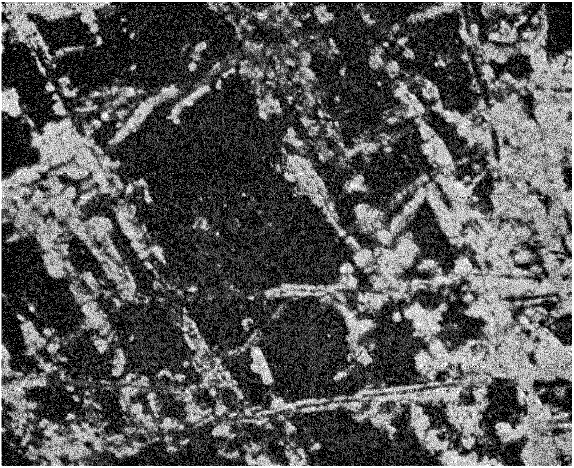

Fig. 35. Submarine weathering, plagioclase to orthoclase

erupted probably in the twelfth millennium B.C. The possibility of a dating of similar but more recent volcanic ash layers, such as those in the Norwegian Sea produced by outbreaks of Mt. Hekla and other Icelandic volcanoes, seems very promising.

7. Recent Investigations on the Stratigraphy of Deep-Sea Sediments

Since April, 1952, when the Silliman Lectures which compose this book were delivered, a highly important contribution to our knowledge of deep-sea sediments and their stratigraphy has been made by Gustaf Arrhenius, geologist of the Swedish Deep-Sea Expedition, in his doctoral thesis, *Sediment Cores from the East Pacific,* published as one of the reports of the Expedition.[1] It was submitted for official discussion at Stockholm's Högskola on November 15, 1953.

The very comprehensive analytical work on which this thesis was based was carried out at Kagghamra, Sweden, by Arrhenius and a staff of collaborators, including two specialists on microfossils, F. Brotzen and R. Kolbe of Stockholm. Generous grants-in-aid for the work were given by the Swedish Research Council, the Lars Hierta Memorial Foundation, and the Wallenberg Foundation, all of Stockholm.

Part 1 of the volume contains the report on the general distribution of properties in the sediments, together with an interpretation by the author of the distributions and relationships found. Part 2 gives a detailed description of the different cores examined, with suggested interpretations. Part 3 contains a summary of the late Cenozoic stratigraphy and the geological evolution of the eastern Pacific pelagic area. Part 4 accounts for the methods used in the study of the sediment cores. Fascicle II, which has not yet been published, will contain special contributions to associated problems.

Arrhenius deals first with the main components of sediment.

1. Of special interest is the hypothetical explanation of the distribution of calcium carbonate and its relation to present and earlier atmospheric and oceanic circulation, notably the formation of calcium carbonate in upwelling water masses rich in nutrient salts, and its dissolution during and after deposition on the ocean floor. From this discussion Arrhenius concludes that the ice ages were characterized by a greatly increased intensity of trade winds, a phenomenon which was not, however, reflected by any marked shift in the latitudes of the equatorial current system.

2. The establishment of a correlation of presumably isochronous strata between the different cores made it possible for Arrhenius to compare regional variations in the amounts of different elements, minerals, and fossils accumulated per unit area between the correlated

time levels. He was especially interested in titanium.* Between localities within the eastern part of the area investigated he found perceptible variations of titanium accumulation, whereas in the Pleistocene strata of the open, topographically regular part of the ocean only a small fraction of the accumulation showed regional variations. The deviations from uniformity in space were given quantitative expression, and from the regional uniformity a corresponding uniformity in time within the area and the time interval in question was inferred. The Pleistocene strata display a marked homogeneity, on which Arrhenius has based a tentative chronology on the assumption of a uniform rate of minerogenous accumulation during the Pleistocene within the east eupelagic area. Arrhenius checked these data against a radiocarbon dating on one core, using the method developed by Libby.[2]

To the view of a constant rate of accumulation of minerogenous matter within the area in question exception has been taken by Kullenberg. For the discussion of these and other aspects of Arrhenius' work the reader may be referred to his rejoinder to various criticisms in *Tellus* (1954).

3. The amount of biogenetic silica in the eupelagic sediments of the eastern Pacific has also been calculated by Arrhenius. He finds the maximum rate of

---

* That titanium is less likely to undergo postdepositional changes than other chemical elements has been urged by various earlier authors such as Correns, Wiseman, and Koczy.

accumulation below the equatorial divergence, where at a certain substage of the Pleistocene glaciation it should have reached 860 milligrams of SiO_2 per square centimeter in 1,000 years. However, a microscopic examination of the cores proves that many siliceous remains are strongly corroded, which makes it probable that a great part of the biogenetic silica is present in colloidal form.

4. Similar analyses deal with the distribution of organic matter (marine humus), with phosphorus, with the carbon-nitrogen relationship, and with the presence of peroxide of manganese, both in dispersed form and as nodules and micronodules.

A great number of excellent diagrams make clear the main relationships found; these relationships enable Arrhenius to establish correlations among the different cores he has examined and to define the limits between the Pleistocene and Pliocene parts of the cores. These conclusions he supports by similar distribution studies of forams, diatoms, and radiolarians in the cores.

Special attention has been given to the reworking of sediments by mud-eating organisms and to recrystallization and chemical redistribution after deposition. Studies of thin sections of carefully washed *Foraminifera* revealed the fact that planktonic forams which are not recrystallized are more easily attacked than are recrystallized shells and benthonic forams, which appear to be remarkably resistant to dissolution.

Arrhenius states that his studies of the East Pacific sediments have not yielded any quantitative results concerning the influence of the weight of the overlying strata on the water content of an underlying stratum. He assumes that the effect is so small—insofar as the uppermost ten meters are concerned—that it is usually masked by other variations in the composition of the sediment. In calcareous facies of the east eupelagic area even the longest core (15 meters) does not give any unquestionable evidence of expulsion of water by compaction.

It is of interest to compare Arrhenius' interpretation of changes in calcareous sedimentation—that they are due to a strong upwelling in equatorial divergences with a consequently improved nutrition of the surface plankton—with the earlier interpretation by Schott, who assumes that during glacial epochs surface water in the tropics was cooled by as much as 10° centigrade, so that the extraction of calcium carbonate was much reduced. If this were true, the glacial stages ought to be characterized by a *low* lime content in the sediments, whereas according to Arrhenius the reverse is the case.

As Revelle has recently pointed out, there is not necessarily any contradiction between the two views.[3] In some regions the cooling of the surface water may have had a predominant effect on tropical pelagic sediments during the glacial periods, whereas in others the increased productivity brought about by intensified atmospheric and oceanic circulation may have been the primary factor. An important remark made by Revelle in the shipboard report of the "Capricorn" Expedition concerns the deposition on the deep-sea floor of sediments high in calcium:

> If the deposition throughout the geologic past had been like that at the present time it would be impossible to arrive at a geochemical balance, because both the deep-sea and continental sediments would be higher in calcium than the igneous rocks from which they are derived. Thus we arrive at another most important conclusion, namely that the character of the deposition on the deep-sea floor has changed radically with time; throughout most of geologic history, deep-sea sediments must have been lower in calcium than the average igneous rocks, whereas the present deposits have an excess of calcium.

Some important contributions toward the knowledge of deep-sea sediments from other workers on the "Albatross" material should also be mentioned.

W. R. Riedel of Adelaide, who worked for two years in Göteborg with the radiolarians from our Pacific and Indian cores, found them useful for dating various sediments.[4] This fact is especially important when calcareous components (the foram tests) are missing. Thanks to Riedel's work it is now possible to date with a certain degree of accuracy sediments from the Upper Cretaceous and various Tertiary periods.

The radiolarians have also proved to be good indicators of the transportation and erosion of sediments in the deep sea. Because the tests are more easily kept in suspension than other microfossils such as *Foraminifera,* they can be carried along even by bottom currents of low velocity and turbulence. Also, they are less liable to undergo solution during erosion and transportation to different environments than are the forams. By examining mixed faunas of radiolarians in deep-sea cores it has been possible to form a general hypothesis concerning erosion by slow bottom currents of small topographical features in the deep ocean.

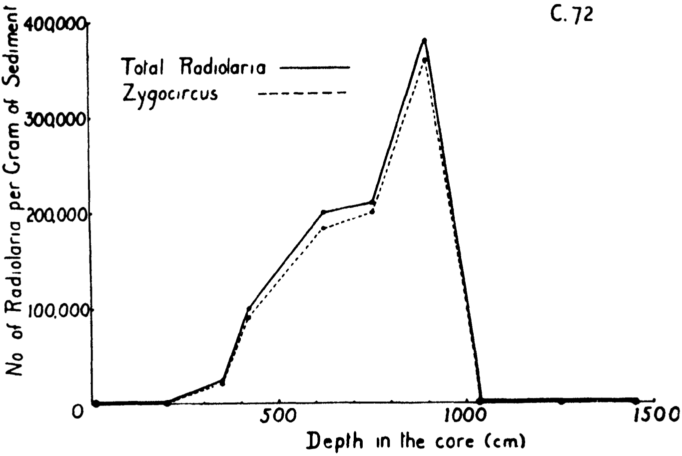

Fig. 36. Abrupt drop in number of radiolarians

Long deep-sea cores taken in areas with a low rate of sedimentation have enabled Riedel to trace the evolution of certain of the groups of *Radiolaria* from the Recent back to at least the Lower Miocene. These evolutionary trends are being checked in Tertiary deposits on land. It appears that a general evolutionary trend can be demonstrated as having occurred simultaneously in all parts of the world within, say, the latitudes of 40° N. and 40° S.

Recent work by Brotzén and Dinesen on forams from cores taken in the central Pacific Ocean has proved that an abrupt change in the fauna occurred in a core at a depth of 4½ meters below the sediment surface. Work by Kolbe has shown the occurrence of an equally abrupt change of the diatom flora in another long core from the same region.[5] Research directed toward finding similar unconformities in cores from the other two oceans is now proceeding. A remarkable find by Kolbe in two cores from the equatorial Atlantic is the occurrence of typical fresh-water diatoms in considerable numbers. Since this find was made in localities several hundred miles from the coast of northwest Africa, the origin of these fresh-water diatoms is puzzling.

Research of considerable interest pursued for some years in Göteborg by Rotschi and Berrit has been devoted to the ferrides present in cores, from both the central Pacific and the equatorial Atlantic, notably the elements Fe, Mn, Ni, and to a certain extent Ti.[6] The origin of iron and manganese in deep-sea sediments is not completely cleared up. Arrhenius and others are inclined to distinguish between "halmyrogenic" manganese and manganese of minerolytic origin, the latter largely derived from submarine volcanic debris which has undergone solution and a subsequent vertical migration in the sediment. The manganese in the shape of its peroxide, braunstein, is known to absorb radium, a subject which will be more fully treated in Chapter 8. Also, the iron precipitated from the ocean water is assumed to play a part with regard to the co-precipitation of the mother element of radium, namely ionium. Again, part of the abyssal iron may be assumed to have a magmatic origin and to have become extruded on the deep ocean floor at great submarine eruptions. The nickel content of certain deep-sea sediments, especially those characterized by an excessively slow rate of accumulation, may in part be of cosmic origin, derived from meteors or micrometeors entering the earth's atmosphere from without. The curve reproduced here in Figure 37 shows the distribution of manganese along a core from the Romanche Deep, taken from a forthcoming paper by Berrit. The isolated high peaks in the manganese curve are to be interpreted, I believe, as products of great submarine eruptions, since they occur also in other cores from the equatorial Atlantic. The importance of titanium for submarine geochronology emphasized by Arrhenius has already been referred to earlier in this chapter.

To study this problem of the geochronology of the deep ocean sediments has been one of the main objectives of our work. Of the methods so far applied to solve this very fundamental problem three appear promising: (1) analysis of the composition of the foram tests, (2) measurements of radioactive elements present in different sediment layers, and (3) the study, within certain regions like the Mediterranean and Indonesian Seas, of volcanic ash layers.

Apart from the work on the "Albatross" cores here referred to, hardly any systematic investigations of long sediment cores have been published. It is indeed unfortunate that these rare abstracts from the records of the deep should—perhaps because of preconceived ideas on the process of deep-sea sedimentation—be allowed to lie fallow and deteriorate for want of suitable storage. It may sincerely be hoped that the increasing amount of international cooperation in deep-sea research will lead to a more respectful treatment of the

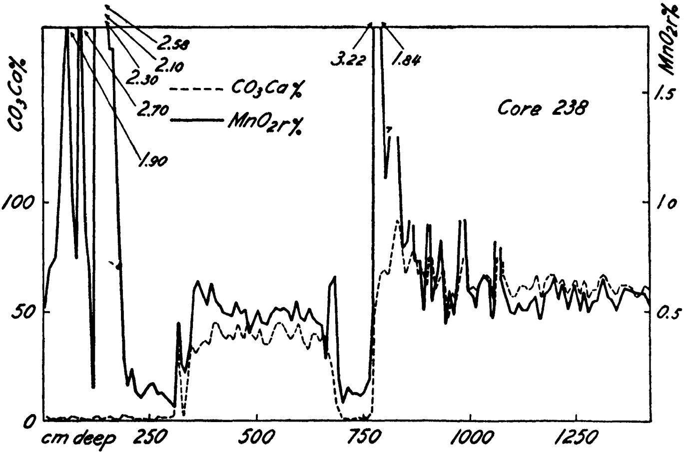

Fig. 37. Lime and manganese distribution in sediment core from the Romanche Deep

long cores collected at great costs from future deep-sea expeditions than has hitherto been the case. Arrhenius' pioneer work on the cores from the eastern Pacific Ocean may in many respects serve as a model.

8. Deep-Sea Radium and the Geochronology of the Ocean Floor

The very long sediment cores which the Swedish Deep-Sea Expedition first managed to raise from great depths have appropriately been called "records of the deep." Every historian or archaeologist knows how annoying it is to come across reliable but undated records from the past. Hence the problem arises of how these unique records of the deep can be dated, so as to afford the basis of an exact geochronology for past happenings on the ocean floor, including the climatic, tectonic, and volcanic catastrophes which have left indelible markings there.

It is well known that geologists studying continental rocks and sediments have labored with the same difficulty, that of dating the "records of the rocks." Thanks to the sequence of different layers or strata in continental sediments, a framework of geological dating was worked out. In this work study of the fossils enclosed in the strata and knowledge of their evolutionary background were very useful. Paleontology helped geologists to order the protocols of rocks and distinguish between different periods of geological evolution. Nevertheless, an *exact* framework was not found until half a century ago, when it was recognized that radioactive elements, each characterized by its own rate of disintegration, are immutable time-keepers. By using the slow transmutation into lead and helium of the two most long-lived ancestral elements, uranium and thorium, the age of rocks can now be determined. The very oldest among them, in which transmutation has proceeded farthest, have ages up to two billion years. Thanks to this discovery of radioactive time-keepers, definite ages can now be ascribed to many different kinds of rocks.

Another discovery, made in the first decade of the present century, was the relatively high radium content in abyssal sediments like red clay and radiolarian ooze. Using the ordinary measure of radium content, namely units of the twelfth decimal place or one million-millionth part of the weight, J. Joly of Dublin found samples of red clay from the "Challenger" collection to hold as many as forty such units. This is nearly fifty times more than the average content of radium in sedimentary rocks from the continents.

The question naturally arose: how does this abyssal radium get down to the deep ocean floor and how can it be utilized for age determinations on different sediment layers?

Forty years ago when I was a young student working under Sir William Ramsay in University College, London, I was taken on a short cruise in the North Sea with Sir John Murray, who there invited me to come over to the "Challenger" office in Edinburgh and work up his deep-sea sediment samples for radium. Pressure of other projects prevented me from taking advantage of this offer. Ten years later Sir John had passed away, but another leader in oceanography, Prince Albert I of Monaco, invited me to his Musée Océanographique in Monaco to work on the collections of deep-sea sediments kept there.

Several years of work, first in Monaco, then in the Institut für Radiumforschung in Vienna, and finally in Göteborg, enabled me to confirm several cases of outstandingly high percentages of radium, like those found by Joly. Joly's first explanation for the origin of deep-sea radium, namely a chemical precipitation of that element as sulphate from ocean water, I could not, however, endorse. A second explanation, also propounded by Joly, that deep-sea radium is "uranium supported" and due to a relatively high concentration of uranium in abyssal depths, has also proved erroneous.

It took several years of teamwork with specialists from Austria and Scandinavia before a satisfactory explanation of the mysterious occurrence of deep-sea radium could be evolved. First, we proved that sea water is relatively poor in radium but instead contains a fair and nearly constant amount of dissolved uranium—according to measurements by Berta Karlik and others[1] about 1.3 × 10^{-6} gram of uranium per liter of ocean water of normal salinity, 35‰.* According to the "equilibrium ratio" † between uranium and radium found in undisturbed rock samples, U:Ra = 3,000,000: 1, there should be .6 × 10^{-12} gram of uranium-supported radium present in each liter of sea water. According to our measurements, the average radium content of ocean water, which is more variable with locality and depth than is the uranium content, is only a fraction, on an average one-eighth of the equilibrium value. In order to explain the relative scarcity of radium in ocean water and its abundance in deep-sea deposits the author in 1937 suggested that an intervening element in the uranium-radium dynasty—namely ionium, the immediate parent substance of radium—is being removed from solution in sea water through precipitation together with iron. From this assumption it would follow that the precipitated ionium will at its disintegration breed its offspring radium.

---

* The usual abbreviation for expressing small fractions is used here, viz. 1 × 10^{-6} for units of the 6th decimal place, or millionths, 1 × 10^{-12} for millionths of millionths, etc. The notation 35‰ may also be written 3.5%.

† Radioactive equilibrium between succeeding members of the same dynasty of radioactive elements is attained in the course of time and is characterized by an equal number of atoms from each element being born and disintegrated in a unit of time.

This obviously opens a road to radioactive age determinations in the deposit, since the two elements will decrease together downward in the sediment with the disintegration of the more long-lived component ionium, i. e. to 50% in 80,000 years, 25% in 160,000 years, etc.

Two American scientists, C. S. Piggot and William D. Urry, were the first to attempt to utilize the hypothesis of ionium precipitation for radioactive age determinations in long sediment cores, obtained from ocean depths by means of the Piggot corer.[2] In a series of papers they very ably discussed the problem of the nonequilibrium system of radioactive elements in deposits, showing how the concentration of radium in the deposit should increase from a low value in the uppermost layer to a near-surface maximum reached after about 10,000 years, when the equilibrium radium:ionium had been attained, and from then on downward present the exponential decline with increasing depth (and age) characteristic of ionium disintegration.[3] Their first results appeared very promising by yielding smooth curves of the expected exponential type, but their later results produced more complicated curves. Those the authors explained as due to changes in the rate of sedimentation, notably through a dilution of more radioactive clay components with less active calcareous deposit.

It is obvious that even under the most favorable conditions of undisturbed sedimentation and ionium precipitation at a constant rate, the time span over which this radioactive age-determination method can be used must be limited to a maximum of 300,000 to 400,000 years, after which the residual radium-ionium content becomes too far reduced for accurate radium determinations. Unfortunately, later experiments have proved that such favorable conditions are rarely met with in nature. The time span within which the method

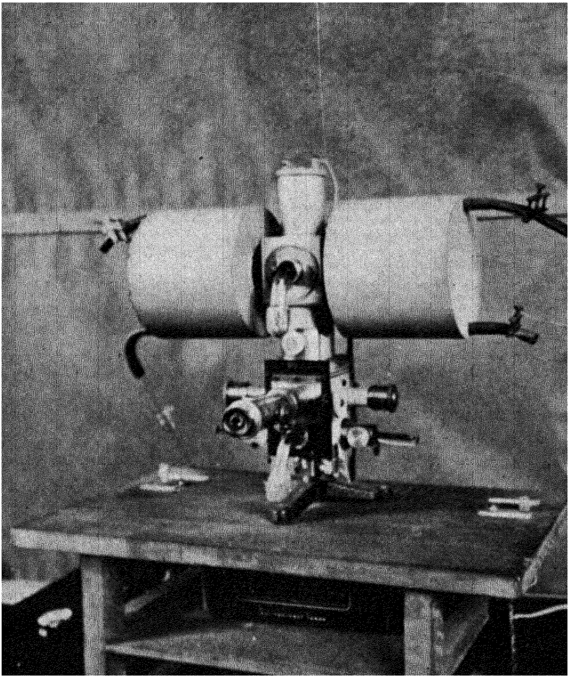

Fig. 38. Equipment for radium measurement

can be used is therefore much more limited than Piggot's and Urry's pioneer work led them to anticipate.[4]

The most extensive investigations of this kind so far undertaken have been made in the Oceanographic Institute of Göteborg on cores taken from great depths during the Swedish Deep-Sea Expedition with the "Albatross." [5] Out of cores from the central Pacific Ocean, consisting largely of red clay or radiolarian ooze, a considerable number of samples have been measured for radium by the standard method of radon determinations, most of the work being done by Kröll.[6] Two of his curves showing radium distribution at varying depths in Pacific sediment cores are here reproduced as Figures 39 and 40.

It is seen that instead of a simple exponential curve, falling off downward below the near-surface maximum expected (see Figure 39), there are two, four, or even more maxima which are separated by equally sharp minima. Moreover, in certain cores there were found relatively high values of radium content at such great depths below the sediment surface that, considering the slow rate of sedimentation, most of the precipitated ionium from the surface layer ought to have had time to become disintegrated.

In spite of the fact that these findings are at variance with theory, Kröll, calculating the total amount of radium in a core down to levels where the ionium-supported radium becomes insignificant, has been able to approximate values of the rate of sedimentation on

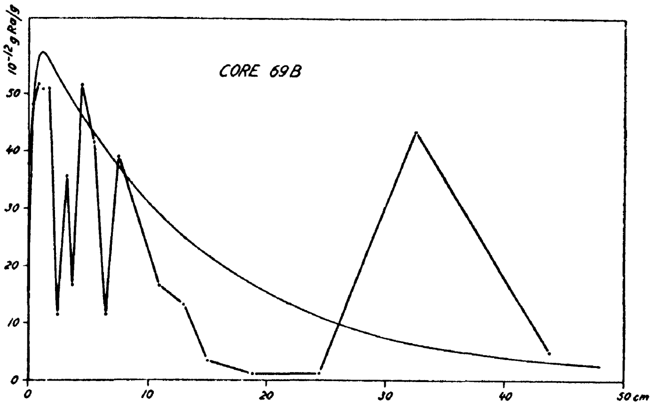

Fig. 39. Radium distribution in the central Pacific

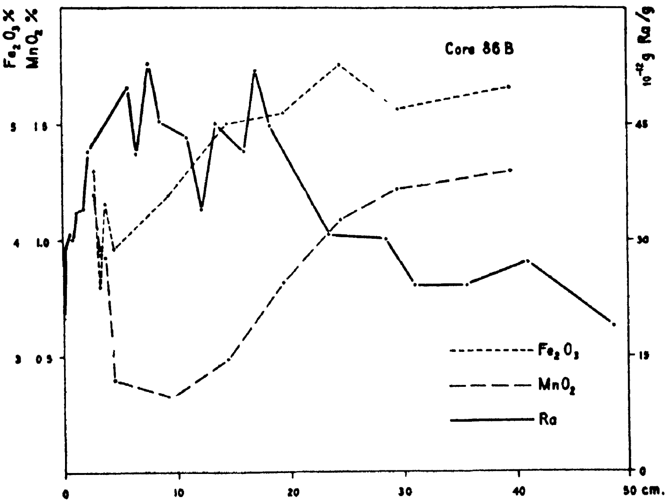

Fig. 40. Radium distribution in the western Pacific

the order of 1 to 2 millimeters of red clay per 1,000 years.[7]

How shall the irregularities found by Kröll in the vertical distribution of radium on cores from the equatorial Pacific Ocean be explained? Variations in the rate of total sedimentation or in the rate of ionium precipitation is an explanation which meets with difficulties when the variations in radium content are very abrupt and the character of the deposit is apparently homogeneous. An alternative explanation—that the variations may be due to a migration of radium to lower levels, leaving its mother element ionium behind—depends on present determinations of ionium by a photographic method. This method has been evolved at the Institut des Recherches Nucléaires in Brussels by Picciotto and his co-workers, in collaboration with and with some support from the Oceanographic Institute in Göteborg.[8] In nuclear photographic plates exposed to the radiation from a sediment sample from which all radioactive elements except thorium and ionium have been eliminated, the short tracks produced by their alpha particles are counted. The results of this important work indicate that there exists radioactive equilibrium between radium and ionium in the maxima of the radium curves, except in the uppermost surface layer, where there is an excess of ionium.

That the superficial radium maxima near the sediment surface cannot well be uranium supported seems obvious, since a concentration of radium as high as 50 units of the twelfth decimal place, i. e. 50×10^{-12} gr Ra / gr sediment,* would require a concentration of uranium 3,000,000 times higher, or 150×10^{-6} gr U / gr sediment! Nevertheless it appeared desirable to find out by dependable measurements how much uranium is actually present in sediment cores, especially in layers where there is a high concentration of radium.

The fluorescence method worked out for measuring uranium in sea water is excellent, but in sediment samples the presence of certain other chemical elements like magnesium and manganese, difficult to separate completely from the uranium, interferes with the fluorescence in ultraviolet light of the latter element.

In earlier attempts to apply the fluorescence method to uranium determinations of deep-sea sediments these difficulties were not completely overcome, and the results were accordingly inaccurate. Thanks to helpful cooperation from Hecht, who devoted two months in Göteborg to collaboration with Kröll, the difficulties were finally surmounted, so that accurate uranium measurements could be carried out on a number of sediment samples. Some of the results obtained by Hecht and Kröll on samples from cores raised by the "Albatross" are set out in the following table. The first column gives the number of the core, the second the depth below its upper end from which the samples analyzed were taken, the third the uranium content in millionths of the weight, the fourth the corresponding

---

* Gram of radium per gram of sediment.

Core Number	Centimeters from Top	10^{-6} gr U/gr	10^{-12} gr Ra/gr	10^{-12} gr Ra/gr sed.
76	1.5–3.0	0.76	0.27	14.4
76	40–41.5	11.4	4.0	1.5
76	200–201.5	7.16	2.5	0.6
76	300–301.5	2.72	0.95	0.1
76	400–401.5	1.8	0.63	0.0
76	500–501.5	1.46	0.51	—
76	600–601.5	1.1	0.38	0.1
76	710–711.5	1.18	0.41	0.2
76	801.5–803	0.96	0.33	0.2
76	910–911.5	2.64	0.92	0.3
76	931.5–933	2.40	0.84	0.3
76	1,030–1,031.5	1.42	0.5(?)	0.4
76	1,130–1,131.5	2.10	0.73	0
76	1,230–1,231.5	2.25	0.78	0
76	1,351.5–1,354	2.26	0.79	0.1
69B *	4.1–5.2	4.4	1.5	51.7
83	4.5–6.5	0.7	0.25	27.9
83	12.5–14.5	1.2	0.42	0.4
86B	6.6–7.7	3.64	1.27	41.0
86B	14.3–15.4	3.33	1.16	45.1
86B	18.2–19.3	2.40	0.84	52.2
86B	30.8–31.9	2.66	0.93	30.2
86B	44.5–45.6	2.4	0.84	27.2
87B	3.0–3.3	4.0	1.4	21.5
87B	40.6–41.7	31.05	10.8	12.4
238	48–49.5	3.50	1.22	3.2
238	128–129.5	1.91	0.66	67.6
238	158–159.5	2.21	0.78	28.0
238	248–249.5	1.91	0.66	8.3
238	418.5–420	1.40	0.49	2.0
238	688–689.5	1.75	0.61	3.4
238	758–759.5	2.43	0.85	6.9
238	968–969.5	1.14	0.40	—
238	1,248–1,249.5	2.94	1.03	1.32
251	447.5–449.5	2.1	0.73	0.88
251	501.5–503.5	2.35	0.82	2.05

* "B" indicates cores of shorter length, taken by means of a gravity corer.

equilibrium value of uranium-supported radium in 10^{-12} gr Ra / gr, and the fifth the radium concentration actually found. The cores numbered 69 to 87 are from the equatorial region of the Pacific Ocean, core 238 was raised from the Romanche Deep in the equatorial Atlantic Ocean, and core 251 was taken near the equator in the same ocean but farther west.

With the exception of two outstandingly high amounts of uranium in core 76 at depths of 40 centimeters and 200 centimeters respectively below surface, and one in core 87B at 41 centimeters, all the uranium amounts found are moderate, ranging from .76 to 4.0 of the sixth decimal place. The corresponding equilibrium values for radium range from .27 to 1.4 units of the twelfth decimal place, whereas in the case of the three outstanding uranium values before mentioned, the figures for uranium-supported radium are 2.5, 4.0, and 10.8 units of the twelfth decimal place. Comparing these latter radium values with those actually found near the surface with maxima of up to 50 units, we may say that at least in the upper levels of the cores and especially in the central Pacific Ocean uranium-supported radium accounts for only a small fraction of the radium actually present.

These results definitely contradict Joly's second explanation for the high radium values found in the upper levels of the red clay: that they are due to an accumulation of uranium in great depths. Obviously the high radium values found near the sediment surface must have another origin. The only acceptable explanation so far advanced is that they are ionium supported. However, no definite proof of this hypothesis had been produced until in the summer of 1952 Picciotto and his co-workers in Brussels developed the photographic method already mentioned for direct measurements of the ionium present in sediment samples.

It is of interest to note that the amount of ionium-supported radium in the upper levels of a core is of the same order as the quantity of potential radium to be expected from the disintegration of the uranium present in the superposed column of sea water, although somewhat in excess of the latter quantity by a factor varying, according to Kröll's measurements, from 1.3 to 2.8. From this fact he infers that the content of uranium and/or ionium in ocean water has been higher during the latter half of the Pleistocene than it is at present, a conclusion supported also by calculations made by Koczy.*

Reverting to the question about the cause of the complicated shape of the curves showing radium distribution in the sediment cores studied by Kröll, one may note that he has calculated the variations in the rate of sedimentation required to explain their shape

---

* Recent measurements by Nakanishi, Smith-Grimaldis, and others indicate a higher uranium value, although at present the most plausible average would seem to be $2 \pm 1 \times 10^{-6}$ gr U L. With this higher value, Ilvöll's factor is reduced to an average value near unity.

and arrived at the conclusion that in the central and western region of the equatorial Pacific Ocean, from which most of the cores he has studied were raised, a general increase in the rate of sedimentation probably occurred about 100,000 years ago, possibly as the result of an increase in submarine volcanic activity. Such an increase is likely to have given rise to a locally increased intensity of bottom currents, which in turn brought about a horizontal transportation of sediment.

That other postdepositional changes in the sediment stratification could have been operative in causing a redistribution of radioactive layers appears to be borne out by the remarkable curve showing the radium distribution in the upper eight meters of core 238, raised from the great depth of 7,500 meters in the Romanche Deep. This being a long core raised by means of the excellent Kullenberg piston-corer, its uppermost part is likely to be missing, which may explain the absence of a superficial layer rich in radium. The surprisingly high radium content of 69 to 58 units of the twelfth decimal place (the highest ever found in any core from the open ocean) occurs at a depth of between 128 and 139 centimeters below the top of the core. Measurements of both uranium (marked by crosses below the curve) and ionium prove that this abnormally high concentration of radium is ionium and not uranium supported.

The most plausible explanation of this distribution of ionium-supported radium is suggested by a consideration of the topography of the Romanche Deep. At a distance of only 10 nautical miles from the great depth out of which the core was obtained the Mid-Atlantic Ridge rises sharply to a level of only 2,600 meters below the water surface, i. e. a difference in level of nearly 5,000 meters, or an average slope of about 25:100. The conditions are thus favorable for a submarine landslide, technically called a slump. It seems reasonable, therefore, to assume that a relatively short time ago—short compared to the half-value period of ionium—a slump carried sediment down from the slope, covering with more than one meter of inactive sediment the former surface layer of the bottom of the great deep, which had earlier been exposed to

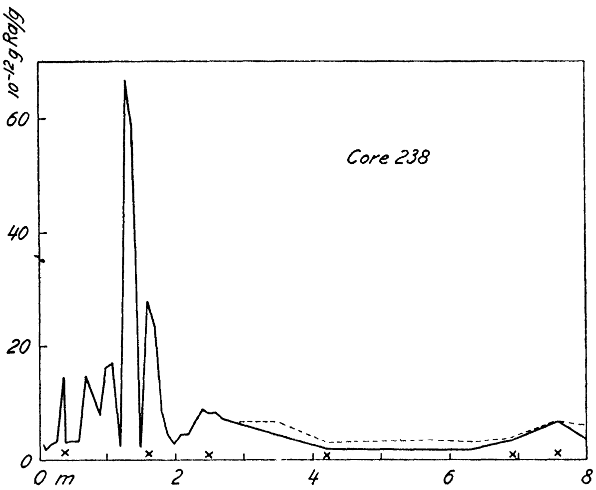

Fig. 41. Radium distribution in the Romanche Deep

sedimentation and ionium precipitation below a water column 7,500 meters high. Obviously it would be futile to attempt to calculate the average rate of sedimentation from radium measurements in the Romanche Deep. It is equally futile to attempt a dating of deep-sea deposits from radium measurements up to one million years back in time, as has recently been attempted by J. L. Hough for a core from the south Pacific Ocean, using radium measurements on the same core Urry used to obtain his data.

It seems necessary to consider here also another way in which radium may become removed from sea water and concentrated on the bottom: through adsorption by peroxide of manganese. That an affinity exists between the two elements, radium and manganese, is well known, manganese deposits from thermal sources on the continents often being rich in radium. Experiments made in Göteborg several years ago proved that braunstein powder, i.e. peroxide of manganese, shaken with a highly dilute radium solution is effective in removing the radium even in concentrations as low as those existing in sea water. The so-called manganese nodules afford striking examples of this tendency of radium to become adsorbed with manganese peroxide. Measuring the radium present in thin concentric layers removed from manganese concretions, the author proved that the radium content falls off rapidly with increasing depth below the nodule surface and becomes too low for accurate measurements at a depth of one centimeter. If the radium in the nodules is unsupported by its predecessors in the radioactive element series, it should decrease to 50% of its surface value after 1,600 years, to 25% in another 1,600 years, etc. In this way it becomes possible to measure the rate of radial growth of a nodule, the results showing a one-millimeter increment in the course of 1,000 years. This is the first known case where the disintegration of radium itself has been used for chronological purposes.[9]

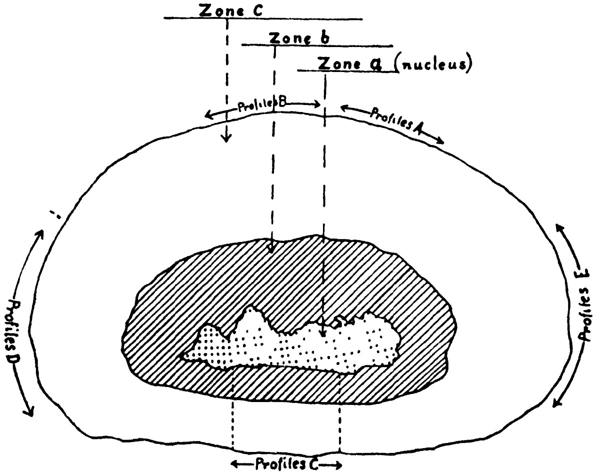

Fig. 42. Radium determination in a manganese nodule

It is naturally possible to ascribe part of the high radium content in the uppermost layers of red clay to an adsorption from sea water of unsupported radium by the dispersed manganese peroxide present in the sediment. However, considering the rapid rate of disintegration of such unsupported radium in relation to the very slow rate of accumulation of the abyssal sediments, such adsorbed radium should have practically disappeared from the upper sediment layer below a depth of 10 to 20 millimeters and cannot, therefore, have contributed to the radium contained in slightly lower layers.

Finally, as regards the long-lived radioactive element thorium, it follows from geochemical considerations that most of the thorium transported to the ocean by rivers becomes precipitated over the shelf and the uppermost parts of the continental slope, which explains the relatively high concentration of thorium in shallow-water sediments. Earlier attempts to measure the amount of thorium contained in sea water gave only upper limits for its concentration.[10] Koczy, working in Göteberg, was the first to compute the thorium content in sea water at between 10^{8} and 10^{-9} gr Th / liter, that is, less than 1% of the uranium present.[11] Whereas in continental rocks and sediments there is an excess of thorium over uranium in the proportion of two to three over one, the reverse is the case in ocean water. Thanks to Picciotto's photographic method of determining the ionium present in sediment samples, their content of thorium has also been determined, giving values of about 6×10^{6} gr Th / gr.[12] This implies that in the deep-sea sediments also there is an excess of thorium over uranium in the proportion of three to one. That thorium is also present in manganese nodules has been proved by Koczy and confirmed by J. Poole and Christine Mathews in Dublin by a photographic method.

Summing up, we may say that of the radioactive elements present in sea water thorium and ionium are particularly rare, owing to their precipitation. The isotope ionium, constantly being produced from the dissolved uranium, is also constantly being removed by precipitation from sea water on the bottom, where it gives rise to its descendant, radium. In the deposit its concentration is decreasing with age, that is with increasing depth below the sediment surface, although this decrease is not as a rule so regular as it should be under completely undisturbed conditions of sedimentation.

The content of uranium in sea water appears to be fairly constant at present but may have varied in earlier epochs because of a changing rate of transportation to the ocean and because of its rate of extraction, together with the extraction of organic residue ("sapropel"). With very rare exceptions the uranium present in the sediments is limited to a few units of the sixth decimal place of gram per gram. The equilibrium value of uranium-supported radium, therefore, is generally of the order of one unit of the twelfth decimal place gr Ra / gr, that is, a small fraction of the radium found in the uppermost layers of the red clay and other abyssal sediments. It is perhaps inevitable that press reports of lectures on the radioactive elements in the ocean should state there are "immense quantities of uranium and radium on the deep ocean floor." We see the statement is not founded on fact.

Among the radioactive elements which lend themselves to age determinations we may nowadays include also the radioactive isotope of carbon, C_{14}, produced from carbon dioxide in the atmosphere through nuclear collisions and subsequently deposited as carbonates on the ocean floor. The method of radiocarbon dating developed by W. Libby in the Institute for Nuclear Studies in Chicago has proved eminently useful to archaeology for dating wood, peat, and other vegetable remains found on prehistoric sites. The time range of such age determinations is, however, limited to less than 20,000 years, as the time for disintegration of radiocarbon to 50% of its original amount is only 5,568 years. This method has recently been applied also in attempts to date the upper layers in one of the "Albatross" cores from the eastern Pacific Ocean, investigated by Arrhenius (in collaboration with Libby and Kjellberg). Since the quantity of calcium carbonate required for obtaining a dependable value of the radiocarbon present is fairly large, it was necessary to work on the material in a core length of 45 centimeters, spanning a total time of deposition of more than 14,000 years, that is, nearly three times the half-value period of radiocarbon already mentioned. This obviously makes the results less accurate than if a core of a much larger section could have been used. In such a case a length of only three to four centimeters cut from such a thick core would have been sufficient. It is to be hoped, therefore, that in future expeditions coring devices of the same diameter as those occasionally used on board the "Albatross," that is with an internal diameter of four inches or ten centimeters, will be employed in order to obtain material for more detailed investigations using radiocarbon dating.[13]

Summary. The study of the radioactive elements uranium, ionium, radium, thorium, and radiocarbon which are present in deep-sea sediments and ocean water has proved well worth pursuing further. Geochronological studies based on radioactive age determinations have proved feasible, although in the case of radium they are complicated by a reshuffling of the sediment. The time span over which such age determinations may be extended, even in the most favorable cases, is limited to 300,000 or at the most, 400,000 years, that is, about half the length of the Pleistocene. The relatively rapid decay of radiocarbon sets still narrower limits to its use of about 20,000 years.

9. The Bottom Waters of the Ocean and Their Movements

Laymen are likely to consider the water in great ocean depths uninteresting. Measurements prove that it is of almost uniform and constant temperature, a few degrees centigrade above zero, and of a salinity very near 35‰. It is never stirred by ordinary waves and, as far as we know, very little by currents—a changeless sea inhabited only by a sparse and highly curious-looking deep-sea fauna. Apart from that, the bottom water may well appear devoid of interest.

The view that what we are profoundly ignorant of is unimportant is not always justified. Modern deep-sea research has had excellent reasons to abandon such a negative attitude and devote considerable attention to the very deepest water layers. The reason is that the contact between the water and the underlying sediment is the seat of a physicochemical activity which profoundly affects both media. We know that an interchange of substance occurs across this boundary. Sediment particles from above come to rest on the bottom, and certain components of this sediment are extracted by the bottom water and thus re-enter the oceanic circulatory system. The remarkable dissolution of lime from the calcareous remains of dead planktonic and benthonic organisms, especially the *Foraminifera,* is due to chemical action by the bottom water. But not only the biogenetic components of the deposit are thus affected. Remarkable discoveries of the last few years by the Swedish mineralogist O. Mellis prove that fragments of abyssal rocks are also subject to progressive "weathering," in which lime is dissolved away and sodium replaced by potassium. Other evidence, obtained by Arrhenius and Riedel from siliceous Pacific cores, proves that siliceous remains are likewise subject to partial dissolution by the bottom water. Finally, the transfer of manganese, iron, and other elements from the water to the sediment through a mechanism not yet fully explained is, at least in part, localized to the very undermost water layers, and the same applies to the radioactive elements ionium and radium.

Obviously all these happenings must be influenced by the state of movement of the deep water layers. If they were absolutely stagnant, the reactions and transfers mentioned would take a tremendously long time, owing to the slowness of diffusion through motionless water. If, on the other hand, the bottom water is moving relative to the sediment, not only will chemical reactions be speeded up through turbulence, but in addition mechanical effects are to be expected, disturbing the settling of sediment particles, perhaps even removing them after sedimentation, by what may conveniently be called "bottom erosion."

The importance of these different questions was not ignored in planning the Swedish Deep-Sea Expedition. Thus, by means of current meters of special construction we had hoped to attack the problem of water movements in the immediate vicinity of the ocean floor. Preliminary attempts made in Swedish fjords before the cruise had given rise to hopes that the bottom currents, previously inaccessible to direct measurements, could in fact be observed. Unfortunately the time allowed us, both for preparing and carrying out the cruise, was so short that this point had perforce to be struck off our program. There remained, however, another task more easily solved, which was to secure water samples at well defined heights close to the bottom itself without disturbing the sediment layer. This aim was realized by a special technique of F. Koczy which made it possible to get perfectly undisturbed water samples at 3, 6, 10, 15, etc. meters above the bottom.[1] Not only could the chemical properties of this near-bottom water be studied but also, by means of a method developed by N. G. Jerlov, optician and hydrographer of the expedition, the samples could be examined for their content of suspended particles.[2] The results are so important that I consider their inclusion here justified.

The technique of water sampling may be clarified by Figure 43, showing how the reversing water bottle was stopped at the desired height above the bottom by means of an extra weight, a dynamometer on deck announcing when the bottom was reached.

It does not appear improbable that the undermost water bottle attached to the wire one meter above the weight could have accidentally enclosed contaminated water. (Such an objection cannot be raised against measurements in the Indian Ocean, where the distance between water bottle and weight was four meters.) However, this disturbing effect could not have extended

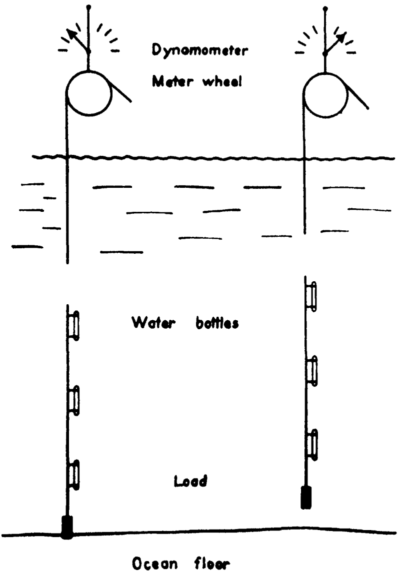

Fig. 43. Water sampling near bottom

as high up as the next water bottle, ten meters above the sediment. During the measurements discussed below the water bottles were kept at their given height over the bottom to within one meter.

The bottles were coated inside with ceresine, a substance resembling paraffin, in order to avoid contamination of the enclosed water by the metal. This is essential for successful Tyndall measurements, and in addition the coating prevents an absorption of oxygen by the metal parts.

The measurements of particle distribution show that a fine stratification appears near the bottom. In particular, a suspension of particles is often present in the first few dozen meters above the bottom. The highly stratified distribution indicates that the turbulence there is very low. But in other places the eddy diffusion due to bottom currents is sufficient to prevent deposition of fine material like organic detritus and lutite, particularly when the bottom is rough.

There are also localities where there is no bottom suspension and the water is extremely clear in close proximity to the floor—depressions, for example, where the currents are vanishing, whereas over ridges and sea mounts the fine material is swept away by currents.

Clouds of particles were often encountered at different heights above the bottom. This indicates that the bottom material in suspension from adjacent rises on the floor is distributed laterally by currents. These conditions were often met with above the rugged parts of the floor of the Atlantic Ocean. In collecting samples from the bottom water we found that preventing dust and atmospheric gases from contaminating the water is essential. Chemical properties were determined at once by our chemist from part of the sample, and from another part the optical properties were studied by the Tyndall method by Jerlov himself. It should be added that similar optical tests were made on samples from other water layers, including surface water, and that the results have proved most illuminating for the study of the dynamics of upper and intermediate water strata. Two figures setting forth Jerlov's results pertaining to the bottom water at a few Atlantic stations are reproduced here.

It is seen that in certain localities the bottom water remains practically crystal clear down to the lowest level examined, proving that there is no apparent stirring up of sediment particles below. In other localities the number of suspended particles distinctly increases as one approaches the bottom, which proves that there is some kind of turbulent motion going on. It is of interest to note also the results of examining samples from somewhat higher levels, where Jerlov found distinct clouds of particles. A similar find was made some years earlier by Kalle, the German oceanographer, working in the North Atlantic Ocean.[3] He assumed these clouds to be remnants of volcanic ash rains that had not had time to settle to the bottom.

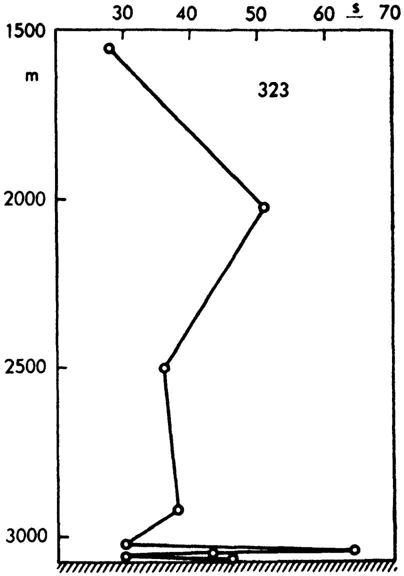

Fig. 44. Turbidity near bottom

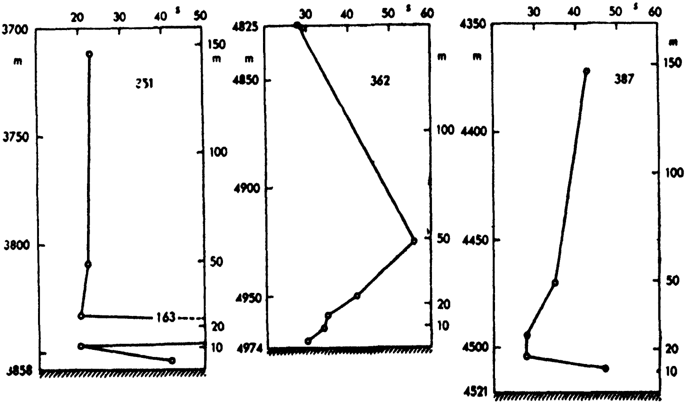

Fig. 45. Types of turbidity changes near bottom

Jerlov's explanation is simpler. He believes that the clouds he has found are derived from sediment covering deep mounts or ridges, and that it has been stirred up and transported to the leeward side of the obstacle by a bottom current passing over it.

It appears fairly well established that in the deepest layers of the ocean, where suspended sediment particles can be taken as current indicators, there are movements by bottom currents. These may be sufficient to erode sediment already deposited and transport older sediment to new places of deposition, mixing it with fresh sediment settling from the surface.

This explanation may serve to explain the surprising discovery—made by Riedel investigating radiolarians from the central Pacific Ocean, by Arrhenius in his study of cores from the eastern Pacific, and by Shepard, Stetson, and Eriksson working up sediment samples from the northwest Atlantic—that sediments of recent origin contain ancient types of radiolarians etc., some even of Tertiary age, and that in certain cases the top of a core may consist of sediment deposited hundreds of thousands, if not millions, of years ago, the superimposed and more recent layers having been more or less completely removed through bottom erosion. There are strong reasons to suspect, especially when one encounters mixed faunas of different ages in the same layer, that a redeposition, falsifying the chronological sequence, has occurred.

As regards the chemical composition of the bottom water, Figure 46 shows one of Koczy's most interesting diagrams, based on observations made in the Romanche Deep from the "Albatross" in the beginning of July, 1948. The Romanche Deep is a highly curious formation, a kind of deep hole in the ocean floor quite close to the most spectacular part of the Mid-Atlantic Ridge just under the equator, where the ridge, running due east to west, is the narrowest and most jagged. We devoted a few days to this region and obtained a record sounding of over 7,600 meters, or well over 25,000 feet, whereas only 10 nautical miles to the southeast of this pit the ridge rises abruptly to about 2,600 meters,

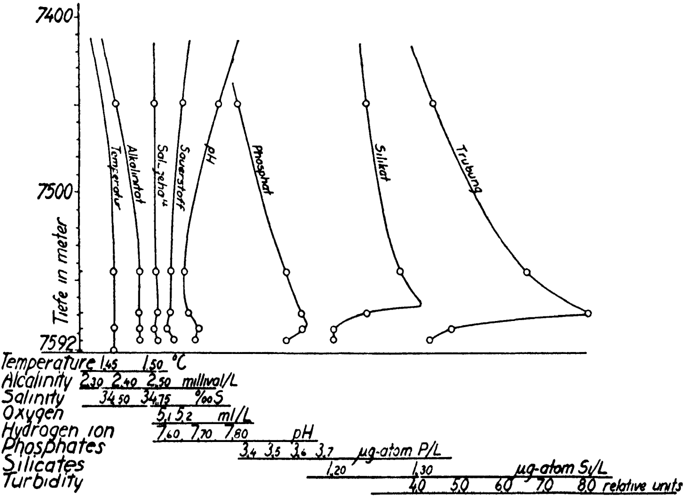

Fig. 46. Changes in water near bottom

or less than 9,000 feet from the surface. This difference in level of 16,000 feet over a distance of 10 nautical miles corresponds to a grade of 25:100.

Here we are quite close to the breakthrough in the ridge, the famous Romanche Channel, which has never been located by soundings but which, according to temperature measurements, opens a passage for the nearly ice-cold Antarctic water from the southwest into the secluded basins of the eastern Atlantic Valley. This channel is assumed to be about 15,000 feet deep. leaving undisturbed the still lower water layers of the Romanche Deep below the threshold level.

Investigating the contents of the water bottles lowered to the bottom of the Romanche Deep, Koczy found that the distribution of certain elements characteristic of the ocean water was as shown in Figure 46. Although there is no noticeable break in the curves for salinity and temperature, there are very pronounced and abrupt changes in the contents of silica, phosphates, and optical particles ("turbidity"), occurring at about 20 meters or, say, 65 feet, above the bottom. From these breaks, corresponding to the maxima in the three curves, there is a gradual decline to the much lower figures found in the deepest water sample, taken only 25 feet from the ocean floor.

How this strange stratification shall be interpreted is largely a matter of conjecture. It should be pointed out, however, that an analogous trend of the curves was observed in other localities, where the depth was also very great. In other words, they are not unique for the configuration of the bottom near the Romanche Deep.

In discussing these results in a paper about to be published, Koczy has entered on the more general problem offered by the interchange between bottom water and sediment. The following abstract is given with his permission.

Near the bottom, apart from hummocks and mounds, there is a laminary current, that is, one without turbulence. On mounds and ridges, on the other hand, a turbulent motion followed by chemical solution seems to prevail.

The most soluble elements like Mn, Ni, Fe, Na, and Ca are, therefore, liable to displacement, their content being reduced in certain localities and increased in others. This does not apply to Ti. Owing to the reduced turbulence, the oxygen content can locally get so low that in hollows in the bottom a reducing milieu may arise, with corresponding changes in solubility, precipitation, and exchange of elements.

It is necessary, however, to return once more to the question of the bottom currents. As mentioned in an earlier chapter, the dominating currents in very great depths are set up by temperature differences produced through the cooling of the surface waters in high northern and, more especially, high southern latitudes, which cause the water to sink to the bottom. From the Antarctic Continent great currents spread northward along the bottom in all three oceans. They are largely responsible for the low temperatures characteristic of the deeper ocean waters. These so-called Antarctic bottom currents, the trend of which is considerably affected by the bottom configuration, have been held responsible, especially by German oceanographers like G. Wüst, for the disappearance of lime from sediments of great depths, that is, for the conversion of *Globigerina* ooze into red clay.

According to climatologists the present polar ice caps were characteristic of Quaternary time and are relicts of the extensive glaciations which at their maxima heaped up millions of cubic miles of water in the shape of inland ice over the continents in higher latitudes. On the other hand, most of the Tertiary Age is assumed to have had a much warmer climate, polar ice being nearly or totally absent. During part of that favored era subtropical vegetation grew on Greenland, Spitzbergen, and probably the Antarctic. With the great ice caps removed from our globe, the main driving power behind the Antarctic and Arctic bottom currents was also removed. Hence one is forced to assume that at that time the vast ocean water masses below the 6,000-foot level must have had a temperature about 10° centigrade higher than at present, that is, comparable to that of the bottom water in the Mediterranean, which is totally cut off from polar influences by the threshold at Gibraltar. Granting this to be true, the bottom water during the Tertiary should have been not only warmer than at present but much more stagnant. That is, the lime-dissolving power of the deepest water layers, which is at present attributed to the cold Antarctic bottom current, should have been absent or at least much less intense during the Tertiary Age. Assuming the production of calcareous shells from the surface plankton to have been as intense then as now (in fact, it should have been greater because of the higher surface temperature), there is no reason why red clay should have been produced at all in Pre-Quaternary time!

This is one reason I was so moved when our first long core of typical red clay was raised from the bottom of the central Atlantic Ocean during the first crossing with the "Albatross." For even if we ascribe as high a figure as 10 millimeters in 1,000 years to the rate of sedimentation of that core (the probable average is only 7 millimeters), its lowest parts would have the respectable age of 1½ million years, thus taking them definitely back into the Pliocene, when the great deterioration of climate characteristic of the Quaternary had not yet set in. Still older red clay was subsequently obtained from the central Pacific Ocean.

How to explain the occurrence of Pre-Quaternary red clay, therefore, seems a baffling task to oceanographers, who have wholeheartedly adopted Wüst's theory of the Antarctic bottom current as the main lime-dissolving factor in great depths.

My own views, which may seem rather heretical to many colleagues, may be set forth in few words. The deep-sea bottom abounds with evidence of submarine volcanic activity. Volcanic minerals—and not merely fragments of pumice—are normal components of red clay, beds of lava are not uncommon, and the submarine ridges, as well as the islands crowning them and all the innumerable islands of the South Seas, testify to the prevalence of submarine volcanism. Add to this the novel idea that the Mid-Atlantic Ridge is due to enormous extrusions of magma during the Tertiary Age, and we can well conceive of the deep-sea bottom as a volcanological laboratory on a gigantic scale.

Now, we know that eruptions of volcanoes on the continents are very often accompanied and followed by exhalations of carbon dioxide and fumes of hydrochloric acid, sulphur dioxide, and sulphuric acid. The South American volcano Puracé is reputed to exhale about 30,000 tons of hydrochloric acid a day, and from the Valley of the Ten Thousand Smokes near Katmai one million tons of hydrochloric acid are said to be discharged annually, even now, 40 years after the great eruption. It would therefore be difficult to deny that submarine volcanoes likewise give off acid fumes. In point of fact, the hot magma welling up through the ocean floor encounters ice-cold water rich in chlorine. It is reasonable to assume that at this encounter hydrolysis must occur on a vast scale, releasing enormous quantities of mineral acids and carbon dioxide.

It should be noted here that if, through volcanic action, lime is removed over large areas of the sediment carpet, the carbon dioxide set free will, because of the high water pressure, remain in solution and increase the capacity of the bottom water for removing more quantities of lime.

If this view is correct, a study of the lime content in stratified cores, especially near volcanic islands or peninsulas, should afford an index of variations in volcanic activity in the past, at least where cores of sufficient length can be obtained.

I have now to take up a highly controversial point regarding the bottom currents and their effect on the sediment. Forty years ago the great American geologist Reginald Daly suggested that the remarkable submarine canyons which cut deep into the coastal shelf and adjoining continental slope (and which sometimes are discernible down to depths of 10,000 feet or even more) may have been excavated by submarine erosion.[4] Water heavily laden with sediment will have its specific weight increased, and sliding down a submarine slope it may acquire sufficient energy to cut deep furrows in unconsolidated, perhaps even consolidated, sediment layers, producing a kind of river bed. This hypothesis of sediment-laden or "turbidity" currents has in recent times been taken up by Kuenen of Groningen who through beautiful experiments in the laboratory has demonstrated both the velocity and the eroding power of turbidity currents artificially produced.[5]

This notion of coastal and subcoastal erosion by turbidity currents was later expanded to include the erosion of sediments at great depths and a reshuffling of sediments which upsets the natural sequence of strata.[6]

Once the ruggedness of the bottom profile in great depths stands revealed, as through the "Albatross" echograms, one condition of turbidity currents, namely steep slopes charged with sediments, is accounted for. The releasing factor, where surface waves are lacking, can be found in submarine landslides set in movement by volcanic eruptions in great depths or by seaquakes. Some adherents of Kuenen's hypothesis have even gone so far as to ascribe to turbidity currents a dominating influence on deep-sea sediments, claiming that their frequent occurrence reshuffles the sediments and makes the taking of long cores useless. Let us see if recent contributions to the knowledge of these important currents justify the emphasis placed upon them.

In Chapter 5 it was pointed out that turbidity currents have been invoked as a means of transportation for bottom sediments to explain, especially, so-called graded bedding, deep-sea sand, and the transfer of shallow-water benthonic organisms into much greater depths. Cases of graded bedding have repeatedly been observed in long sediment cores raised from the "Albatross," both in the Mediterranean and in the equatorial Atlantic Ocean. It seems very probable that masses of sediment may be set in motion along slopes too steep for an angle of repose or where disturbances by tectonic or volcanic forces occur, so that conditions for the setting up of turbidity currents as defined by Kuenen may be fulfilled locally. Many geologists, however, incline to the view that such turbidity currents are rather exceptional occurrences. So far they have not been directly observed in the open ocean, and their importance in eroding the consolidated material in submarine canyons is doubtful since the water they carry is already overloaded with sediment. This view is shared by Shepard, the American authority on submarine canyons. Attempts to set up artificial turbidity currents along submarine canyons through explosions have so far failed. Recent observations carried out in moderate depths within a Swedish fjord where great quantities of sediment were dumped failed to give any evidence for turbidity currents of any notable velocity.

However, in echograms from the equatorial Indian Ocean to the south of Ceylon, obtained during the "Albatross" cruise, Koczy has found indications of shallow submarine values in great depths, which may possibly be due to turbidity currents. This view has been further expounded in a recent paper by Dietz.[7]

Recently, Kullenberg published a criticism of the paper in which Heezen and Ewing attribute the breaks of the submarine cables over the Grand Banks after an earthquake in 1929 to turbidity currents set up by the quake (see Chap. 5, n. 1). Studying in detail the topography of the area where the breaks occurred, Kullenberg finds the hypothesis that turbidity currents caused the breaks incompatible with the fact that the direction of flow would have carried the current over obstructions in its path. In particular, Kuenen's endorsement of the American authors' belief that some of the breaks may be attributed to individual fast arms of the hypothetical current is rejected. Summing up Kullenberg's different arguments, one may say that postulating a turbidity current solely on the *ad hoc* evidence of its effects on submarine cables appears to be a highly dubious proceeding, quite apart from the fact that an exorbitant velocity must in that event be ascribed to it.

The present evidence, we may conclude, hardly affords clear proof that turbidity currents have played any dominant part in sculpturing the ocean floor. Both their extension over the deep ocean bottom and their velocities on steep slopes appear to have been overestimated by Heezen and Ewing.

10. Life in Great Depths

The important part played by marine biology in stimulating interest in deep-sea research has already been referred to in Chapter 2. Systematic investigations by Forbes of the fauna in the Aegean Sea (1840–41) led him to the conclusion that the number of species and individuals decrease in inverse proportion to the depth until a zero line is reached at a depth of 1,800 feet, where an azoic zone begins. This conclusion was strongly contested during the following decades by British and Scandinavian biologists who, along the coasts of northwest Europe, found an abundant fauna of marine organisms in depths considerably exceeding that of Forbes' zero line. To continue and extend this work into the still greater depths of the open oceans was one of the main reasons for sending out the great circumnavigating deep-sea expedition with H.M.S. "Challenger" (1872–76) followed by expeditions from the United States and countries in Europe.

During the "Challenger" cruise living organisms were raised from depths ten times greater than that of Forbes' zero line. In the beginning of this century the late Prince Albert I of Monaco obtained northwest of Madeira from a depth exceeding 6,000 meters a bottom-living abyssal fish, *Grimaldichtys profundissimus*. Nearly half a century later, in 1948, O. Nybelin of the Swedish Deep-Sea Expedition with the "Albatross" obtained bottom-living organisms from a depth exceeding 7,600 meters.[1]

However, there is no doubt that with increasing depth there is a decrease in the density of population on the ocean floor, and the question of whether the very deepest layers of the ocean are azoic or are not remained open. Laboratory experiments by Fontaine seemed to indicate that pressures exceeding 700 atmospheres, equivalent to 7,000 meters of water, have destructive effects on the protoplasm of living cells.[2]

Life in very great depths must be highly precarious. No trace of daylight can penetrate even the clearest sea water below a depth of approximately 3,000 feet. The progressive loss of light is due to an absorption by the water itself and to light scattering against suspended particles, water molecules, and salt ions. Such rapid attenuation of light naturally limits plant life to a relatively thin, euphotic, surface layer, where enough radiant energy to support photosynthesis is present. This total lack of abyssal plant life must have serious consequences for the maintenance of animal life, which in great depths apparently can subsist only on crumbs falling from the sunlit table near the surface.

These crumbs obviously must get scarcer and scarcer the deeper they sink, since they are avidly consumed by marine bacteria and by pelagic animals living in great depths. Only over the bottom of shallow seas is organic detritus from the uppermost water strata profusely scattered, giving rise to an abundant fauna of bottom-living organisms, the bottommost being mud-eaters which burrow into the upper sediment layers; yet the presence in great depths of invertebrate animals and fish proves that some means of subsistence actually exists there. The invertebrates living on the abyssal plain, especially crustaceans, worms, mussels, and echinoderms, appear to be the main supporters of the bottom-living fish. (See also page 163, below.)

The absence of daylight naturally has a profound influence on deep-sea fish, many of which have only rudimentary eyes or even lack eyes altogether. Hence it seems rather surprising that among bottom-living fish blindness is *not* the rule. Many of them have large, well-developed eyes, proving that they are capable of reacting to light.

Whence comes this light of the abyss? The answer is simple: from the animals themselves, a high percentage of which are provided with special light-emitting organs or are capable of giving off secretions which emit a diffuse light. The feeble light existing in great depths is thus animal light. It is produced by a highly interesting process of chemicoluminescence caused by the oxidation of a substance called luciferine, a process assisted by an enzymatic component called luciferase. Very often this process is occasioned or accelerated by bacterial action.

Some of the bathypelagic fish have highly perfected light-emitting organs, evidently used for attracting their prey of smaller organisms. In other cases the emission of light may serve the propagation of the species, the individuals recognizing each other at some distance by the light they emit.

The very fact that animal light plays an important part in the life of deep-sea animals confirms the assumption that water in great depths, including the layers immediately above the bottom, must have a high degree of transparency, that is, it must be almost free from suspended particles. Investigations made by Jerlov from the "Albatross," mentioned in Chapter 9, bear out this assumption.

The third factor which limits animal life (besides scarcity of nutrients and lack of illumination) is the high pressure. To the supporters of the theory that the great ocean depths are azoic this factor seemed of paramount importance. It certainly is astounding that living creatures can support pressures comparable to those inside a modern field gun when the projectile is leaving its barrel—pressures from 10,000 to 15,000 pounds per square inch. Obviously, such enormous external pressures must be counterbalanced by equally high pressures existing in the tissues of the animals supporting them. A swimbladder containing gas of this enormous pressure must inevitably cause the violent explosion of a fish rapidly raised to the surface.

From a private letter from the eminent American zoologist Rolf Bolin, whom I was fortunate enough to meet in San Francisco after his return from the "Galathea" Expedition, I am allowed to quote the following passages of special interest for the preceding as well as the ensuing remarks.

"I know of no real deep-sea fish which has an air-filled swimbladder. This organ either drops out entirely or is modified into a fat-storage organ. The first mention of the latter condition I know of was published about three years ago, so there is not much literature on the subject. . . .

"With the tendency to a loss of eyes in deep-sea forms, there has come a concomitant development of other sense organs. In some cases the impression of the surroundings is gained through tremendously enlarged olfactory organs. In others the 'lateral line' is astonishingly developed, so that the fish can 'hear' things around it; and in still others long filaments, developed from extended fin rays or from barbels, are used to pick up vibrations in the water. All of these, however, are to be found just as commonly in depths of about 3,000 meters as in the great depths."

Most fishes from great depths are of slender build and because they lack powerful muscles are not very good swimmers. On the other hand they are in general provided with very big mouths and highly distensible jaws, somewhat resembling those of snakes. Obviously their chances of getting a square meal from the sparse bottom fauna are so rare that each occasion has to be utilized to the full. Cases are known of a fish from a great depth which when discovered had recently swallowed another fish considerably bigger than itself (Figure 47). The whole problem of the nutrition of abyssal fauna presents interesting aspects and raises many questions which will have to be answered by future deep-sea expeditions.

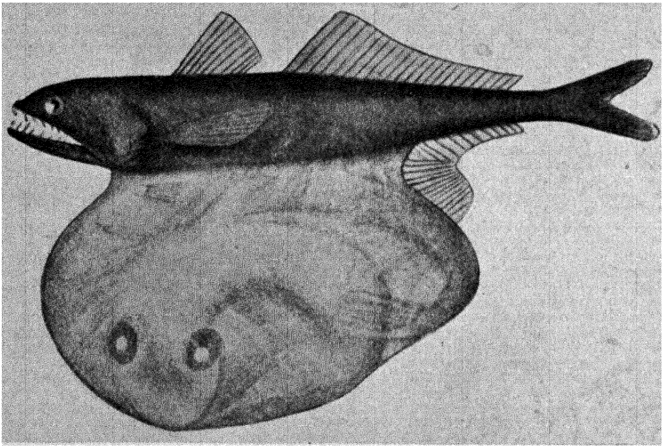

Fig. 47. Deep-sea fish after a square meal

Trawling in Great Depths

The most efficient gear for collecting animals from very great depths is the trawl, a wide-open sack of netting towed along the bottom at the end of a long, tapering, steel cable. The shape as well as the width of the trawl can vary within wide limits, from the otter trawl used in 1910 by Hjort in great depths in the North Atlantic on board the "Michael Sars," the width of which was about 50 feet, to the so-called sledge trawl used from the "Galathea," the gap of which, kept open by an iron frame, had a width of 10 feet. The prawn trawl and an otter trawl used by Nybelin from the "Albatross" had a width of 30 feet.[1]

Three great improvements in the technique of deep-sea trawling were utilized during the "Albatross" cruise. First, the depth at which the trawl was towed was kept under continuous control by means of our excellent recording fathometer. With 30,000 feet of cable or more it is essential to ascertain beforehand that the bottom over which the trawl is moving is suitable for undisturbed hauls. Second, thanks to theoretical and experimental work by Kullenberg, the exact length of cable required for keeping the trawl in contact with the bottom could be calculated.[3] Third, because of the powerful electric deep-sea winch built for the "Albatross," the trawl could be lowered and raised at the speed required without undue loss of time.

The difficulties of deep-sea trawling naturally increase with the depth and with water movements due to strong surface currents. The relatively low power of the "Albatross" engine, which allowed the ship a maximum speed of less than two knots with 30,000 feet of cable being towed, greatly added to the difficulties of making successful hauls. The powerful engines of the "Galathea" put her in a more fortunate situation. Moreover, essential parts of her gear, especially the electric winch and the tapering steel cables, were taken over from the "Albatross," and the same type of fathometer was used for controlling the depth and studying the configuration of the bottom over which the trawling was carried out. The brief description given below of a

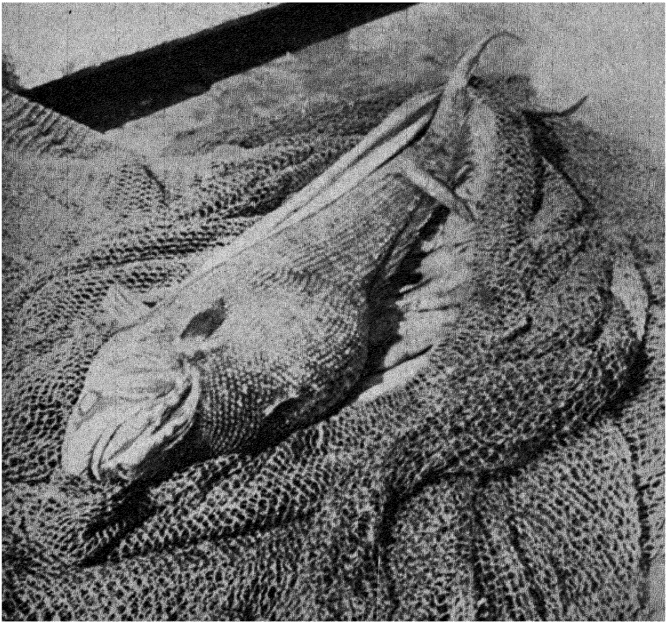

Fig. 48. Our largest deep-sea fish

remarkable haul made by the "Galathea" in the Philippine Trench I owe to the leader of the expedition, A. Bruun.

Preliminary studies by echograms proved the very deepest part of the trench, below the depth of 10,000 meters, to be a narrow strip of nearly flat bottom, only one to two nautical miles wide and 100 miles long. The slopes on both sides of the trench are relatively steep, making it difficult to keep the trawl from becoming torn or lost, especially since the equatorial current keeps the surface water masses moving at right angles to the trench with a velocity of one to two knots. To make a successful haul under these conditions in a depth of nearly 10,500 meters requires expert handling of the ship and gear.

After fourteen hours the trawl was raised to the surface and the catch was highly satisfactory. It included seventeen sea anemones, sixty-one sea cucumbers, four mussels, and one amphipode. It proved conclusively that even in this enormous depth bottom-living organisms exist. Equally important was the discovery in the mud brought up from this great depth of numerous bacteria, a fact which I shall refer to later.

No fish were caught. Later work by the "Galathea" in the Java Deep, the Solomon Deep, and the Kermadec Trench, however, brought up a comparatively large number of invertebrate bottom-living animals from depths exceeding 9,000 meters. In the Java Trench a benthonic fish, *Bassogigas,* was brought up by the trawl from 7,300 meters, together with over 3,000 holothurians and other invertebrate bottom animals.

In the Kermadec Trench, to the north of New Zealand, where the "Galathea" worked a few months later and where the slope on the eastern side is much more moderate than that of the Philippine Trench, both the sledge trawl and the otter trawl could be used and a series of hauls was made in depths between 2,500 and 8,500 meters. The catches made here in fourteen hauls were surprisingly rich. No less than 216 different species were caught, among which the crustaceans, with over seventy species, were predominant. The deepest haul, in 8,500 meters, also yielded excellent results, netting sixteen bottom-living species, some of them represented by as many as twenty individuals. In more moderate depths, that is, higher up on the slope, forty fish were caught, representing sixteen different species. The largest fish was over 3½ feet long, with a very large head and the tapering tail characteristic of bottom fish. In general the hauls made in the Kermadec Trench revealed a surprisingly large number of individuals and species, marking this trench as a most promising field for future deep-sea trawling.

Most marine organisms brought up from very great depths arrived on board the ship dead or in a dying condition. This is especially the case with abyssal fish. Workers in the field seem to agree that it is not primarily the great decrease in pressure which is fatal to abyssal life, but rather the rise in temperature. In tropical waters, where the surface temperature may approach 30° centigrade, the bottom water where the animals have been living is ice cold, generally between 1.5° and 2.5° centigrade.

Another cause of high mortality is the rough handling of the catch on its way up, especially when large quantities of the deposit or occasionally even stones enter the trawl, so that the abyssal fishes arrive on deck in a mangled and mutilated condition. Technical improvements of the gear to protect the catch against mechanical damage and retard the rise in temperature, have been considered but so far have not led to practical tests.

One method of catching deep-sea animals, tried by the Prince of Monaco, is to lower into the depths cages or traps, with a luminous bait inside, utilizing the phototactic reactions of the abyssal animals to attract them into the cage. With free-swimming bathypelagic animals the method appears hopeful, but its use for bottom-living organisms would be complicated by the necessity of keeping the ship immovable for a considerable length of time.

Bacterial Life in Great Depths

The question of whether bacteria can exist in great depths has repeatedly been asked. A plan to search for abyssal bacteria was included in the original program of the Swedish Deep-Sea Expedition, but the investigation had to be abandoned for lack of time and the requisite instruments. Otherwise, a special attempt would have been made to find out whether bacterial action is involved in the growth of the manganese nodules, as has been suggested by a Russian scientist.

The Danish expedition with the "Galathea" was more fortunate, as they were well provided with resources for collecting and cultivating bacteria from the sediment in great depths and moreover had elicited the cooperation of the world's foremost expert on marine bacteria. Claude ZoBell of Scripps Institution of Oceanography. The following is a brief summary of ZoBell's report on his investigations on board the "Galathea," which he had the kindness to show me in manuscript shortly after his return to Scripps.[4]

Microscopic examination of a sample of mud raised to the surface from a depth of 7,200 meters in the Java Trench revealed the presence of more than one million bacteria per gram. Measured amounts of the mud were inoculated into tubes with a nutrient medium. Little or no growth was observed at ordinary atmospheric pressure or at 30° centigrade, but in tubes incubated at 3° centigrade and placed in steel cylinders with a hydrostatic pressure of 700 atmospheres, equivalent to a water depth of about 7,000 meters, from ten to a hundred times more bacteria were reproduced. Also, many more bacteria were demonstrated in bottom deposits than in the overlying water. In mud taken from the Philippine Trench at a depth of 10,400 meters the bacteria cultivated at a pressure of 1,000 atmospheres were a thousand times more numerous than in cultures under one atmosphere. Other experiments made with bacteria from relatively shallow water prove that they do not grow at the high pressures characteristic of extremely deep water. Obviously the bacteria found in deep-sea mud must be species indigenous to the deep sea.[4]

It is well known that most of the organic matter in the sea is produced by photosynthesis in the euphotic zone, that is, in the topmost few hundred meters of water. How much of this organic matter reaches the deep-sea floor is problematical. The low organic content of many deep-sea bottom deposits suggests that a relatively small amount of organic remains reaches abyssal depths. What then is the source of food for deep-sea organisms? ZoBell, in 1946, suggested that the organic matter in oceanic depths is supplemented to a significant extent by bacteria, which are known to serve as a source of food for many types of marine animals. Heterotrophic bacteria synthesize cell substance by utilizing dissolved and other suspended organic matter, commonly found in sea water in amounts of about 5 milligrams per liter.

By their assimilation of dissolved, colloidal, detrital, or other forms of organic matter and conversion of 30% to 40% of it into nutritious cell substance, bacteria may serve as an important source of organic nutriment for marine animals. This may be true especially in the deep sea, where the influx of dissolved organic matter is dependent on the movement of water masses. It is of particular interest to find at the greatest known depths sufficient bacteria to contribute to the nourishment of bottom-feeding animals. It is equally interesting to note that most of the animals found on the deep-sea floor are types adapted to feed on very small particles like bacteria.

Earlier investigations of marine bottom deposits collected from different parts of the world have demonstrated the occurrence of bacteria capable of attacking virtually all kinds of organic compounds. Such bacteria are believed to play an important part in the mineralization of organic matter in the sea and in the formation of carbon dioxide, ammonium sulphate, phosphates, and other plant nutrients.

Large numbers of bacteria that reduce sulphates to hydrogen sulfide are commonly found in bottom deposits. The activities of such bacteria are often responsible for the vitiation of water in stagnant basins. By catalyzing the transformation of both organic and inorganic constituents of marine mud, bacteria appear to be the principal dynamic agencies that affect its hydrogen-ion concentration and oxidation-reduction potential; this fact may have a pronounced effect on the composition, chemical reactivity, diagenesis, color, biological population, geochemistry, and other properties of recent sediments.

Notes

The following sources are cited in shortened form:

Am. Journ. Sc.	*American Journal of Science.*
Bull. Geol. Soc. Am.	*Bulletin of the Geological Society of America.*
Medd. Oc. Inst.	*Meddelanden från Oceanografiska Institutet i Göteborg,* formerly *Meddelanden från Göteborgs Högskolas Oceanografiska Institution.*
Reports	Reports of the Swedish Deep-Sea Expedition 1947–1948 (Göteborg).

Chapter 1. The Oceans and Their History

1. A. Kitson, *Captain James Cook, R. N., F. R. S., "the Circumnavigator,"* London, 1907.
2. H. C. Urey, *The Planets, Their Origin and Development,* New Haven, 1952.
3. R. W. Fairbridge, "The Juvenility of the Indian Ocean," *Scope, 1* (1948), 29–35.
4. H. von Ihering, *Die Geschichte des Atlantischen Ozeans,* Jena, 1927.
5. A. L. Wegener, *Die Entstehung der Kontinente und Ozeane,* Braunschweig, 1920.
6. F. B. Taylor, "Bearing of the Tertiary Mountain Belt on

the Origin of the Earth's Plan," *Bull. Geol. Soc. Am., 21* (1910), 179–226.

Chapter 2. Envisaging the Past and Future

1. W. W. Rubey, 'Geologic History of Sea Water," *Bull. Geol. Soc. Am., 62* (1951), 1111–47.
2. R. Revelle, in an unpublished paper delivered before a meeting of the British Association for the Advancement of Science, in Liverpool, Sept., 1953; and in personal communications to the author.
3. V. I. Vernadskii, *Geochemie in ausgewählten Kapiteln,* tr. E. Kordes, Leipzig, 1930.

Chapter 3. Exploring the Ocean Floor

1. T. Nöldeke, *Beiträge zur Geschichte des Alexander-Romans,* Wien, 1890.
2. L. F. Marsigli, *L'Histoire physique de la mer,* Académie Royale des Sciences, 1735.
3. E. Forbes, *Report on the Mollusca and Radiata of the Ægean Sea,* London, 1843.
4. G. Schott, *Geographie des Atlantischen Ozeans* (Hamburg, 1926), p. 117.
5. J. Murray and J. Hjort, *The Depths of the Ocean,* London, 1912.
6. Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition auf dem Forschungs- und Vermessungsschiff "Meteor" 1925–1927, Berlin, 1938–39.
7. H. Pettersson and B. Kullenberg, "A Vacuum Core-Sampler for Deep-Sea Sediments," *Nature, 145* (1940), 306.
8. B. Kullenberg, "The Piston Corer," *Svenska Hydrogra-*

fisk-Biologiska Kommissionens Skrifter, 3d ser. (Hydrography), *1,* No. 2 (1945), 46 pp.

9. H. Pettersson, "The Swedish Deep-Sea Expedition 1947–48," *Deep-Sea Research, 1* (1953), 17–24.
10. M. Ewing, "Exploring the Mid-Atlantic Ridge," *The National Geographic Magazine, 94* (1948), 275–94.
11. I. Tolstoy and M. Ewing, "North Atlantic Hydrography and the Mid-Atlantic Ridge," *Bull. Geol. Soc. Am., 60* (1949), 1527–40.
12. F. B. Phleger, Frances L. Parker, and Jean F. Peirson, *North Atlantic Foraminifera,* Fascicle I of *Sediment Cores from the North Atlantic Ocean,* Reports, *7* (1953).
13. "Discovery" Reports, Cambridge, the University Press, 1929–47.

Chapter 4. The Sediment Carpet and the Substratum

1. Ph. H. Kuenen, "Rate and Mass of Deep-Sea Sedimentation," *Am. Journ. Sc., 244* (1946), 563–72; "Geochemical Calculations concerning the Total Mass of Sediments in the Earth," *Am. Journ. Sc., 239* (1941), 161–91.
2. W. Weibull, "The Thickness of Ocean Sediments Measured by a Reflexion Method," *Medd. Oc. Inst., 12* (1947), 17 pp.
3. M. Ewing, A. P. Crary, and H. M. Rutherford, "Geophysical Investigations in the Emerged and Submerged Atlantic Coastal Plain," *Bull. Geol. Soc. Am., 48* (1937), 753–801.
4. E. C. Bullard and T. F. Gaskell, "Submarine Seismic Investigations," *Proceedings of the Royal Society of London,* Ser. A, *177* (1941), 476–99.
5. B. Gutenberg, "Crustal Layers of the Continents and Oceans," *Bull. Geol. Soc. Am., 62* (1951), 427–39.

6. I. Tolstoy, "Submarine Topography in the North Atlantic," *Bull. Geol. Soc. Am., 62* (1951), 441–50.

Chapter 5. Recent Developments in the Investigation of the Deep Ocean Floor

1. B. C. Heezen and M. Ewing, "Turbidity Currents and Submarine Slumps, and the 1929 Grand Banks Earthquake," *Am. Journ. Sc., 250* (1952), 849–73. Cf. refs. to Kuenen, Chap. 9, n. 6.
2. See M. N. Hill, "The Floor of the Atlantic Ocean," *Nature, 171* (1953), 857–60. This is a summary of the discussion of the subject before the Royal Society of London; a complete report will appear in the *Proceedings of the Royal Society of London* for 1954.

Chapter 6. The Deep-Sea Deposits and Their Stratigraphy

1. J. D. H. Wiseman and H. Bennett, *The Distribution of Organic Carbon and Nitrogen in Sediments from the Arabian Sea,* The John Murray Expedition, 1933–34, Scientific Reports, *3,* No. 4, London, 1940.
2. F. W. Locher, "Kurzer Bericht über die sedimentpetrographische Untersuchung zweier Lotkerne der Albatross-Expedition," *Heidelberger Beiträge zur Mineralogie und Petrographie, 3* (1952), 193–218. Cf. Locher, "Ein Beitrag zum Problem der Tiefseesande im westlichen Teil des äquatorialen Atlantiks," *op. cit., 4* (1953), 135.
3. O. Mellis, "Replacement of Plagioclase by Orthoclase in Deep-Sea Deposits," *Nature, 169* (1952), 624.
4. O. Mellis, "The Coarse-Grained Horizons in the Deep-Sea

Sediments from the Tyrrhenian Sea," in H. Pettersson, "Three Sediment Cores from the Tyrrhenian Sea," *Medd. Oc. Inst., 15* (1948), 47–72.

Chapter 7. Recent Investigations on the Stratigraphy of Deep-Sea Sediments

1. G. S. Arrhenius, Fascicle I of *Sediment Cores from the East Pacific,* Reports, *5* (1952).
2. W. F. Libby, E. C. Anderson, and J. R. Arnold, "Age Determination by Radiocarbon Content: World-wide Assay of Natural Radiocarbon," *Science, 109* (1949), 227–8.
3. R. Revelle, "Shipboard Report of 'Capricorn' Expedition," unpublished manuscript in custody of Scripps Institution of Oceanography, ref. no. 53–15 (1953), p. 36.
4. W. R. Riedel, "Tertiary Radiolaria in Western Pacific Sediments," *Medd. Oc. Inst., 19* (1952), 24 pp.
5. R. W. Kolbe, "Diatoms from Equatorial Pacific Cores," in Fascicle II of *Sediment Cores from the West Pacific Ocean,* Reports, *6* (1954).
6. H. Pettersson and H. Rotschi, "The Nickel Content of Deep-Sea Deposits," *Geochimica et Cosmochimica Acta, 2* (1952), 81–90.

Chapter 8. Deep-Sea Radium and the Geochronology of the Ocean Floor

1. F. Hernegger and Berta Karlik, "Uranium in Sea-Water," *Medd. Oc. Inst., 12* (1935), 15 pp. See also E. Föyn, Berta Karlik, H. Pettersson, and Elizabeth Rona, "The Radioactivity of Seawater," *op. cit., 2* (1939), 7.

2. C. S. Piggot, "Radium Content of Ocean-Bottom Sediments," *Am. Journ. Sc., 25* (1933), 229–38.
3. C. S. Piggot and W. D. Urry, "The Radium Content of an Ocean-Bottom Core," *Journal of the Washington Academy of Sciences, 29* (1939), 405–10; "Radioactive Relations in Ocean Water and Bottom Sediments," *Am. Journn. Sc., 239* (1941), 81–91; "Apparatus for Determination of Small Quantities of Radium," *op. cit.,* 633–57; "The Radium Content of Sediments of the Cayman Trough," *op. cit., 240* (1942), 1–12; Urry, "Concentrations of the Radio-Elements in Marine Sediments of the Southern Hemisphere, *op. cit., 247* (1949), 257–75.
4. W. D. Urry, "The Radio-Elements in Non-Equilibrium Systems," *Am. Journ. Sc., 240* (1942), 426–36; Urry and Elizabeth Rona, "Radium and Uranium Content in Ocean and River Waters," *op. cit., 250* (1952), 160.
5. H. Pettersson, "Radium and the Deep Sea," *American Scientist, 41* (1953), 245.
6. V. St. Kröll, "Vertical Distribution of Radium in Deep-Sea Sediments," *Nature, 171* (1953), 742.
7. V. Kröll, *On the Distribution of Radium in Deep-Sea Sediments,* Fascicle II of Reports, *9* (1954).
8. E. Picciotto and Nadine Isaac, "Ionium Determination in Deep-Sea Sediments," *Nature, 171* (1953), 742–3.
9. H. Pettersson, "Manganese Nodules and the Chronology of the Ocean Floor," *Medd. Oc. Inst., 6* (1943), 43 pp.
10. Föyn, Karlik, Pettersson, and Rona, p. 38.
11. F. F. Koczy, "Thorium in Sea Water and Marine Sediments," *Geologiska Föreningens i Stockholm Förhandlingar, 71* (1949), 238–42.
12. E. Picciotto and S. Wilgain, "Thorium Determinations in Deep-Sea Sediments," *Nature, 173* (1954), 632–3.
13. G. Arrhenius, G. Kjellberg, and W. F. Libby, "Age De-

termination of Pacific Chalk Ooze by Radiocarbon and Titanium Content," *Tellus, 3* (1951), 222.

Chapter 9. The Bottom Waters of the Ocean and Their Movements

1. L. Bruneau, N. G. Jerlov, and F. Koczy, "Physical and Chemical Data," in Fascicle II of *Physics and Chemistry,* Reports, *3,* Pt. IV (1953).
2. N. G. Jerlov, "Particle Distribution in the Ocean," *op. cit.,* *3,* Pt. III.
3. K. Kalle, "Die Erscheinung eines leuchtenden 'Strahlenkranzes' an der Meeresoberfläche," *Annalen der Hydrographie und maritimen Meteorologie, 67* (1939), 22–3.
4. R. A. Daly, "Origin of Submarine 'Canyons,' " *Am. Journ. Sc., 31* (1936), 401–20.
5. Ph. H. Kuenen, "Experiments in Connection with Daly's Hypothesis on the Formation of Submarine Canyons," *Leidsche geologische Mededeelingen, 8* (1937), 327–51.
6. Ph. H. Kuenen and C. I. Migliorini, "Turbidity Currents as a Cause of Graded Bedding," *Journal of Geology, 58* (1950), 91–127; Kuenen, "Properties of Turbidity Currents of High Density," *Society of Economic Paleontologists and Mineralogists, Special Publication,* No. 2 (1951), p. 14; Kuenen and H. W. Menard, "Turbidity Currents, Graded and Non-Graded Deposits," *Journal of Sedimentary Petrology, 22* (1952), 83–96; Kuenen, "Estimated Size of the Grand Banks Turbidity Current," *Am. Journ. Sc., 250* (1952), 874–84; Kuenen, "Significant Features of Graded Bedding," *Bulletin of the American Association of Petroleum Geologists, 37* (1953), 1044–66.
7. R. S. Dietz, "Possible Deep-Sea Turbidity-Current Chan-

nels in the Indian Ocean," *Bull. Geol. Soc. Am., 64* (1953), 375–7.

Chapter 10. Life in Great Depths

1. O. Nybelin, "Introduction and Station List," in Fascicle I of *Zoology,* Reports, *2,* Pt. I (1952), 3–27.
2. M. Fontaine, "Recherches expérimentales sur réactions des êtres vivants aux fortes pressions," *Annales de l'Institut océanographique,* n. s., *8* (1930), 1–100.
3. B. Kullenberg, "On the Shape and the Length of the Cable during a Deep-Sea Trawling," in Fascicle I of *Zoology,* Reports, *2,* Pt. II (1952), 31–44.
4. C. E. ZoBell, "Bacterial Life at the Bottom of the Philippine Trench," *Science, 115* (1952), 507–8.

Index

Silliman Memorial Lectures

Published by Yale University Press

OUT OF PRINT

Electricity and Matter. By Joseph John Thomson
Experimental and Theoretical Applications of Thermodynamics to Chemistry. By Walter Nernst
Radioactive Transformations. By Ernest Rutherford
Theories of Solutions. By Svante Arrhenius
Irritability. By Max Verworn
Stellar Motions. By William Wallace Campbell
Problems of Genetics. By William Bateson
The Problem of Volcanism. By Joseph Paxson Iddings
Problems of American Geology. Dana Commemorative Lectures
Organism and Environment as Illustrated by the Physiology of Breathing. By J. S. Haldane
A Century of Science in America. By Edward Salisbury Dana and others
The Intestinal Flora. By Leo F. Rettger and Harry A. Chaplin
Respiration. By J. S. Haldane
After Life in Roman Paganism. By Franz Cumont
The Anatomy and Physiology of Capillaries. By August Krogh
Lectures on Cauchy's Problem in Linear Partial Differential Equations. By Jacques Hadamard
The Theory of the Gene. By Thomas Hunt Morgan
The Anatomy of Science. By Gilbert N. Lewis

Molecular Hydrogen and Its Spectrum. By Owen Willans Richardson

The Changing World of the Ice Age. By Reginald Aldworth Daly

The Realm of the Nebulae. By Edwin Hubble

Embryonic Development and Induction. By Hans Spemann

Protein Metabolism in the Plant. By Albert Charles Chibnall

The Material Basis of Evolution. By Richard Goldschmidt

IN PRINT

The Integrative Action of the Nervous System. By Charles S. Sherrington

The Evolution of Modern Medicine. By Sir William Osler

Blood: A Study in General Physiology. By Lawrence J. Henderson

On the Mechanism of Oxidation. By Heinrich Wieland

Centennial of the Sheffield Scientific School. Edited by George A. Baitsell

Elementary Particles. By Enrico Fermi

Paleontology and Modern Biology. By David M. S. Watson

The Planets. Their Origin and Development. By Harold C. Urey