UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGY AND BIOLOGY OF NORTH ATLANTIC DEEP-SEA CORES

SUMMARY, FOREWORD, AND GENERAL INTRODUCTION

PART 1. LITHOLOGY AND GEOLOGIC INTERPRETATIONS

PART 2. FORAMINIFERA

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GEOLOGY AND BIOLOGY OF NORTH ATLANTIC DEEP-SEA CORES BETWEEN NEWFOUNDLAND AND IRELAND

SUMMARY OF THE REPORT

FOREWORD, BY C. S. PIGGOT

GENERAL INTRODUCTION, BY W. H. BRADLEY

PART 1. LITHOLOGY AND GEOLOGIC INTERPRETATIONS
By M. N. BRAMLETTE AND W. H. BRADLEY

PART 2. FORAMINIFERA
By JOSEPH A. CUSHMAN AND LLOYD G. HENBEST

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SUMMARY OF THE REPORT

In May and June 1936 Dr. C. S. Piggot of the Geophysical Laboratory, Carnegie Institution of Washington, took a series of 11 deep-sea cores in the North Atlantic Ocean between the Newfoundland banks and the banks off the Irish coast. These cores were taken from the Western Union Telegraph Co.'s cable ship *Lord Kelvin* with the explosive type of sounding device which Dr. Piggot designed. In the fall of that year he invited a group of geologists of the United States Geological Survey to study the cores and prepare a report. Biologists of the United States National Museum, the University of Buffalo, and chemists of the United States Department of Agriculture cooperated in the investigation and contributed to the report.

The westernmost core of the series (No. 3) was taken in the blue mud zone, but all the others were taken in parts of the ocean where the bottom is blanketed with globigerina ooze. The shortest cores are No. 8, taken on the mid-Atlantic ridge in 1,280 meters of water, and No. 11, taken where the core bit struck volcanic rock. The cores range in length from 0.34 to 2.93 meters and average 2.35 meters. They were taken at depths ranging from 1,280 to 4,820 meters.

Lithology and geologic interpretations.—In about 20 representative samples from each core the percentages of calcium carbonate, clay and silt, and sand were determined and plotted, and the relative abundance of Foraminifera, coccoliths, and diatoms was estimated. Material between these guide samples was examined microscopically, especially in certain critical zones.

Two zones were noted in which silicic volcanic ash (refractive index near 1.51) is common. The upper ash zone was found in all the cores except No. 11, but the lower one was found only in the lower part of cores 4 to 7. In core 3 the upper ash zone is represented by shards scattered very sparsely all through the core, as this core, despite its length of 2.82 meters, apparently did not reach the bottom of the ash zone. The upper ash zone, together with other adjacent lithologic zones, serves to correlate the cores, and the lower ash zone, found west of the mid-Atlantic ridge, helps to confirm the correlation.

Besides the zones of volcanic ash four other zones distinctive in lithologic character were found. These zones are characterized by a relative abundance of sand and pebbles, by a smaller percentage of calcium carbonate, and by a sparsity of Foraminifera and coccoliths. They are distinctive also in texture. The pebbles are subrounded to angular and include a wide variety of rock types—sandstone, gneiss, soft shale, and limestone—of which limestone is the most common. Some of the pebbles are as much as 2 centimeters across. These zones are interpreted as glacial marine deposits formed during the Pleistocene glacial epoch, when continental glaciers were eroding the land. Drift ice from the continental glaciers apparently transported considera-able quantities of rock debris far out into the ocean basin.

Between the glacial marine zones found in the North Atlantic cores the sediments consist chiefly of foraminiferal ooze or marl, much like that which is forming today in the same area.

The uppermost glacial marine zone is represented in all the cores except Nos. 3 and 11 and lies just below the upper volcanic ash zone. In cores 4 to 7 the glacial zones are relatively thin and are spaced at approximately equal intervals; between the third and fourth glacial zones (in descending order) is the lower volcanic ash. East of the mid-Atlantic ridge only the uppermost glacial zone has been identified. Other glacial marine deposits are recognizable but their correlation is less certain.

Three interpretations are offered as possible explanations of the four glacial marine zones. The first is that each glacial marine zone represents a distinct glacial stage of the Pleistocene and that each zone of foraminiferal marl separating two glacial marine zones represents an interglacial stage. This interpretation seems least probable of the three. The second interpretation is that the upper two glacial marine zones and the intervening sediment may correspond to the bipartite Wisconsin stage, whereas the lower two represent distinct glacial stages of the Pleistocene separated from each other and from the zone representing the Wisconsin stage by sediments that represent interglacial epochs no greater in length than postglacial time. This interpretation seems to imply too short a time for most of the Pleistocene epoch. The third interpretation, which is favored by the authors, is that each of the four glacial marine zones represents only a substage of the Wisconsin stage. This implies that the North Atlantic at approximately 50° north latitude for comparatively long periods of time alternately contained an abundance of drift ice and then was quite, or nearly, free of ice, while on land a continental ice sheet persisted, though it alternately waned and grew.

In the four cores in which the postglacial sediments are thickest the pelagic Foraminifera, according to Cushman and Henbest, reveal an interesting condition. These organisms indicate that during the middle part of the postglacial interval the temperature of the surface water in that part of the North Atlantic was somewhat higher than prevails today.

On the assumptions that the top of the uppermost glacial marine zone represents the beginning of the postglacial epoch as defined by Antevs, and that this was probably as much as 9,000 years ago, the postglacial sediment in these cores accumulated at a rate of about 1 centimeter in 265 years; but, because the sea probably cleared of detritus-laden drift ice long before the land in the same latitude was cleared of the retreating continental ice sheet, the average rate of accumulation may have been as low as 1 centimeter in 500 years.

Coarse-grained sediment on the tops of ridges and fine-grained sediment in the deeper basins indicate that currents move across these ridges with sufficient velocity to winnow out the finer particles and sweep them into deeper basins beyond.

The fact that the glass shards in the volcanic ash zones have been reworked and distributed without any gradation in size through many centimeters of the overlying sediments leads us to believe that mud-feeding animals are continually working over these shards and other particles of sand and silt so that they are redistributed at successively higher levels. The shards and other particles may also be reworked by gentle bottom currents that move the material from mounds and ridges on the sea floor and drift it about over the adjacent flatter areas.

Several layers in the cores are sharply set off by the coarser grain size of the sediment or by a regular gradation in grain size from coarsest at the base to fine at the top. These may be a result of submarine slumping.

The term globigerina ooze is used loosely in this report to designate sediment, half or more than half of which, by weight, consists of Foraminifera. This usage accords more closely with the usage adopted by Correns in the *Meteor* reports than with the usage of Murray and Chumley in the *Challenger* reports, which was based solely on the carbonate content. Limy muds containing a lesser but still conspicuous number of Foraminifera are referred to as foraminiferal marl. The carbonate content of the globigerina ooze in these cores ranges from 46.6 to 90.3 percent and averages 68.2 percent. In 191 samples representing all the lithologic types, the carbonate content ranges from 10.0 to 90.3 percent and averages 41.3 percent. Coccoliths are abundant in many parts of the cores, but by reason of their small size they rarely make up as much as 10 percent of the sediment. Pteropods are rather numerous in parts of the cores taken on the mid-Atlantic ridge and on the continental slope off the Irish coast.

Most of the calcium carbonate in these sediments consists of the tests and comminuted fragments of calcareous organisms. The finest particles of carbonate are of indeterminate origin, but their irregular shape and range in size suggest that they are largely the finest debris of the comminuted organisms rather than a chemical precipitate. Clusters or rosettes of calcium carbonate crystals were found in many samples, but they are not abundant. They evidently formed in the mud on the sea floor.

No conclusive evidence of an increase in magnesium carbonate with depth was found, though some of the data suggest it. The magnesium carbonate is somewhat more abundant in the glacial marine zones than elsewhere, but its concentration in those zones is probably accounted for by the presence of clastic grains and pebbles of dolomite.

Diatom frustules, radiolarian skeletons, and sponge spicules are the most common siliceous organic remains found in the cores, and these generally form less than 1 percent of the sediment. One notable exception is the sediment in the middle part of core 9, just east of the mid-Atlantic ridge, which contains 50 percent or more of diatoms.

Ellipsoidal and elongate or cylindrical pellets that appear to be fecal pellets are plentiful in the mud at the tops of cores 10 and 12, taken in the eastern part of the North Atlantic, but were not found elsewhere. No attempt was made to identify them further.

The sand-size material showed no marked variation in the mineral composition of the clastic grains at different horizons within individual cores and no conspicuous lateral variation from core to core. The mineral grains in the sand-size portions were not separated into light and heavy fractions, but simple inspection showed that grains of the heavy minerals are somewhat more common in the glacial marine deposits than elsewhere. Well-rounded sand grains are sparsely scattered through all the cores, but they are rather more plentiful in the glacial marine zones. These grains, which range in diameter from about 0.1 to 1.0 millimeter and average 0.5 millimeter, have more or less frosted surfaces. They may have been derived from the reworking of glacial marine deposits or they may have been rafted by seaweeds. Little was done with the clay minerals other than to note that most of them have the optical properties of the beidellite or hydrous mica groups.

Six samples were tested with a 10-inch spectograph, which revealed the presence of appreciable amounts of barium and somewhat less of boron in each sample. All the samples gave negative tests for antimony, beryllium, bismuth, cadmium, germanium, lead, silver, tin, and zinc.

The original porosity of several samples in core 3 was calculated from the porosity of the dried samples. The original porosity plotted against depth in the core seems to indicate that fine-grained blue muds buried to a depth of 2 or 3 meters in the ocean floor are appreciably compacted.

Partial mechanical analyses of nearly 200 samples were made and plotted, but only four complete mechanical analyses were made. The complete analyses were made by the sedimentation method and include four distinctive types of sediment.

Pumiceous fragments and smaller shards of basaltic volcanic glass (index of refraction near 1.60) are scattered throughout all the cores, but are somewhat more common east of the mid-Atlantic ridge than west of it. Unlike the alkalic volcanic ash it shows no conspicuous concentration in zones. Most of the basaltic glass and pumice has a thin surface alteration film of palagonite. The films are thickest on fragments in cores taken from ridges where oxygen-bearing waters had free access to the sediments. Two varieties of palagonite are recognized.

Core 11 represents only 34 centimeters of the sea floor because the core bit encountered deeply altered olivine basalt. About 15 centimeters of globigerina ooze rests on and within irregular cavities of the upper surface of a mass of clay that is apparently altered basalt. This clay is impregnated with manganese and contains nodular lumps of altered basalt. Part of the basalt near the base of the core is less altered. The clay contains scattered grains of sand and foraminiferal shells in which the original calcium carbonate has been replaced by a zeolite resembling phillipsite. This core may have penetrated the upper, deeply altered part of a submarine lava flow, but the evidence is not conclusive.

Core 10 contains two rather thick beds of distinctive clayey mud. About half of this mud is a beidellite or hydrous mica type of clay and the other half is made up of silt-size particles of basaltic glass, magnetite, augite, and calcic plagioclase. It contains very little common clastic material and exceedingly few Foraminifera. The composition and texture suggest that this mud was derived largely from a submarine volcanic eruption that threw into suspension clay particles perhaps partly from the normal sediment and from deeply altered basalt. A complete chemical analysis of this mud is given.

Foraminifera.—From these cores 184 samples representing every lithologic zone were examined for calcareous fossils. All but five samples contained Foraminifera. As in existing oceans deeper than several hundred meters, pelagic Foraminifera greatly outnumber the bottom-dwelling forms, though in variety of form and in number of genera and species the bottom forms greatly exceed the pelagic. Several zones of relatively pure globigerina ooze were found, and many in which the ooze was clayey or sandy. Though variations in temperature were reflected by faunal changes, the general bathymetric facies of the faunas appear to be rather uniform throughout each core. The bottom faunas are least varied and prolific in cores from the deepest water, whereas in cores from the shallowest water they are by far the most varied and prolific. Cores from intermediate depths contain faunas of intermediate bathymetric facies. These relations to depth are, in general, characteristic also of faunas in the existing oceans. A few scattered specimens of *Elphidium* or *Elphidiella* were found. These genera thrive in shallow water, but in these cores the shells are so rare, so erratically distributed, and in some so poorly preserved that it seems probable they were rafted in by seaweeds or ice and therefore have no significance as indicators of depth. No species peculiar to the Miocene or Pliocene were found. It appears, therefore, that all the sediments penetrated by the cores are younger than Pliocene. Alternation of faunas that are characteristic of the warm and cold climates of the present day indicates great climatic changes during the time represented by these cores. The foraminiferal facies characteristic of cold and warm climates correlate with the alternating sequence of glacial-marine and warmer-water sediments indicated by the lithology. This correlation suggests that all the sediments in these cores are of Recent and Late Pleistocene age.

Diatomaceae.—Fifty-two species and varieties of diatoms were found in these cores. A large percentage of the species are neritic, warm-water forms that are foreign to the region today. Several alternations of warm-water and cold-water diatom floras occur in most of the cores, but their position in the cores is not in accord with the alternations of temperature inferred from lithology and foraminiferal facies. It is suggested that this disagreement may be due to the much longer settling time of the diatoms and that allowance should be made for it. The time equivalent of this difference of phase, as calculated from the vertical displacement necessary for the best approximation to agreement between the foraminiferal and lithologic data on the one hand and the diatom data on the other is of the order of 23,000 years. This figure appears absurdly high and a figure of several hundred years, based on extrapolation of experimentally timed settling in a relatively small vessel, is considered more reasonable. The action of cold and warm currents, some surficial and some deep seated, is suggested as the possible cause of the apparently erratic distribution of the diatoms. The possibility that the phase difference of 23,000 years mentioned above is related to shifts of ocean currents caused by advances and recessions of drift ice is offered as a speculation. Of 52 species and varieties illustrated, 2 species and 1 variety are described as new.

Ostracoda.—In preparing a series of samples from the cores for the study of the Foraminifera about 175 specimens of Ostracoda were found. These belong to 13 genera and 27 species, all living forms, though 12 of the species are known also as fossils. Most of the ostracodes were found in three cores that were taken in the shallowest water (1,280 to 3,230 meters). One of these cores (No. 8) was from the top of the mid-Atlantic ridge and the other two (Nos. 12 and 13) were from the continental slope southwest of Ireland. In the cores from deeper water (3,250 to 4,820 meters) ostracodes were scattered very sparsely. Like most marine ostracodes, all the species found in the cores are bottom dwellers. Most of the species are decidedly cold-water forms that are found in tropical waters only at great depth, where the temperature is near freezing. Northern forms predominate; only 2 of the species have not previously been known from northern waters, and 10 species are definitely Arctic forms. A few species that have a wider temperature range live not only in cold waters but also in the deep warm water of the Mediterranean.

The predominance of distinctly cold-water ostracodes and the prevalence of Arctic forms suggest that the temperature of the water in this part of the North Atlantic was formerly somewhat lower. But, as might be expected from the fact that all the species in these cores are bottom dwellers, their distribution in the cores shows no evident relationship to the cold and warm zones indicated by the composition and texture of the sediments and by the pelagic Foraminifera.

Mollusca.—The mollusks recovered from these cores can be divided into two groups, the pteropods and the other gastropods and pelecypods. The pteropods are by far the more numerous. All the specimens of the pelecypods and gastropods, other than pteropods, are representatives of deep-water species that are now living in the same boreal or cold-temperate waters. Also, the fragments that could not be identified specifically belong to forms that have congeners now living in these waters. The fauna of these cores, even that taken from the lower parts of the cores, shows no appreciable difference from that now living in the same localities. Among these mollusks no evidence of shallower or considerably deeper water is demonstrable. Molluscan remains, other than those of pteropods, are too scarce to attempt to differentiate cold- and warm-water facies, as was done with the foraminiferal faunas.

The Pteropoda, which are far more abundant in the cores than the other mollusks, belong to two genera and three species. One of the species is new. The geographic distribution of the pteropods is limited more by the temperature of the surface water than by any other factor. Nevertheless, as one species is cosmopolitan, one boreal, and one a new species thought to be the northern analogue of a more southern species, and as all three species occur together, they have no significance for differentiating cold- and warm-water facies. These organisms are pelagic and their shells have a rather wide distribution, but, as they are found on the sea floor at depths ranging from 247 to 3,750 meters, they are of little aid as indicators of depth of the ocean at the time these deposits were laid down.

Echinodermata.—The remains of 9 species of Echinodermata were found in the cores. These include 1 ophiuroid, 7 echinoids, and 1 crinoid. No remains of asteroids were found. All the echinoderms found belong to species now living in that part, or adjacent parts, of the North Atlantic. Echinoderm remains are rather uniformly distributed among the cores, but they are most numerous in core 8, which was taken in 1,280 meters of water on the crest of the mid-Atlantic ridge. By far the commonest species is *Pourtalesia miranda,* remains of which were found in nearly two-thirds of the 82 echinoderm-bearing samples and in all the cores except 8 and 11.

Because the association of species in the cores is closely similar to the association of living species in that part of the North Atlantic and because the association of species within each core is independent of the distance below the top of the core it appears that neither the distribution nor the composition of the echinoderm fauna has changed significantly during the interval represented by these cores. No evident relationship was found between the distribution of the various species of echinoderms and the cold- and warm-water facies of the sediments indicated by both the Foraminifera and the lithology.

Miscellaneous fossils and significance of faunal distribution.—The principal fossil groups represented in the cores, listed in order of abundance, are foraminifers, diatoms, echinoids, siliceous sponges, radiolarians, ophiuroids (spines and plates), ostracodes, and pteropods. Remains of barnacles, brachiopods, pelecypods, holothuroids, bryozoans, gastropods, and teleost fishes (otoliths) were also found, but all these are rare. The foraminifers, diatoms, ostracodes, echinoderms, pelecypods, and gastropods were studied separately by specialists. The other groups are briefly noted and illustrated for the sake of the record. The most varied and prolific faunas were found in the three cores that were taken from the shallowest water and the least varied and least prolific were found in those from the deepest water. The bottom-living faunas throughout each core have a broadly similar bathymetric facies, and the bathymetric facies of each core appears to correspond to that of the fauna now inhabiting that locality. Faunas having the characteristics of very shallow-water marine faunas are either absent or, if present, are so rare and erratically distributed that they appear to be foreign in origin rather than indigenous. Ostracodes and pteropods are locally abundant in the cores from the shallower water, but are absent or rare at all horizons in those from the deeper water. The distribution and bathymetric facies of the faunas weigh heavily against the hypothesis of extreme changes in ocean level during the later part of the Pleistocene.

Organic matter content.—The content of organic matter, as determined from 123 samples, ranges from 0.1 to 1.0 percent of the total weight of the sediments, and the average is about 0.5 percent. As in near-shore sediments, it is influenced by the configuration of the sea bottom. It is small on ridges and large in the deeps. It is particularly large in the sediments at the base of the east slopes of ridges, owing in part, probably, to material washed from the vicinity of the ridges by eastward-sweeping ocean currents. The organic matter content of the upper layers of the sediments in the abyssal deeps is greater for a few hundred miles east of the mid-Atlantic ridge than it is for a similar distance west of the ridge. The organic content does not vary consistently with depth except in core three, taken at the foot of the continental slope east of the Grand

Banks, where it seems to decrease about 25 percent in the first 1.5 meters. The organic matter content of the sediments tends to be greater in the warm zones, than in the cold zones, and in general it is slightly greater in sediments which, according to Cushman's determination of the Foraminifera, were probably deposited in areas in which the surface water was relatively warm. The organic content is rather closely related to the texture, and increases with increasing fineness of the sediments. The rate of deposition of organic matter is greater east of the mid-Atlantic ridge than west of it, presumably owing in part to a greater supply of plankton and in part to a slower rate of decomposition of the organic matter after it is laid down in the sediments. The slower rate of decomposition within the sediments is inferred from the greater state of reduction of the sediments, which is indicated by the nitrogen-reduction ratio. The nitrogen-reduction ratio suggests a slight increase in state of reduction with increasing depth of burial in the upper part of the deposits, but indicates no significant change in the lower part. The percentage of organic content tends to increase as the percentage of Foraminifera in the sediments decreases, but it shows no relationship to the calcium-carbonate content.

Selenium content and chemical analyses.—As a part of a comprehensive investigation of the distribution of selenium in marine sediments and soils derived from them complete fusion analyses were made of 20 samples from the suite of 11 cores. These samples were taken from the tops of the cores and at intervals of approximately 1 and 2 meters below the top. In addition, 1 core taken on the continental shelf off Ocean City, Md., and 3 cores from the Bartlett Deep were sampled and analyzed, making a total of 31 analyses. The results of the analyses include all the normal analytical data obtained in a so-called complete soil analysis by the fusion method, and, in addition, determinations of organic matter, nitrogen, chlorine (in all but 12 analyses), hygroscopic water, and selenium. All the samples were analyzed with the entrained sea salts. The core from the continental shelf off Ocean City contained the most selenium—at the top 0.6 part per million, at 1 meter 1.0, and at 2 meters 2.0 parts per million. The samples from the North Atlantic cores showed a selenium content ranging from 0.06 to 0.8 part per million. Of the samples from the Bartlett Deep one contained 0.2 part per million of selenium, but all the others contained less than 0.08 part per million. No evidence was found of a relation between the selenium content and volcanic activity.

The silica-sesquioxide and silica-alumina ratios are tabulated and their significance as means of comparing the analyses is discussed.

FOREWORD

By C. S. Piggot [1]

During the last cruise (1927–29) of the nonmagnetic ship *Carnegie* of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington a number of samples of the deep ocean bottom were obtained by means of the telegraph snapper. The Geophysical Laboratory determined the radium content of these samples and found that they contained a concentration of radium [2] as astonishingly high as that reported by Joly [3] and Pettersson [4] from similar samples taken by the *Challenger* and *Princess Alice II*. This high radium concentration in the surface layer of the ocean bottom, which constitutes 72 percent of the surface of the globe, raises questions of great significance to both oceanography and geophysics. An obvious question is whether radium in so high a concentration is present down through all deep-sea sediments or only at the surface.[5] If the first hypothesis is correct it indicates the presence of uranium throughout the sediments, whereas the second indicates the existence of radium itself, presumably separated out from the sea water. The study of this question requires samples of a type analogous to the cores so extensively used in subsurface exploration on land. Inquiries among oceanographic organizations established the fact that although some cores a meter or more in length had been obtained from relatively shallow water, many of them were much distorted by the time they reached the laboratory, and none as long as 1 meter had been obtained from a depth of 4,000 meters or more.[6] Those engaged in such research emphasized the need of apparatus capable of obtaining undistorted cores from great depths. In 1933 the Council of the Geological Society of America approved a grant for the development of such apparatus.[7] Fortunately, cooperation was obtained from several special agencies, particularly the Burnside Laboratory of the E. I. du Pont de Nemours, whose ballistics expert, Dr. B. H. Mackey, offered fundamental suggestions and made many essential calculations and tests; also the United States Bureau of Lighthouses, from whose lightship tender, the *S. S. Orchid*, many experimental soundings were made. Several forms of the apparatus were developed and tested, and in August 1936 14 satisfactory cores were obtained from the canyons in the continental shelf off New Jersey, Delaware, and Maryland, and another from the ocean floor below 2,500 meters of water.[8] This first deep-sea test was made possible by the cooperation of the Woods Hole Oceanographic Institution and was carried out in connection with an investigation of the submarine canyons by H. C. Stetson of that institution. This test demonstrated the feasibility of the apparatus as built but suggested some minor changes in design. These were incorporated in another apparatus, which was put aboard the cable ship *Lord Kelvin* at Halifax, Nova Scotia. Through the courtesy of Mr. Newman Carlton, Chairman of the Board of Directors of the Western Union Telegraph Co., the Carnegie Institution of Washington was invited to have a member of its staff accompany the *Lord Kelvin* while that ship was engaged in making repairs to the North Atlantic cables, in order to test the apparatus in deep water. This offer was gladly accepted, and in May and June of 1936 I was on board the *Lord Kelvin* with the apparatus.

Because of the personal interest and cooperation of the commanding officer, Lt. Comdr. Bredin Delap, Royal Navy, retired, the undertaking was more successful than had been anticipated, and a suite of 11 excellent cores was obtained, extending from the Grand Banks of Newfoundland to the continental shelf southwest of Ireland.

All but two of these cores (Nos. 8 and 11) are more than 2.43 meters (8 feet) long, and all contain ample material for study. Of the two short cores, No. 8 was taken from the top of the Faraday Hills, as that part of the mid-Atlantic ridge is known, where the material is closely packed and more sandy and consequently more resistant; No. 11 came from a locality where the

[1] Geophysical Laboratory, Carnegie Institution of Washington.

[2] Piggot, C. S., Radium content of ocean-bottom sediments: Am. Jour. Sci., 5th ser., vol. 25, pp. 229–238, 1933.

[3] Joly, J., On the radium content of deep-sea sediments: Philos. Mag., vol. 16, pp. 190–197, 1908.

[4] Pettersson, Hans, Teneur en radium des dépots de mer profonde: Resultats de Campagnes Scientifiques par Albert I er Prince Souverain de Monaco, vol. 81, 1930.

[5] Piggot, C. S., op. cit., p. 233.

[6] Since these inquiries were made D. Wolansky has published her review in the Geologische Rundschau (Band 24, Heft 6, p. 399, 1933), in which she refers to the work of A. D. Archanguelsky in the Black Sea (Soc. Naturalistes Moscow Bull., new ser., vol. 35, pp. 264–281, 1927). Wolansky mentions cores 3 to 4 meters long from depths of 2,237 meters. See also Wiss. Ergeb. Deutschen Atlantischen Exped. *Meteor*, 1925–27, Band 3, Teil 2, Lief. 1, pp. 4–28, 1935.

[7] Piggot, C. S., Apparatus to secure core samples from the ocean bottom: Geol. Soc. America Bull., vol. 47, pp. 675–684, 1936.

[8] Cushman, J. A., Henbest, L. G., and Lohman, K. E., Notes on a core sample from the Atlantic Ocean bottom southeast of New York City: Geol. Soc. America Bull., vol. 48, pp. 1297–1306, 1937.

apparatus apparently landed on volcanic rock that may be part of a submarine lava flow. Soundings at the localities where the cores were taken show depths ranging from 1,280 meters at the top of the Faraday Hills to 4,820 meters in the deep water between the mid-Atlantic ridge and the continental shelf.

The thorough test made possible by the interested cooperation of everyone on board the *Lord Kelvin* fully demonstrated the capacity of the apparatus and produced material from strata of oceanic sediments deeper than have ever before been available.

In order that this pioneer material might be examined to the best advantage and an adequate estimate made of the potentialities of cores of this type, a group of investigators representing various fields of science was invited to examine them. Efforts have been made to arrange the sequence of these investigations in such a way that the maximum information may be obtained with the minimum destruction of the samples.

The cores are now at the Geophysical Laboratory of the Carnegie Institution of Washington, where they and others that may be obtained by this laboratory will be held available for further research.

GENERAL INTRODUCTION

By W. H. Bradley

SIGNIFICANCE OF THE INVESTIGATION

The long cores of deep-sea sediment considered in this report represent a longer span of the earth's late geologic history, as recorded in abyssal sediments, than has been heretofore accessible. In a measure, therefore, this study has been exploratory. Because of that exploratory aspect we have not only presented the observations but also have deliberately speculated upon various possible interpretations of the features observed in the cores and upon their relations with one another. Because the cores are few in number and widely spaced, we offer many of the interpretations not as definite conclusions but rather as suggestions to be tested by whatever coring may be done in the future in that part of the North Atlantic.

From this investigation it appears that glacial marine deposits may prove to be sensitive indicators of the climatic changes that caused the growth and decay of continental ice sheets during the Pleistocene. In particular, it seems that the glacial marine record may throw light on the climatic fluctuations that determined substages of the Pleistocene. The marine record was the result of a continuously operating series of causes such that the deposits of each glacial substage were separated from one another by the deposits of the intervening warmer substage. The record of each substage has remained intact and was not obliterated by readvances of the ice. As the equatorward extent of the glacial marine deposits implies a corresponding expansion of continental ice sheets, the extent of the deposits may be used as a measure of the intensity of the climatic changes, and their thickness may be used as a rough indicator of the duration of glacial substages. Similarly, the thickness and poleward extent of tongues of nonglacial sediment—the foraminiferal marl—are measures of deglaciation. The areal extent of these tongues of sediment can be determined by additional cores taken at properly located stations.

When the glacial marine record is more fully known it should provide a basis for correlating the Pleistocene history of Europe and North America.

Cores taken along the meridians in series extending from the Arctic regions into the tropical parts of the Atlantic should make it possible to map the southern limits of pack ice in the sea during successive glacial maxima, at least for the later part of the Pleistocene. As the pelagic Foraminifera in these abyssal sediments are reliable indicators of surface-water temperatures in the Recent and Pleistocene epochs, it should be possible to trace southward into the tropics layers or beds of foraminiferal ooze that are the time equivalents of glacial marine zones. Such layers of foraminiferal ooze could then be correlated with the layer of globigerina ooze in the tropics that Schott [9] identified as a relatively cold-water deposit that probably represents the last glacial epoch of the Pleistocene.

The study of climatology as well as geology may be advanced by the information to be derived from long sea-bottom cores. Significant evidence bearing on postglacial climatic changes may be obtained from minutely detailed study of the Foraminifera in cores taken in parts of the ocean where postglacial sedimentation has been comparatively rapid, as, for example, near the seaward edge of the blue-mud zone. On the assumption that such sediment accumulates at an essentially uniform rate, climatic fluctuations may be located approximately in time within the postglacial interval and may be correlated from place to place along the ocean margins from the Arctic to temperate or even tropical latitudes and perhaps also from continent to continent.

Archeology, also, might profit from the knowledge of a relatively timed and correlated sequence of climatic changes, for such changes may well have made a significant impress on the habits and migrations of peoples, particularly those that dwelt in regions where small changes in either temperature or rainfall were critical. As I have pointed out in an earlier paper,[10] students of archeology and early history, particularly in the Mediterranean region, might profit much from detailed studies of long cores of the sediment in the deep basins of the Mediterranean. In cores from that sea, as elsewhere, changes in the foraminiferal faunas would indicate climatic changes, and the sediments would yield, in addition, evidence of volcanic eruptions and earthquakes. The time when the Sahara became a desert should also be recorded in the Mediterranean sediments by wind-blown sand. Such a change might conceivably be integrated with the wealth of archeo-

[9] Schott, W., Die Foraminiferen in dem äquatorialen Teil des Atlantischen Ozeans: Wiss. Ergeb. Deutschen Atlantischen Exped. *Meteor*, 1925-27, Band 3, Teil 3, Lief. 1, pp. 120-128, 1935.

[10] Bradley, W. H., Mediterranean sediments and Pleistocene sea levels: Science new ser., vol. 88, pp. 376-379, 1938.

logical records of the region, and the later volcanic eruptions and earthquakes might be correlated with early history.

Some of the problems sketched so briefly here are touched upon in the several chapters of this report, but most of them must be left for future investigators. Nevertheless, methods by which such problems may be attacked are described and discussed at considerable length, particularly in the chapters on "Lithology and geologic interpretations" and "Foraminifera."

LOCATION OF THE CORE STATIONS

The cores were taken along a slightly irregular line between the easternmost part of the Newfoundland Banks and the banks off the southwest coast of Ireland, as shown in plate 1. Each core obtained by the Piggot coring device is numbered to correspond with the station number of the cable ship *Lord Kelvin*. Stations 1 and 2 were trial stations at which preliminary tests were made to familiarize the crew with the apparatus, and no cores were preserved. The 11 cores studied are numbered consecutively, 3 to 13. The relation between the core stations and the submarine topography is shown in figure 1, which is a profile along the dashed line in plate 1 that connects the stations and extends from St. Johns, Newfoundland, to Lands End, England.[11]

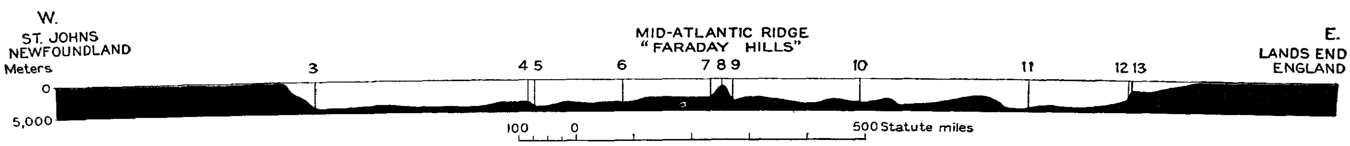


FIGURE 1.—Profile across the North Atlantic Ocean along the line of the numbered core stations shown on plate 1.

TABLE 1.—*Geographic location, length of the cores, and depth of the water from which they were taken*

Core number	Depth of water (meters)	Length of core (meters)	Lat. N.	Long. W.
3	4,700	2.81	46°03′00″	43°23′00″
4	3,955	2.71	48°29′00″	35°54′30″
5	4,820	2.82	48°38′00″	36°01′00″
6	4,125	2.90	49°03′30″	32°44′30″
7	3,250	2.62	49°32′00″	29°21′00″
8	1,280	1.24	49°36′00″	28°54′00″
9	3,745	2.76	49°40′00″	28°29′00″
10	4,190	2.97	49°45′00″	23°30′30″
11	4,820	.34	48°38′00″	17°09′00″
12	3,230	2.43	49°37′00″	13°34′00″
13	1,955	2.21	49°38′00″	13°28′00″

PERSONNEL AND COMPOSITION OF THE REPORT

At the request of Dr. C. S. Piggot, of the Geophysical Laboratory of the Carnegie Institution of Washington, the following six members of the United States Geological Survey undertook a systematic study of the 11 deep-sea cores from the North Atlantic: W. H. Bradley, M. N. Bramlette, J. A. Cushman, L. G. Henbest, K. E. Lohman, and P. D. Trask. As the biologic phase of the work progressed it became evident that other organisms than the foraminifers and diatoms should be studied. Accordingly Mr. Henbest invited Dr. Willis L. Tressler, of the University of Buffalo, to examine the ostracodes, Dr. Austin H. Clark of the United States National Msueum, to examine the echinoderms, and Dr. Harald A. Rehder, also of the United States National Museum, to examine the mollusks.

The organic matter content of the sediments was studied by Mr. Trask in collaboration with Messrs. H. Whitman Patnode, Jesse LeRoy Stimson, and John R. Gay, all members of the American Petroleum Institute.

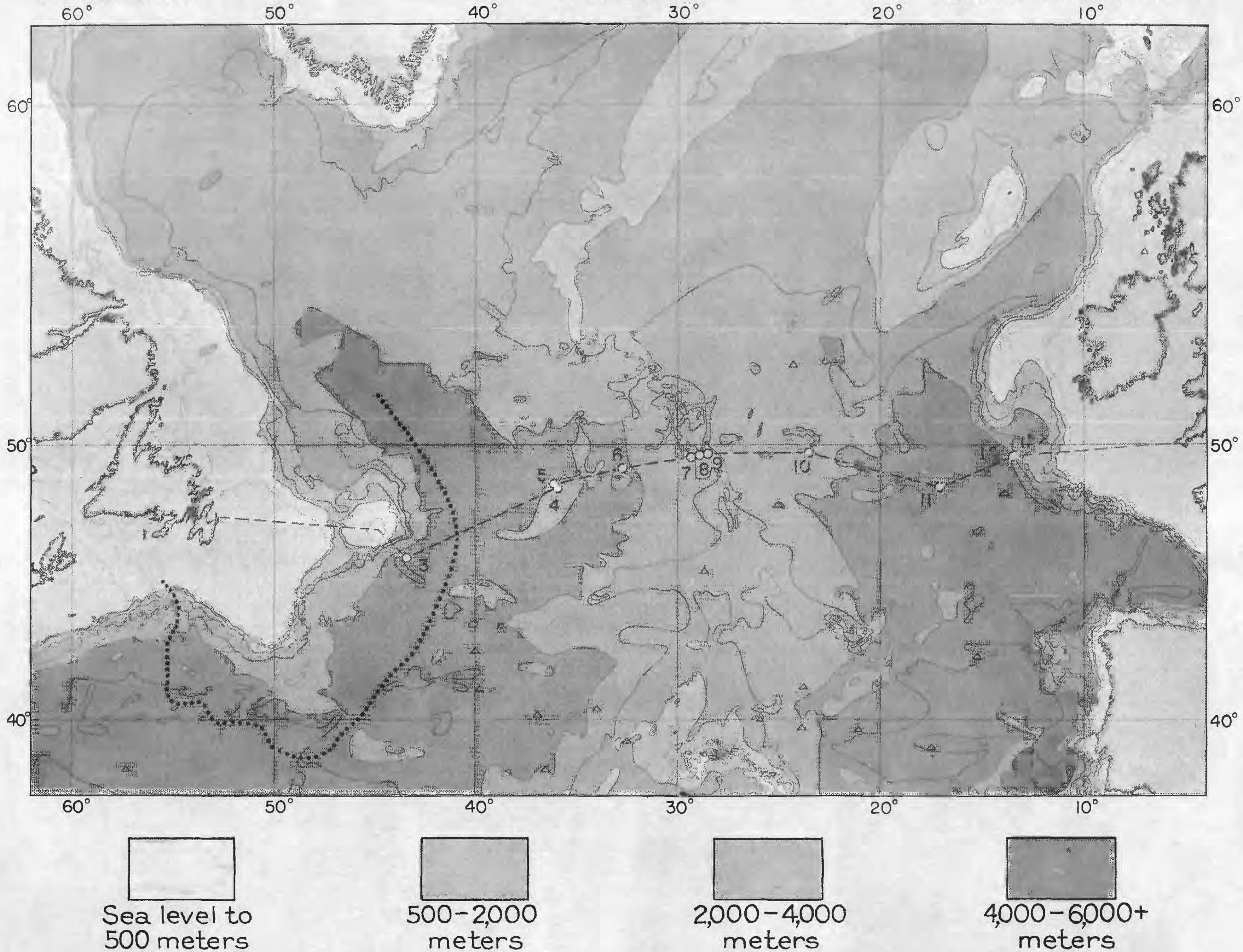
As part of a comprehensive research project on the distribution of selenium in marine sediments and the soils derived from them Dr. H. G. Byers and Mr. Glen Edgington, of the Bureau of Chemistry and Soils, United States Department of Agriculture, made complete chemical analyses of 20 samples from these deep-sea cores. These analyses, together with analyses of samples from several other deep-sea cores and a discussion of the occurrence of selenium, are included in the chapter on "Selenium content and chemical analyses."

METHODS OF SAMPLING AND EXAMINATION

The Piggot coring device [12] takes the cores in brass sampling tubes that have an inside diameter of 4.9 cm. As soon as a core is taken, the tube is cut off at the approximate length of the core and sealed. The cores here discussed were opened under Dr. Piggot's direction at the Geophysical Laboratory of the Carnegie Institution of Washington. A longitudinal cut was made along one side of each brass core barrel by means of a milling cutter so adjusted that it did not cut quite through the wall of the tube. The thin strip remaining was then ripped out without letting brass chips get into the core. After allowing the mud cores to dry somewhat, but not enough to shrink away from the tube walls, the cores and core barrels were cut in half longitudinally with a metal-cutting band saw. In this cutting, the milled slot was held uppermost so that the saw cut only the lower wall of the core barrel and threw the cuttings downward, away from the core.

[11] Data for plate 1 and figure 1 were taken from International Hydrographic Bureau, Carte Générale Bathymétrique des Océans, 3d ed., sheets A-1 and B-1, copies of which were furnished by the U. S. Hydrographic Office.

[12] Piggot, C. S., Apparatus to secure core samples from the ocean bottom: Geol. Soc. America Bull., vol. 47, pp. 675-684, 1936.



BATHYMETRIC CHART OF A PART OF THE NORTH ATLANTIC OCEAN.

The numbered circles indicate the core stations. The dashed line connecting them is the line of the profile shown in figure 1. The light dotted line along the coasts is the 200-meter depth contour. The usual limit of drift ice is shown by the heavy dotted line. The small triangles indicate the position of icebergs reported far beyond their normal range during the period January 1900 to July 1916, according to information compiled by J. T. Jenkins (A Textbook of Oceanography, fig. 14, London, Constable & Co., 1921).

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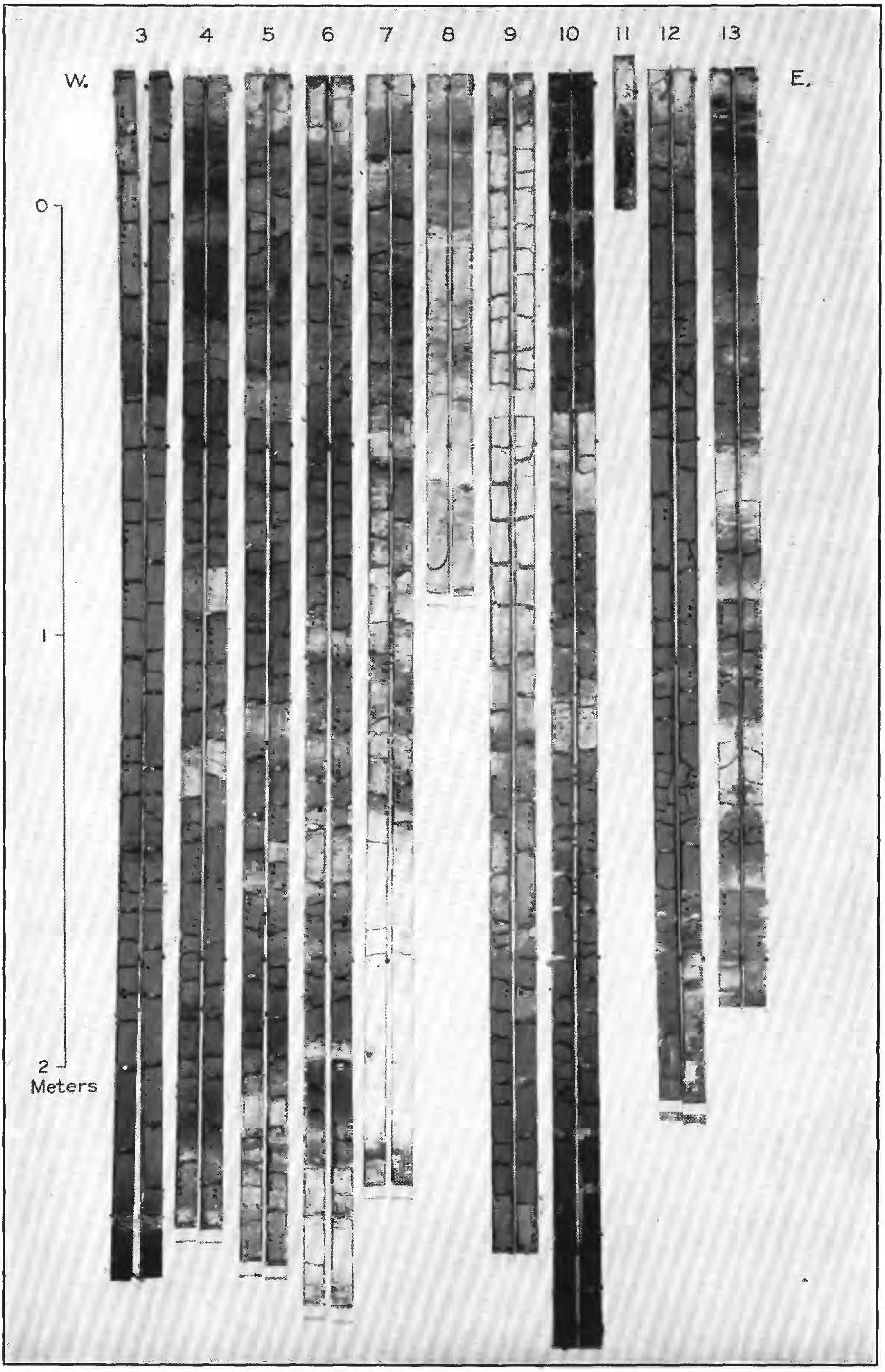


LONGITUDINAL SECTIONS OF THE AIR-DRIED CORES.

Half of the core barrel was removed from core 11, but the core itself was not cut. Photograph by Geophysical Laboratory, Carnegie Institution of Washington.

Each half core then remained undisturbed in its half cylinder cradle of brass core barrel. (See pl. 2.)

As several months elapsed between the time the cores were opened and the time this investigation began, the mud had dried thoroughly when Mr. K. E. Lohman took a succession of overlapping photographs of each core, about one fifth natural size. These photographs were then assembled as a key chart upon which were marked the parts from which samples for all phases of the investigation were taken. The dried segments of mud shifted somewhat from their original places each time samples were removed, though care was taken to see that during sampling the segments kept their original order and orientation. By reference to this photographic key the findings of all the investigators have been correlated.

Most of the material was hard enough to be sawed into blocks with a hack saw, but a few of the most friable parts were sampled with small channel-shaped scoops of sheet metal after the loose material on the surface had been brushed away.

Samples for all phases of this investigation were taken from only one half of each core, the other half being held intact in the Geophysical Laboratory.

GEOLOGY AND BIOLOGY OF NORTH ATLANTIC DEEP-SEA CORES BETWEEN NEWFOUNDLAND AND IRELAND

PART 1. LITHOLOGY AND GEOLOGIC INTERPRETATIONS

By M. N. Bramlette and W. H. Bradley

EXAMINATION AND ANALYSIS OF SAMPLES

Before sampling the deep-sea cores from the North Atlantic Ocean we made a record of the general aspect of the sediments, noting particularly the more obvious changes from one kind of sediment to another. These descriptive notes served as a guide in selecting the samples. As the combined length of the 11 cores is nearly 26 meters, a continuous sequence of samples 2 or 3 centimeters long would have necessitated the study of nearly 1,000 samples. With the time available it seemed preferable to take fewer samples and give them a more thorough examination than could be given so large a number. This decision was reached after the preliminary examination had shown that layers or zones of the mud penetrated were essentially uniform for considerable lengths of each core. Accordingly, the samples for the lithologic study were taken at intervals that averaged 10 to 12 centimeters, but the interval was varied from place to place in order to obtain samples representative of the obviously different lithologic types. (See pl. 3.)

Only one half of each core was used for sampling. Each sample for lithologic study was 2 or 3 centimeters long but included only part of the material, leaving the remainder at that place to be sampled for other phases of the work. Most of the individual samples represent sediment of a fairly uniform lithologic type, but the detailed examination showed that a few included sediment of two distinctly different types. Unfortunately, the samples sent to the chemical and hydrologic laboratories for determination of total carbonate and for mechanical analysis were representative portions of whole samples, taken out before the significance of the various lithologic units was realized. Therefore, in the few samples that include two types of sediment the quantity of total carbonate and the mechanical analyses are not truly representative of either type. This is illustrated most strikingly by sample B-58-59 from core 5. Microscopic examination showed that the upper part of this sample was distinctly different in composition and texture from the lower part. Had the two parts been analyzed separately the data plotted in plate 3 would have shown a clear distinction between two lithologic zones rather than features that are intermediate between the two.

The samples were first examined under a binocular microscope, at which time the film of mud that had been smeared down along the walls of the core barrel as it penetrated the sediments was removed. In the few cores taken in places where the mud through which the core barrel passed was sticky, lumps and rolls of the sticky mud were carried downward below their normal stratigraphic position and squeezed into the core. Contamination of this sort, however, was easily recognized, and the contaminating mud was removed. In the examination of the samples under the binocular microscope the general lithologic type was noted, together with any evidence of bedding or other textural or structural features, such as borings. This examination also included estimates of the percentage of Foraminifera and of recognizable inorganic constituents, such as zones of more abundant volcanic glass shards, pebbles and aggregates of tiny spherules of iron sulphide.

A little material scraped from a clean face of the sample was immersed in a liquid whose refractive index was 1.545, for examination under the petrographic microscope, and the relative abundance of the finer organic and inorganic constituents was estimated. These constituents included the diatoms and other siliceous organisms and the minute calcareous algae belonging to the Coccolithophoridae. Accurate determination of the amounts of these constituents would have required a great deal more time than seemed warranted. The relative accuracy of these estimates is considered under the heading "Carbonante content of the sediments."

The samples were next submitted to the chemical laboratory of the Geological Survey, where E. T. Erickson determined the approximate content of total carbonate in all samples by treating them with hot dilute hydrochloric acid until the solution was slightly acid as indicated by methyl orange. This procedure, though rather crude, was adopted for its speed, so that many samples could be tested. The results are subject to errors of several percent.

In samples taken near the top, middle, and bottom of each core Erickson also determined quantitatively the MgO, CaO, and MnO in a representative part of each sample. The insoluble residues from each of the samples were then wet-screened for mechanical analysis in the hydrology laboratory of the Geological Survey, under the direction of C. S. Howard. Before screening they were shaken in a mechanical agitator for about 4 hours with a comparatively large volume of distilled water, to which had been added a small quantity of dilute sodium oxalate solution. Like the carbonate determinations, these mechanical analyses are only approximations, owing largely to the difficulty of dispersing the sediment that had been treated with acid and thoroughly dried.

The screened fractions were then examined microscopically for a closer estimate of the proportions of certain noncalcareous constituents, such as volcanic ash and siliceous organisms. In this examination the rather large percentages of clay aggregates in the sand-size fractions, obviously the result of incomplete disintegration of some of the more clayey samples, were also estimated, in order to correct the mechanical analyses, the results of which are plotted in plate 3.

This examination revealed the need of supplementary data from certain parts of the cores between samples; accordingly, additional samples were taken and subjected to the same tests, and the results were also plotted in plate 3. Much of the material between samples was then examined for a few particular features, in order to delimit the zones of volcanic glass shards and zones of glacial marine deposits and also to make certain that no zones of volcanic material had been missed.

ACKNOWLEDGMENTS

In the preparation of this chapter on the lithology and physical geology of the cores we have had the benefit of discussion with many of our colleagues in the Geological Survey and with various members of the Geophysical Laboratory of the Carnegie Institution. Acknowledgment is made at appropriate places in the text for analyses and tests made for several phases of the investigation, and we wish to express here our thanks to C. S. Howard, of the hydrology laboratory, and R. C. Wells and George Steiger, of the chemical laboratory, for their ready cooperation and for the laboratory space and facilities which, to their own inconvenience, they generously placed at our disposal.

PRESENTATION OF DATA

Many of the data obtained from the investigations outlined above are presented graphically in plate 3 to facilitate general comparison, although the variations of any one constituent are somewhat less easily followed in so comprehensive a diagram. The boundary between material of silt size and sand size as used in this report is 0.074 millimeter, instead of the 0.0625 millimeter commonly accepted as the upper size limit of silt, because, of the sieves available, the one having openings of 0.074 millimeter was the nearest. Likewise, the boundary between sand size and coarse sand size was taken as 0.59 millimeter, rather than the generally accepted 0.5 millimeter, because 0.59 millimeter was the nearest sieve size available. The proportion of coarse sand in the sand-size fraction of the sample seemed significant enough to be indicated on the diagram, but the difficulty of showing effectively small percentages necessitated special plotting. Consequently, the percentage of coarse sand in the sand-size fraction of each sample is plotted in a separate column to the right of the column representing the core. The right-hand column shows also samples that contain one or more pebbles 3 millimeters or more in mean diameter. In view of the apparent significance of these pebbles, it is unfortunate that the data are not adequate to show their relative abundance. In the course of sampling it became evident that only samples from cores of diameter much larger than the ones available could show the true quantitative distribution of pebbles as large as these, therefore no attempt was made to show in plate 3 whether the sample contained one or several. Supplementary examination of the whole cores, however, indicated that adequate data on their distribution in the cores would show more clearly their zones of occurrence in the sediments.

The column representing the core samples shows also the relative abundance of Foraminifera and of coccoliths, both of which are discussed further in connection with the carbonate content of the sediments. (See pp. 17–21.) The coccoliths are minute calcareous plates, most of which are between 0.002 and 0.015 millimeter in diameter. The symbol "common" means that they are numerous, though by reason of their small size they make up roughly only about 1 percent of the whole sample; "abundant" indicates that they make up about 5 percent or more of the sample. Even where most abundant, however, they probably do not make up more than 10 percent of the sediment.

The lines between cores shown in plate 3 indicate the correlation of zones of distinctive sediment. The evidence upon which these zones are distinguished and correlated is given below in considerable detail, together with interpretations of their significance.

STRATIGRAPHIC UNITS

VOLCANIC ASH ZONES

Shards of volcanic glass are rather abundant in the upper part of most of the cores and are sufficiently plentiful to characterize a zone. This upper volcanic ash zone is indicated in plate 3 by the uppermost stippled zone. The volcanic ash is abundant only in the lower part of the zone, and the base of the zone is rather sharply delimited. Above the base of the zone the shards rapidly decrease in abundance upward, though they are sparsely scattered through the sediment to the top of each core. The ash consists of unaltered vitric shards that have an index of refraction near 1.51, which suggests that the glass is of alkalic or calc-alkalic composition. The characteristic form of the shards makes all but the finest grains recognizable, even under the binocular microscope. A reexamination of material from this ash zone, including samples intermediate between those represented in plate 3, showed that near the base of the upper ash zone in most of the cores there are generally several thin layers in which the ash is distinctly more abundant or, in some samples, forms the dominant constituent; but between these more or less distinct layers shards are mixed with a greater proportion of other sediment. In cores 7 and 9 the ash is not concentrated in distinct layers and the only marked difference is the increase in abundance downward to the well-defined base of the zone. The apparent significance of this scattered distribution of the shards within the zone of volcanic ash is considered under the headings "Evidence of bottom currents" and "Role of mud-feeding organisms." (See pp. 14–15, 22–23.)

Although volcanic ash is the dominant constituent, in some of the ill-defined layers one to several millimeters thick, it rarely makes up more than 5 percent of the total sediment in an ordinary sample 2 to 3 centimeters long from the upper ash zone, and it averages nearer 1 percent. In the noncalcareous residues of these samples, however, the volcanic ash commonly makes up about 25 percent of the sand-size material and is therefore a distinguishing feature of this zone. In the upper ash zone the volcanic ash is present in greatest concentration in core 9, and there also the concentration is greatest in the lower part of the zone. Much of the scattered ash in the upper part of the zone in this core may represent contributions winnowed from the sediment on nearby areas of much shallower water. (See p. 14.)

A correlation of this upper ash zone from one core to another is suggested in plate 3, and though this correlation appears to be somewhat less certain in core 8 on the mid-Atlantic ridge and thence eastward, other lines of evidence, considered on page 6, seem to confirm the interpretation indicated.

Cores 4 to 7, on the west side of the mid-Atlantic ridge, penetrated a lower zone of volcanic ash, which is similar to the upper one. In the lower zone, the vitric shards, as in the upper zone, have a refractive index of 1.51 and are scattered through the zone rather than occurring in one or more sharply defined layers. The lower zone differs from the upper one in commonly having smaller shards and fewer of them. Reasons for the failure to find this lower ash zone in core 8, and in any of the cores east of the mid-Atlantic ridge are considered on page 6, where the correlations are discussed.

An occasional shard of volcanic glass having a refractive index of 1.51 was found in several samples between the upper and lower ash zones. Because these stray shards are so rare it seems probable that they were reworked from the lower ash zone up to their present positions by mud-feeding organisms or that they were derived from nearby mounds or ridges on the sea floor where the lower ash zone is exposed to the action of gentle currents. (See pp. 14–15.) The stray shards, however, are most common in samples B–53 and B–55 of core 5 and in sample B–214 of core 12. Taken alone, the relative abundance of volcanic ash in these samples suggests the existence of other ash zones, comparable to those just described though thinner and with a lower percentage of volcanic material. An unusual significance attaches to these three samples, however, for reasons other than their content of volcanic ash. The layers that they represent have unusually sharp boundaries at both base and top, they contain relatively little of the usual fine-grained constituents, and they have other distinctive physical characteristics, all of which suggest that they resulted from submarine slumping. These anomalous samples are considered more fully under the heading "Submarine slumping" (pp. 15–16).

The similarity of the alkalic glass shards to ash from explosive volcanic eruptions and the distribution of the shards in the upper and lower ash zones suggest that each of these zones represents an accumulation of normal volcanic ash that was transported through the air out over the ocean. No progressive increase in either the amount or grain size of the pyroclastic material in a particular direction was detected, but original variations of this sort may well have been obscured by the local variations believed to be due to redistribution of the shards.

The source of the alkalic glass shards in these cores is unknown. Geologically recent eruptions in the Azores include trachytic as well as ferromagnesian materials, and possibly the ash may have come from there. Alkalic volcanic rocks are associated with the basaltic volcanics of Iceland and Jan Mayen and, according to Peacock,[1] some of the volcanic activity in Iceland occurred during Pleistocene and post-Pleistocene time. The volcanoes of these northern islands that expelled the more silicic material may have been the source of the ash that characterizes the zones of volcanic ash in the cores.

GLACIAL MARINE DEPOSITS

From a little below the base of the upper volcanic ash zone downward for a short distance, most of the cores show a decrease in the amount of calcium carbonate and a corresponding decrease in the number of both Foraminifera and coccoliths, which are the dominant calcareous organisms. (See pl. 3.) As these limy

[1] Peacock, M. A., Geology of Viðey, southwest Iceland: A record of igneous activity in glacial times: Royal Soc. Edinburgh Trans., vol. 54, pp. 441–465, 1925–1926.

constituents decrease the clastic sediment increases correspondingly and is marked particularly by a greater content of coarse sand, granules, and pebbles. The granules and pebbles range in diameter from several millimeters to more than a centimeter. Most of them are somewhat rounded, but some are angular. They represent a wide variety of rock types, of which limestone is the most abundant; but various types of dark-colored shale, mudstone, sandstone, and gneissic and schistose rocks are also common. Less common are granules and pebbles of dolerite, granodiorite, quartzite, granulite, chert, and probably other rocks.

The size of these rock grains and the wide range of lithologic types that are representative of continental rocks rather than rocks of volcanic islands lead us to believe that their occurrence in these deep-sea sediments, far from land, means that they were transported by drifting ice. The same explanation has been given to account for the many pebbles, cobbles, and boulders that have been dredged from different parts of the North Atlantic. Peach [2] and Flett [3] have given detailed descriptions of some of the pebbles and boulders found in the dredgings. Some of the larger pebbles and cobbles have facets and striated surfaces like the cobbles found in glacial moraines. Their transportation to deep parts of the ocean remote from land, seems to be reasonably explained only by the assumption that they were carried by drifting ice. Cobbles of this sort have been dredged from the ocean floor as far south as the Azores [4] and at stations north of Madeira,[5] which suggests that they were transported by floating ice during the Pleistocene, when glaciers filled the Irish Sea and extended out over large areas of the continental platform into the North Atlantic.

The large amount of rock debris that may be transported by drifting icebergs, particularly those from glaciers and inland ice, as contrasted with drifting shelf ice, is suggested by Tarr's statement,[6] "There are thousands of tons of boulders, gravel, and clay sent into the sea from the front of the Cornell glacier every year, and much of this passes beyond the fjord out into Baffin Bay." Pratje [7] reported that icebergs from land ice in the South Atlantic have been found to carry as much as 16 cubic centimeters of sediment per liter of ice, or about 1½ percent by volume.

Philippi's study [8] of the bottom sediments from the Antarctic collected by the *Gauss*, in part by coring and in part by dredging, helps greatly to explain analogous sediments in the North Atlantic cores. The sediments adjacent to the ice front in Antarctica contain little calcium carbonate but consist dominantly of clastic material, including coarse sand and pebbles of various metamorphic and igneous rocks. The fraction of finer sediments consists of silt rather than the clayey material that is typical of the common oceanic blue mud. These sediments, which Philippi appropriately named "glacial marine deposits," apparently extend northward only about as far as the northern limit of pack ice. Core samples from farther north, however, revealed the highly significant fact that these glacial marine deposits extend northward beneath the diatom ooze that is forming today in a wide belt north of the pack ice. Cores from yet farther north contained glacial marine deposits below a layer of globigerina ooze, which is the kind of sediment accumulating today in that part of the ocean north of the area of diatom ooze. The diatom and globigerina oozes cover the glacial marine deposits to a depth of 10 to 20 centimeters. The glacial marine deposits now being formed in the region of pack ice led Philippi to believe that the similar deposits farther north were deposited during the Pleistocene epoch, when the ice front was much farther north. He also suggested [9] that the downward decrease in calcium carbonate, commonly observed in cores of ocean-bottom sediments a meter or less in length, even in the equatorial Atlantic, reflects a climatic control and that the lesser quantity of calcium carbonate is a consequence of the colder water during the Pleistocene.

The zone of sediment underlying the upper ash zone in our North Atlantic cores (see pl. 3) is so similar to the glacial marine deposits of Philippi that it is interpreted as a glacial marine deposit of the last glacial stage of the Pleistocene. This interpretation is confirmed by Cushman and Henbest (see pl. 4), who conclude from their study of the foraminiferal faunas that this zone is characterized by a pelagic fauna from colder water than that of the overlying globigerina ooze. Below the glacial marine zone just described we found in some of our cores, particularly cores 4 to 7, which were taken west of the mid-Atlantic ridge, an alternating sequence of glacial marine zones and zones of sediment resembling rather closely those forming today in that part of the ocean. All these glacial marine zones have the distinctive features that have already been described—namely, the pebbles, the coarse sand, the relatively

[2] Peach, B. N., Report on rock specimens dredged by the *Michael Sars* in 1910, by H. M. S. *Triton* in 1882, and by H. M. S. *Knight Errant* in 1880: Royal Soc. Edinburgh Proc., vol. 32, pp. 262–288, 1913.

[3] Flett, J. S., Report on the rock specimens and some of the oozes collected by the S. S. *Faraday* and S. S. *Minia* from the bed of the North Atlantic in 1903, in Murray, Sir John, and Peake, R. E., On recent contributions to our knowledge of the floor of the North Atlantic Ocean: Royal Geog. Soc., Extra Pub., pp. 23–30, 1904.

[4] Andrée, K., Die Geologie des Meeresbodens, p. 294, Leipzig, 1920.

[5] Idem, p. 379.

[6] Tarr, R. S., The Arctic sea ice as a geological agent: Am. Jour. Sci., 4th ser., vol. 3, p. 228, 1897.

[7] Pratje, O., Bericht über die geologische Arbeiten der deutschen atlantischen Exp. *Meteor*: Gesell. Erdkunde Berlin Zeitschr., 1926, p. 257.

[8] Philippi, E., Die Grundproben der deutschen Südpolar-Expedition, in Von Drygalski, E., Deutsche Südpolar-Expedition 1901–1903, Band 2, Heft 6, pp. 431–434, 1912.

[9] Philippi, E., Über das Problem der Schichtung und über Schichtbildung am Boden der heutigen Meere: Deutsche geol. Gesell. Zeitschr., vol. 60, pp. 346–377, 1908.

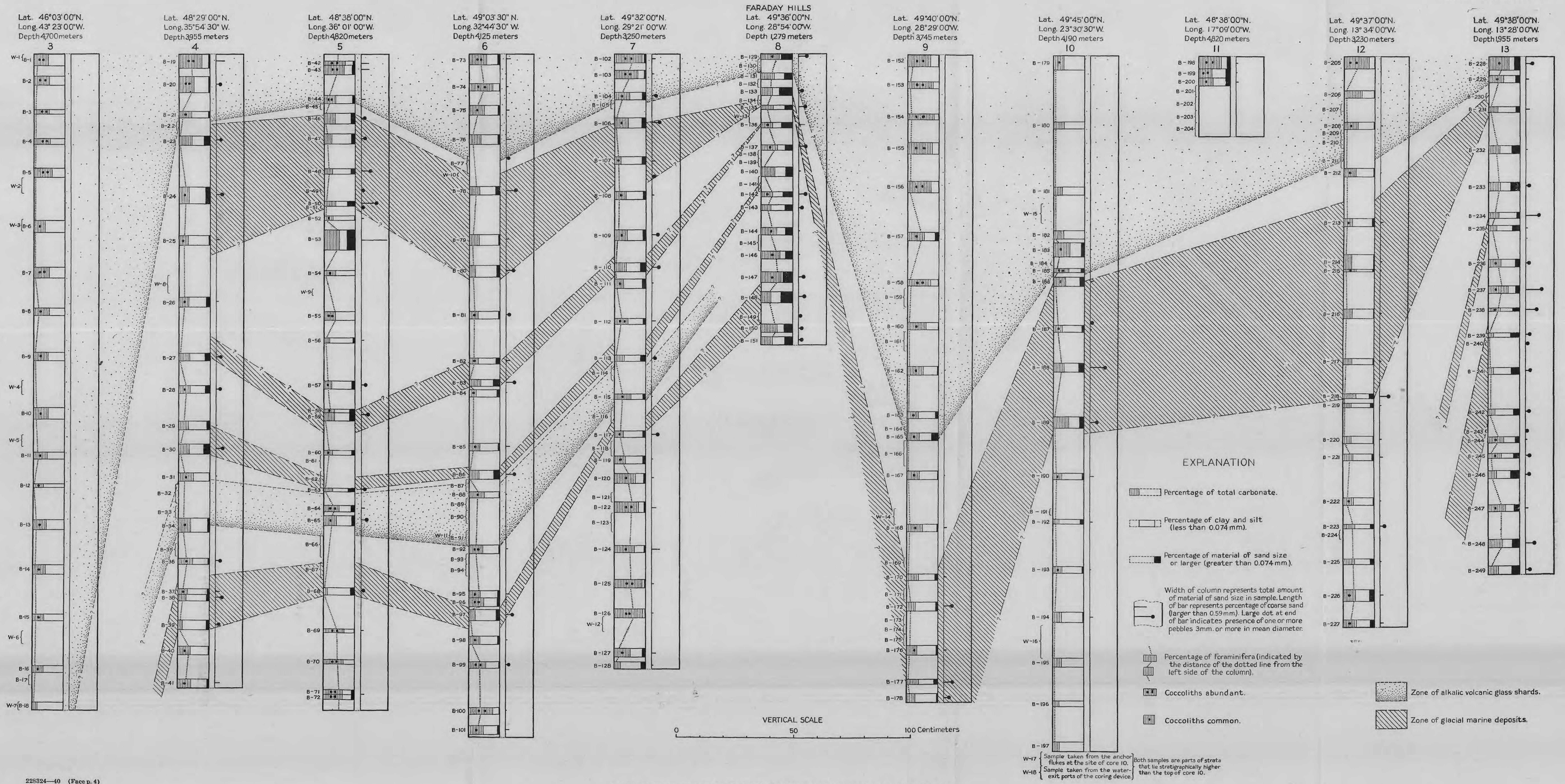


DIAGRAM SHOWING THE CORRELATION OF THE LITHOLOGIC ZONES IN THE CORES.

Each core is represented by two vertical columns. The patterned rectangular blocks in each left-hand column represent samples that were taken for routine mechanical and chemical analyses and microscopic examination. The parts of the cores from which samples were taken for special purposes or supplemental examination are indicated by braces. The samples are numbered in two series distinguished by the prefix letters B and W. The width of each column is taken to represent 100 percent by weight of the sediment, and the horizontal length of each pattern within a sample block represents the percentage of the constituent. The left-hand column shows the percentage of carbonate, clay and silt, sand, and Foraminifera and the relative abundance of coccoliths. The right-hand column indicates the percentage of coarse sand and the presence of pebbles.

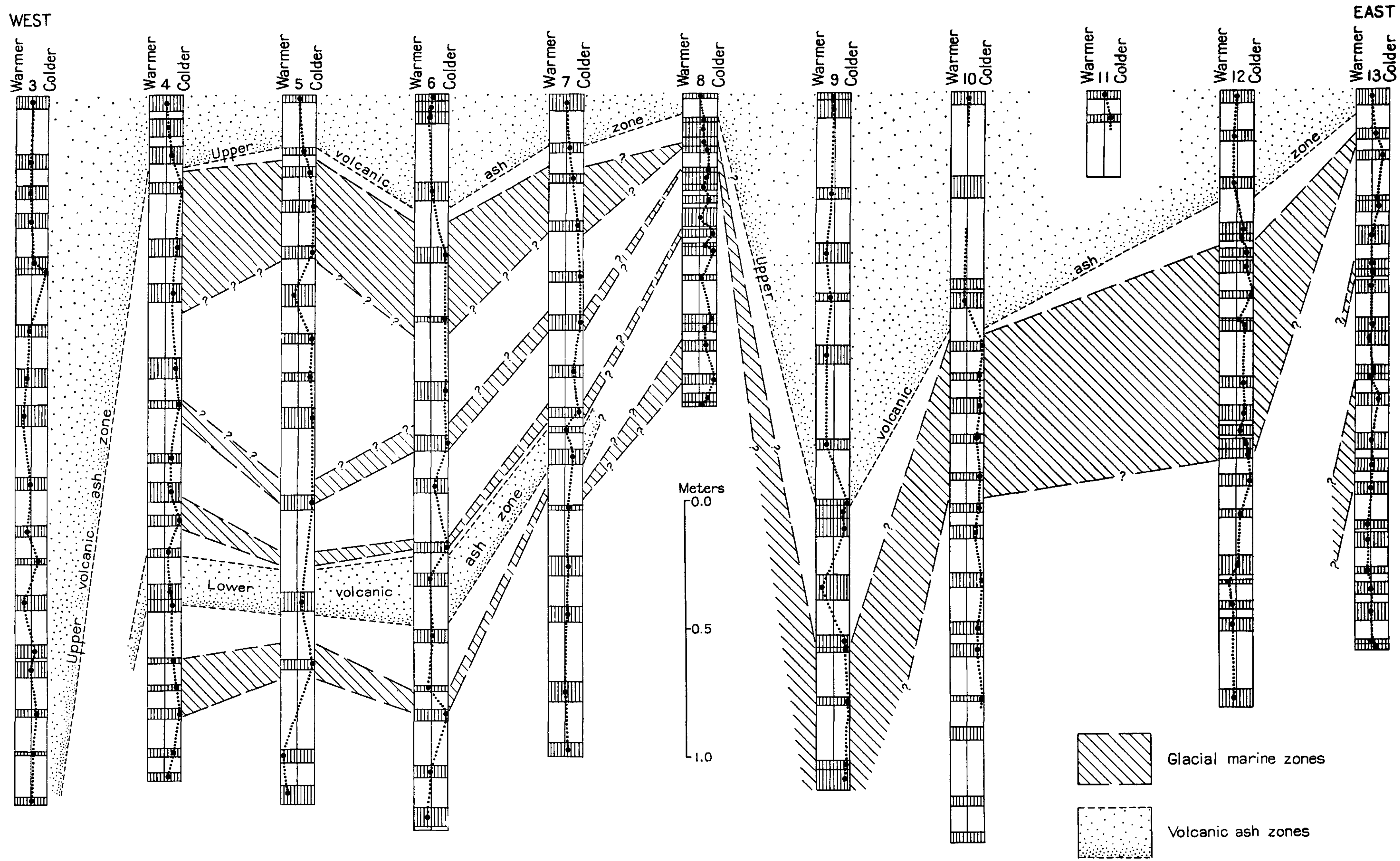


DIAGRAM SHOWING PAST FLUCTUATIONS IN THE TEMPERATURE OF THE SURFACE WATER AT THE SITE OF EACH CORE.

The shaded blocks represent samples taken for the study of the organisms by J. A. Cushman, L. G. Henbest, W. L. Tressler, Austin Clark, and H. A. Rehder. The center line of each column represents the present surface-water temperature. The large dot in each shaded block indicates qualitatively the deviation from the present temperature. The dotted line connecting these points shows the trend of the temperature change from one sample to the next. The extremes of temperature in different columns are not necessarily the same though they are comparable. Interpretation by J. A. Cushman and L. G. Henbest, based on the pelagic Foraminifera.

small percentage of calcium carbonate, the small number of Foraminifera, and the virtual absence of coccoliths. They have other features characteristic of the glacial marine deposits, such as a smaller quantity of clay, which is evident from the texture and the smaller shrinkage of the air-dried samples, and, locally at least, a lumpy structure, which appears to represent ellipsoidal or tubular borings that were subsequently filled with the adjacent mud to form coprolite-like pellets. Some of the pellets are as much as a centimeter in diameter. Whether these are coprolites or mud-filled borings of molluscs, worms, or some other organism is not known, and the significance of their occurrence in the glacial marine deposits in greater abundance than in other sediments is not apparent.

Schott's recent study [10] of the Foraminifera in the cores from the equatorial Atlantic collected by the *Meteor* expedition led to a similar interpretation of Pleistocene and post-Pleistocene deposits in that part of the ocean. His interpretation was based only on the ecology of the Foraminifera, as the sediments of that part of the Atlantic showed no accumulations of ice-rafted sand and pebbles. The cores, which averaged less than a meter in length, were sampled in the upper, middle, and lower parts. They showed a surface layer containing a warm-water fauna, a lower layer containing a cold-water fauna, and some of the longest cores showed a still lower layer containing a warm-water fauna. In the two layers that indicated a warm-water environment the Foraminifera were essentially like those living today in that part of the ocean. Schott interpreted the intermediate layer, that layer representing a cold-water environment, which in most places contained less calcium carbonate, as a deposit formed during the latest Pleistocene glacial stage; the lowest layer as a deposit of the last interglacial stage; and the uppermost layer as a post-Pleistocene deposit.

The correlation of the glacial marine zones and other distinctive zones that we found in our North Atlantic cores is discussed below, together with an interpretation of their significance.

CORRELATION OF ZONES REPRESENTED IN THE CORES

Layers or zones of alkalic volcanic ash in general are reliable for use in correlating strata because this kind of ash is erupted from volcanos of the explosive type and is distributed widely in the air. It must therefore accumulate on the sea floor at essentially the same time throughout the extent of its dispersal. When such ash zones are parts of a sequence of distinctive beds and the sequence is repeated at the several localities between which strata are to be correlated the reliability of the ash zones is further enhanced. As indicated in plate 3, cores 4, 5, 6, and 7 contain two ash zones and have the same sequence of glacial marine deposits between the ash zones. Below the lower ash zone in each core there is another glacial marine zone, which is underlain by foraminiferal marl similar to that found today at the surface of the ocean floor. The sequence of zones in these four cores agrees so well that their correlation seems well established in this area west of the mid-Atlantic ridge.

Core 3 is markedly different, as might be expected from its position within the area of terrigenous mud, or blue mud, near the Newfoundland Bank. This core consists of a remarkably uniform calcareous mud. Three thin and rather widely spaced layers of less limy mud and one thin silty layer near the bottom mark the only departures from the apparent homogeneity of this core. Small shards of alkalic volcanic ash like those in the ash zones of the other cores are very sparsely disseminated throughout this core but are not concentrated in any zone. The sediment of this core contains only an insignificant amount of sand-size clastic grains and no zones of coarse sand and pebbles, such as are found in the glacial marine zones of the other cores. The interpretation by Cushman and Henbest of the Foraminifera in this core (see pl. 4) is that the surface-water temperature was nearly uniform while the sediments represented by the core were accumulating, except for the three thin clay zones. The pelagic Foraminifera in the clay zones indicate colder water. Despite these thin cold-water zones, the distribution of the volcanic ash shards and the absence of sand and pebble zones lead us to believe that this core represents only sediments of post-Pleistocene time that accumulated in an area where the rate of sedimentation was more rapid than at the sites of the other cores. A core of greater length from this locality would be of particular interest to check this interpretation and give a basis for comparison of the post-Pleistocene rate of accumulation at this station with the rate at other core stations.

Core 3 contains no coarse sand and not even a single pebble, a fact that seems at first somewhat surprising, because this is the only one of the 11 cores that comes from within the present usual limits of drift ice. (See pl. 1.) However, the investigations of a number of explorers, notably Böggild and Nansen, have shown that much of the floor of the Arctic Ocean well within the limits of drift ice is covered with a deposit made up only of silt and clay that is free from sand and pebbles.[11] The explanation seems to be that even the berg ice in the Arctic and North Atlantic now contains but little clastic material, and apparently much of that little is dropped between Greenland and North America before it reaches the region south and southeast of the Newfoundland Banks. During the glacial epochs, however, the continental glaciers presumably furnished

[10] Schott, W., Die Foraminiferen in dem äquatorialen Teil des Atlantischen Ozeans: Wiss. Ergeb. Deutschen Atlantischen Exped. *Meteor*, 1925-27, Band 3, Teil 3, Lief, 1, pp. 120-130, 1935.

[11] Andrée, K., Geologie des Meeresbodens, pp. 378-379, 469-475, Berlin, Gebrüder Borntraeger, 1920.

many more bergs, and these bergs carried much clastic debris into the ocean.

Core 8, which was taken in 1,280 meters (700 fathoms) of water on the Faraday Hills part of the mid-Atlantic ridge, does not show the well-defined sequence of zones noted in cores 4 to 7, consequently its correlation with them is rather uncertain. The sediments throughout this core consist largely of sand and sand-size calcareous organisms, and the proportion of fine-grained material is so small that the dry core is friable. As is discussed later under the heading "Evidence of bottom currents" (pp.14–15) the sediment at this place seems to have accumulated where currents moved over the ridge with sufficient velocity to winnow out most of the finer constituents. As a result of this selective process the upper ash zone in core 8 contains comparatively few shards, but these are large and thick. Shards were found as far down as the top of sample B–131, which is therefore taken as the base of the upper ash zone. Because the shards are less numerous and the zone less well defined than in other cores, the correlation line at the bottom of the upper ash zone is indicated in plate 3 as doubtful. Although other lines of evidence make it seem probably that core 8 penetrated deep enough to have passed through the lower ash zone, no ash was found. Inasmuch as the shards in this lower zone are generally finer and less abundant than those in the upper ash zone, it is possible that they may all have been winnowed out, as have most of the shards in the upper zone, so that no trace remains at this site. The glacial marine zones are likewise less surely identifiable in this core, for the reason that the coarser sand and pebbles characteristic of the glacial marine deposits are less distinctly concentrated at definite horizons, perhaps because they have been more reworked and mixed with interglacial and postglacial sediments. Correlation of the glacial zones in core 8 with those in the other cores is therefore unsatisfactory, and this uncertainty is indicated in the correlation lines shown in plate 3.

Core 9 contains an exceptional abundance of volcanic ash in the middle part, and shards are scattered rather sparsely through it from the middle to the top. The distribution of the ash inclines us to believe that this ash zone corresponds with the upper ash zone of the cores west of the mid-Atlantic ridge. This belief is strengthened by the absence of coarse-grained material of the glacial marine type, either scattered or in beds, within the ash zone, and by the occurrence of a well-defined glacial marine zone a short distance beneath the base of the ash. The unusual concentration of thin, delicate volcanic glass shards in this core and the unusual abundance of other fine-grained constituents such as diatoms, coccoliths, and clay-size particles are discussed more fully on page 14.

The correlation of core 10 with the others is somewhat unsatisfactory for two reasons—first, the coring device penetrated deeper than the length of the core barrel, so that an unknown amount of sediment was lost through the water ports above the top of the core barrel; and second, at this station there are two rather thick beds of an extraordinary type of mud not represented in any of the other cores. At the time this core was taken Piggot collected some of the mud that had come out of the top of the core barrel and lodged in the water-exit ports. This sample (W–18) was of the same peculiar mud that makes up the uppermost quarter of the core, but it contained a moderate quantity of small pebbles and coarse sand. Piggot also collected, at this same station, a sample (W–17) of the globigerina ooze that stuck to the anchor flukes. Thus we know that at this station globigerina ooze blankets the sea floor, as it does at all the other stations except No. 3. Apparently all of the layer of globigerina ooze, the thickness of which is unknown, and some of the peculiar mud that makes up the top of core 10 was lost through the water ports. Nevertheless, it seems probable that the volcanic ash zone in this core is the upper ash zone of the other cores because of the abundance and general coarseness of the shards; because the shards continue upward, though sparsely, to the top of the core; because they were found also in the globigerina ooze above; and because there is a relatively thick glacial marine zone just below the base of the ash. The coarse sand and pebbles in the mud a little above the top of this core might be interpreted as material dropped from a stray iceberg as are other scattered or isolated pebbles found outside the glacial marine zones in the other cores. However, as this particular sample came from a disturbed core, not too much significance can be attached to its peculiarities.

Core 11 struck hard volcanic rock before penetrating any of the recognizable zones used in correlating the cores. This rock was hard enough to bend the core bit and stop it after it had penetrated the sediments for only about 34 centimeters. The thin deposit of globigerina ooze overlying the rock contains no shards of alkalic glass such as are scattered through the other cores, sparingly but continuously, from the base of the upper ash zone to the surface of the sea floor. The possible significance of this is considered on page 32, where the volcanic rock encountered in this core is discussed.

Core 12 penetrated the upper volcanic ash zone and the usual subjacent zone of glacial marine deposits, which at this site is thicker and somewhat less clearly defined than in most of the other cores, particularly those west of the mid-Atlantic ridge. This lack of clear definition may be due to the location of the station at which the core was taken, near the base of the continental slope, where material swept from the platform above may have diluted the glacial marine deposit. The bottom half-meter of this core consists of sediment containing an abundance of calcareous organisms of types that indicate a warm-water pelagic fauna.

(See pl. 4.) It also contains a larger percentage of sand and granules than the postglacial deposits at the top of the core. The larger grain size and the presence in abundance of pteropods and ostracodes suggest that the material in the lower part of this core may have accumulated in water shallower than now exists at this place, namely 3,230 meters (1,770 fathoms). According to Murray and Hjort,[12] 2,740 meters (1,500 fathoms) is about the extreme lower limit for pteropod shells, and ooze characterized by pteropods is rarely found in water deeper than about 1,825 meters (1,000 fathoms). It should be borne in mind, however, that the depth at which pteropod shells dissolve is dependent upon the saturation of the water with respect to calcium carbonate and that in the geologic past the ocean water may at one time have been saturated with calcium carbonate to a depth considerably greater than it is today and at another time less. The number of ostracodes in the lower part of core 12 is rather unusual. According to Tressler (chapter on "Ostracoda"), these organisms are more plentiful in the cores from less depth, particularly core 8, from 1,280 meters, and core 13, from 1,955 meters.

As the pteropod-bearing sediment in water deeper than would be expected is in the general vicinity of core stations 10 and 11, where volcanic rock was found, the suggestion is offered that foundering of the ocean floor may have occurred contemporaneously with the volcanic activity. Additional cores might provide interesting data bearing on the possibility that this part of the North Atlantic represents a foundered part of the Arctic or Thulean basaltic province,[13] which includes part of northwestern Scotland, northern Ireland, Iceland, Jan Mayen, and southeastern Greenland. Another possibility is that at the time this pteropod sediment was accumulating the water was saturated with calcium carbonate to greater depth than it is today and for that reason the pteropod shells were not dissolved. A third suggestion, that the sediment containing the pteropods, ostracodes, and sand may have slumped from its original position higher on the continental slope, is discussed more fully on pages 15–16.

Core 13 resembles core 8 in having throughout an abundance of sand, pebbles, sand-size Foraminifera, and rusty stain. As in core 8, nearly every part of core 13 is friable, owing to the relatively small quantity of fine-grained constituents. The position of this core near the edge of the continental platform suggests a further analogy with core 8, namely, that it owes its textural characteristics and the general indistinctness of the ash and glacial marine zones to the combined action of bottom currents and the activity of bottom-dwelling organisms.

[12] Murray, J., and Hjort, J., The depths of the ocean, p. 173, London, Macmillan Co., 1912.

[13] Tyrrell, G. W., The principles of petrology, p. 144, London, Methuen & Co., 1926.

The correlation of strata in the cores is thus less satisfactory from core 8 eastward than it is west of the mid-Atlantic ridge, but the consistent relation between an upper ash zone and the uppermost glacial marine zone appears to be a reliable basis for tying together all the cores except 3 and 11. The number and correlation of the glacial marine zones east of the mid-Atlantic ridge and on the ridge are somewhat dubious.

INTERPRETATION OF THE GLACIAL MARINE SUCCESSION

More than ordinary interest attaches to the interpretation of the zones of glacial marine sediments revealed by these cores because they may ultimately be correlated with events on land during the Pleistocene epoch and because cores of ocean-bottom sediments open a new approach to the study of glacial epochs. Nevertheless, before considering the various possible interpretations it may be helpful to attempt to visualize the conditions in the North Atlantic that gave rise not only to the zones of glacial marine sediment but also to sediment of the kind that lies between those zones.

SOURCES OF DETRITUS

The gravel, sand, and terrigenous silt found in the glacial marine zones must have been derived chiefly from bergs of glacial ice crowded from the land out into the sea by the continual growth of the glaciers behind. The sea ice, or pack ice, can contain no terrigenous debris, other than wind-blown material, except what it picks up by freezing to the bottom in shallow water or receives from the outwash of flooding rivers.[14] Thus, the presence of extensive layers of glacial marine deposits in the part of the North Atlantic from which these cores were taken makes it necessary to assume that the sea south of the fiftieth parallel of latitude contained much berg ice from continental glaciers and probably also much shore ice. While the sea level was low, during the glacial stages, extensive shoal-water platforms probably furnished large volumes of detritus to grounded sea ice, as described by Sverdrup [15] for the north coast of Siberia. Detritus from this source may have contributed as much as bergs. From further comparison with conditions as they now exist in both

[14] Böggild, O. B., On the bottom deposits of the north polar sea: The Norwegian North Polar Expedition 1893–1896, Scientific results, vol. 5, pp. 50–51, 1906. Trask, P. D., The sediments: The *Marion* Expedition to Davis Strait and Baffin Bay, 1928, U. S. Treas. Dept. Coast Guard Bull. 19. pt. 1, pp. 73–74, 1932. Fuchs, V. E., and Whittard, W. F., The east Greenland pack-ice and the significance of its derived shells: Geog. Jour., vol. 76, pp. 419–425, 1930. Stetson, H. C., The bottom deposits, in Scientific results of the *Nautilus* expedition, 1931, pt. 5: Massachusetts Inst. Technology and Woods Hole Oceanogr. Inst., Papers in Physical Oceanography and Meteorology, vol. 2, No. 3, pt. 5, pp. 32–35, 1933. Sverdrup, H. U., Notes on erosion by drifting snow and transport of solid material by sea ice: Am. Jour. Sci., 5th ser., vol. 35, pp. 372–373, 1938.

[15] Idem., pp. 372–373.

polar seas, we may infer that the drift ice[16] did not form a close pack or unbroken sheet over the site of the cores but instead was broken and probably was melting rather actively, for the zones of glacial marine sediment contain also some pelagic Foraminifera and diatoms that must have lived in the open water. Pelagic Foraminifera and diatoms are rare or absent from the bottom deposits beneath the continuous sheets of pack-ice in both the Arctic and Antarctic.[17]

TEMPERATURE OF THE OCEAN, AS INDICATED BY THE DEPOSITS

Rapid melting of the drift ice at essentially its southern limit in this part of the North Atlantic may well have been due to the warm North Atlantic current,[18] which probably flowed there much as it does today, though with somewhat less volume and lower temperature during the glacial maxima of the Pleistocene.[19] Many of the warm-water Foraminifera and Coccolithophoridae brought in by the current, however, are killed off when they reach the cold polar water.[20]

The convergence of a warm current from the south upon the melt water of an ice-filled sea and the tendency of the warm current to drift northward create a condition that readily accounts for a rather abrupt transition between the glacial marine zones and the overlying and underlying foraminiferal marl[21] with its warm-water fauna. As the areas of drift ice expand southward, glacial marine deposits accumulate where earlier the remains of warm-water pelagic organisms had been accumulating. So also, as the southern limit of the drift ice retreats northward, the warm current follows it northward, showering the top of the glacial marine layer with warmer-water Foraminifera and coccoliths. From this concept it follows that the zone of sediment between the uppermost pair of glacial marine zones in cores 4 to 8, which has a cold-water foraminiferal fauna and a texture intermediate between that of the glacial marine zones and the zones of foraminiferal marl, represents an interval when the southern limit of abundant drift ice had not receded much farther north than the line of core stations, or perhaps had shifted back and forth across that line. The forminiferal mud in the other parts of these cores, however, with its fauna of the type that lived in surface water, nearly but not quite so warm as that of today, indicates stages during which the drift ice had retreated nearly as far north as it is today.

The succession of events that led to the deposition of glacial marine and other sediments in alternating sequence may be illustrated somewhat as Lidén[22] illustrated a sequence of Pleistocene events in northern Europe. (See fig. 2.)

[16] The term drift ice is used essentially as Priestly defined it (Wright, C. S., and Priestly, R. E., Glaciology: British (*Terra Nova*) Antarctic Expedition, pp. 393–394, London, 1922), that is floating ice where the pieces of ice are separated by open water whose area exceeds that of the ice. The ice is derived from any source whatever. It is equivalent to "open pack ice" and to the German "Treibeis."

[17] Nansen, F., The oceanography of the North Polar Basin: The Norwegian north polar expedition 1893–1896, Scientific results, vol. 3, pp. 422–427, 1902. Philippi, E., Die Grundproben, in Von Drygalski, E., Deutsche Südpolar-Expedition 1901–1903, Band 2, Heft 6, pp. 433–434, 1912. Stetson, H. C., Op. cit., pp. 32–35.

[18] The northeastward extension of the Gulf Stream according to Iselin's nomenclature. Iselin, C. O., A study of the circulation of the western North Atlantic: Massachusetts Inst. Technology and Woods Hole Oceanogr. Inst., Papers in Physical Oceanography and Meteorology, vol. 4, No. 4, pp. 73–75, 1936.

[19] Brooks, C. E. P., Climate through the ages, pp. 89–90, New York, R. V. Coleman, 1926.

[20] Nansen, F., op. cit., pp. 422–427. Hendey, N. I., The plankton diatoms of the southern seas: *Discovery* Repts., vol. 16, pp. 156–159, 1937.

[21] Definitions of the terms foraminiferal marl and globigerina ooze as used in this report are given on p. 17.

[22] Lidén, Ragnar, Geokronologiska studier öfver det Finiglaciala skedet: Sveriges Geol. Undersökning, ser. Ca., No. 9, pl. 7, 1913.

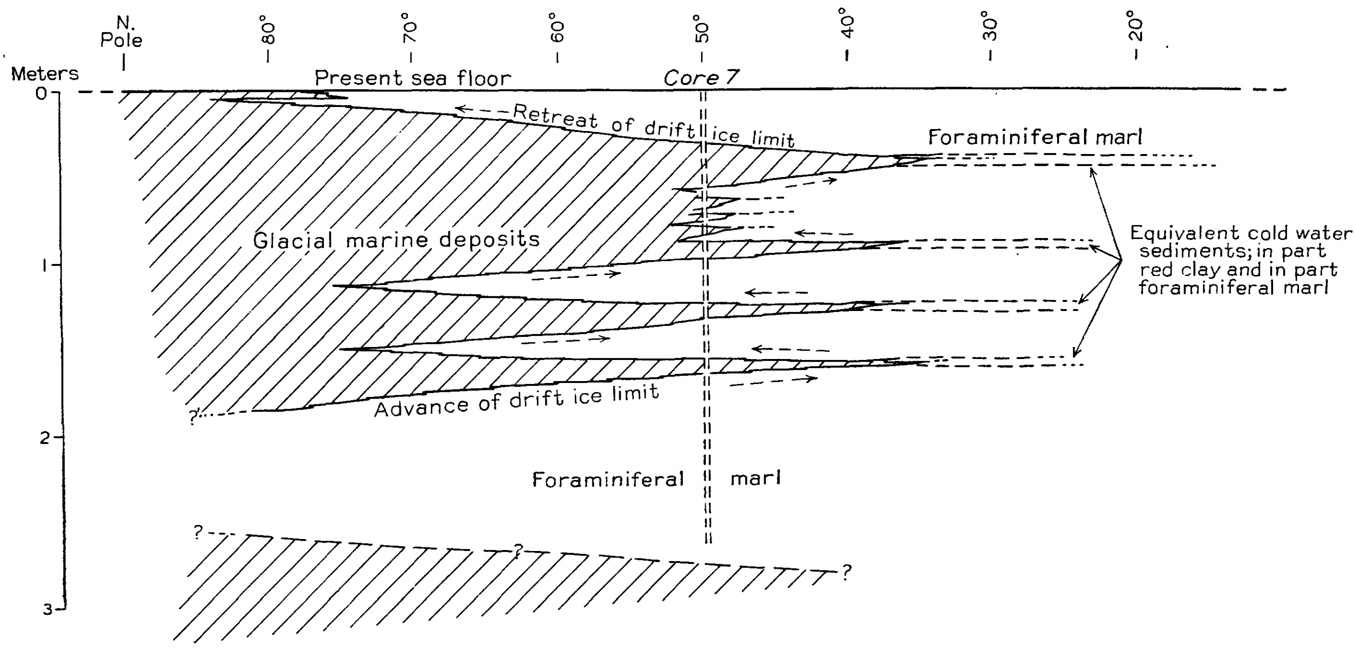


FIGURE 2.—Diagram showing the distribution of glacial marine deposits and foraminiferal marl in core 7 and the inferred distribution of these two types of deposit in a meridional section running through the site of this core. The maximum southward extension of the glacial marine deposits and the northward extension of the foraminiferal marl are unknown and are therefore purely hypothetical. The inference that other glacial marine deposits may underlie the bottom of core 7 is likewise hypothetical and is based only upon the physical characteristics of the bottom of core 7 and the absence of any suggestion of pre-Pleistocene Foraminifera. Core 7 was chosen for this diagram because it represents the longest period of time of any of these cores.

If traced northward from the latitude of the cores, the top of the uppermost glacial marine deposits should rise in relation to the surface of the sea floor until in the region of perennial pack ice, it or its Arctic equivalent, should form the surface deposit, the wedge of foraminiferal marl having thinned out and disappeared somewhere south of the region of drift ice. This is suggested by the deposits now forming in the western part of Davis Strait in latitude 60° to 65° N., which are derived chiefly from the ice brought there by the Labrador current,[23] whereas, according to Murray and Hjort,[24] foraminiferal marl carpets the sea floor a little farther southeast between Greenland and Labrador. If traced southward from the latitude of the cores, the uppermost glacial marine deposits should wedge out or grade into a southern equivalent—perhaps red clay or foraminiferal marl.

Data obtained by Schott in his recent work [25] on the Foraminifera from the cores taken on the *Meteor* expedition suggest that the uppermost glacial marine zone of the Piggot cores may be represented in the equatorial Atlantic by a zone of sediment containing Foraminifera that indicate surface water cooler than that now found in the same locality. Schott interprets this zone as probably the equivalent of the last glacial maximum in higher and lower latitudes. In parts of the equatorial Atlantic he found also that the upper boundary of the cool-water zone coincided approximately with the top of a zone of red clay of unknown thickness. The top of this zone, which lacks the tropical pelagic Foraminifera, ranges in depth below the surface of the sea floor from 10.5 to 66 centimeters. In our cores from the North Atlantic, except 3, 9, 10, and 11, the top of the uppermost glacial marine zone ranges in depth below the sea floor from a little less than 20 to a little more than 60 centimeters. In cores 3, 9, and 10 it ranges from more than 1 meter to 3 meters or more (core 3). The zone in the equatorial region that contains relatively cool-water Foraminifera is underlain in some places by globigerina ooze containing the same tropical forms that are now accumulating there. The cool-water zone averages a little more than 22 centimeters in thickness.

The probability that this cool-water zone in the equatorial Atlantic may be the equivalent of the uppermost glacial marine deposit of the North Atlantic cores is strengthened somewhat by Philippi's description and interpretation of the cores taken by the *Gauss* in the South Atlantic and southern Indian Ocean.[26] Philippi pointed out the absence of tropical Foraminifera in a layer of ooze below that now forming and noted that the lower boundary of the zone of tropical Foraminifera coincided with the top of red clay deposits in several parts of the South Atlantic and Indian Oceans. He interpreted both the absence of the tropical Foraminifera and the presence of red clay below a blanket of globigerina ooze as indicating generally colder water throughout the ocean and suggested that the deposits formed at that time probably represented the last glacial stage. Red clay was deposited in many parts of the ocean at depths where now foraminiferal marl is accumulating and in places where only the more delicate shells are being dissolved. It seems reasonable to conclude, as he did, that the greater extent of areas in which red clay was deposited in the past was due to the solvent and oxidizing effect of the greater quantities of carbon dioxide and oxygen that the cold water of that epoch could hold. As has already been noted, Philippi found in cores of bottom sediments from the southern Indian Ocean at approximately latitude 45° S., globigerina ooze overlying glacial marine deposits, and in cores from latitude 50° S. southward to the ice front, diatom ooze overlying glacial marine deposits.

An epoch when all the oceans were colder than they are today seems to be implied by the fact that three types of cool-water or cold-water deposits formerly had a greater areal extent than they do today and are, therefore, locally buried beneath a comparable thickness of foraminiferal ooze or limy blue mud such as that now forming in various parts of the ocean. The old glacial marine deposits extended much farther from the poles, in both northern and southern hemispheres, than the glacial marine deposits now forming; the areas of red-clay deposition were much larger; and the sediments characterized by a colder-water foraminiferal fauna extended even into the equatorial regions. Some very general cause seems necessary to explain these three types of colder-water deposits, all buried beneath a comparable thickness of warmer-water deposits. The conclusion seems logical that they are all essentially contemporaneous and represent the last glacial maximum of the Pleistocene. How much of the Pleistocene may be represented by these and other deeper-lying cold-water deposits penetrated by the cores is quite another question, which leads us back to further consideration of cores 4 to 7, from the western part of the North Atlantic. Each of which shows four more or less distinct zones of glacial marine deposits.

[23] Trask, P. D., The sediments: The *Marion* Expedition to Davis Strait and Baffin Bay, 1928, U. S. Treas. Dept. Coast Guard Bull. 19, pt. 1, pp. 70–78, 1932.

[24] Murray, J. and Hjort, J., The depths of the ocean, map 4, London, Macmillan & Co., 1912.

[25] Schott, W., Die jüngste Vergangenheit des äquatorialen Atlantischen Ozeans auf Grund von Untersuchungen an Bodenproben der *Meteor*-Expedition: Naturf. Gesell. Rostock. Sitzungsber. Abh., ser. 3, Band 4, pp. 48–57, 1933. Schott, W., Die Foraminiferen in dem äquatorialen Teil des Atlantischen Ozeans: Wiss. Ergeb. Deutschen Atlantischen Exped. *Meteor*, 1925–27, Band 3, Teil 3, Lief. 1, pp. 120–128, 1935.

[26] Philippi, E., Die Grundproben, in Von Drygalski, E., Deutsche Südpolar-Expedition 1901–1903, Band 2, Heft 6, pp. 591–595, 1912.

INTERPRETATION OF THE GLACIAL MARINE ZONES IN TERMS OF STAGES OR SUBSTAGES OF THE PLEISTOCENE

Three possible interpretations have been considered: First, that each glacial marine zone represents a separate glacial stage of the Pleistocene epoch; second, that the two upper glacial marine zones, which are less distinctly separated, represent a bipartite last-glacial (Wisconsin) stage, whereas each of the two lower glacial marine zones represents a pre-Wisconsin glacial stage; and third, that all four glacial marine zones represent only substages of advance and retreat within the Wisconsin stage. (See fig. 3, A, B, C.)

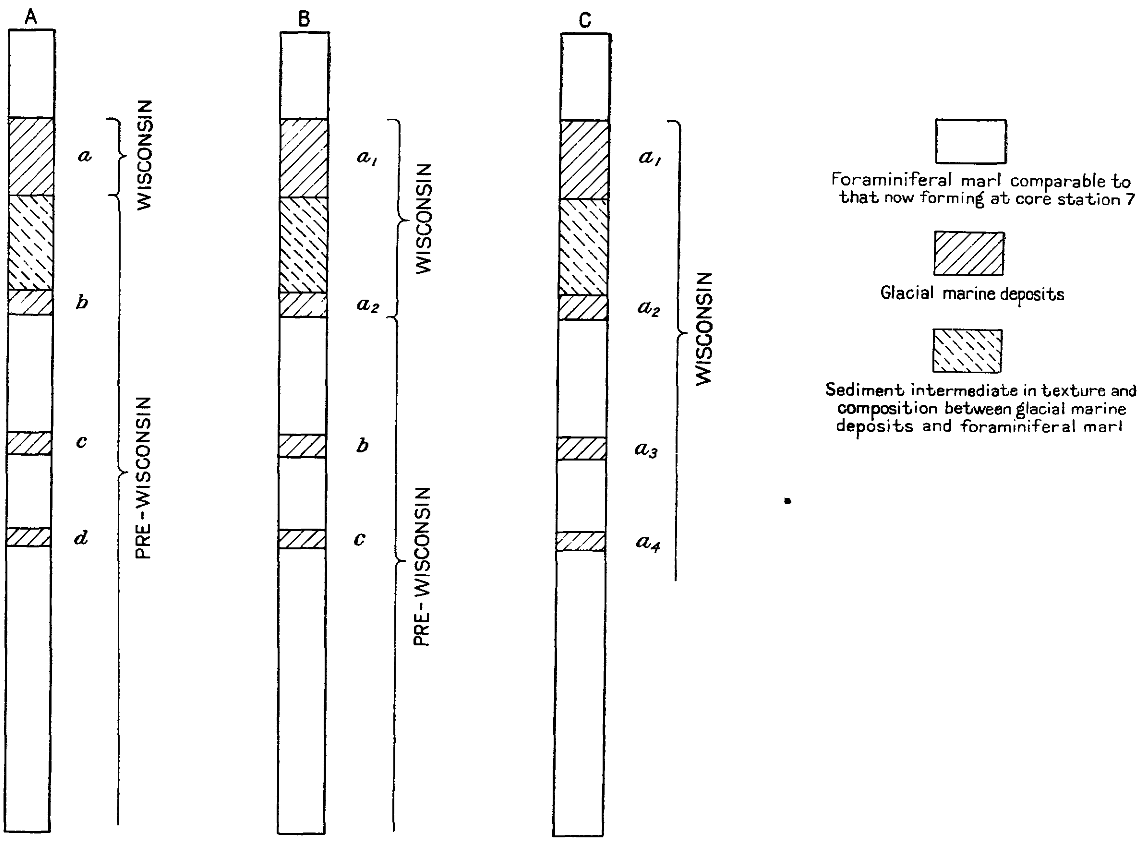


FIGURE 3.—Diagram showing three possible interpretations, A, B, and C, of the glacial marine zones in core 7, in terms of stages or substages of the Pleistocene. *a* signifies the latest, or Wisconsin stage; *b*, *c*, and *d* signify earlier, separate glacial stages of the Pleistocene. a_1, a_2, a_3, and a_4 signify glacial substages of the Wisconsin stage. Core 7 was chosen for this diagram because it represents the longest period of time of any of the cores.

The hypothesis that each of the four glacial marine zones represents a separate glacial stage of the Pleistocene (see fig. 3, A) now seems to us least probable, although this was the opinion we held earlier in the investigation.[27] Cushman and Henbest found, however, that the Foraminifera in the zone between the uppermost two glacial marine zones indicate, in general, water quite as cold as do those in the glacial marine deposits. (See pl. 4.) This, together with the texture and composition of the sediment in this zone, which is intermediate between glacial marine deposits and foraminiferal marl, leads us to believe that, in the interval between these two uppermost glacial marine zones, the southern limit of drift ice repeatedly migrated back and forth across the site of these cores. The uppermost two glacial marine zones seem to be too closely connected by deposits that represent conditions that were almost glacial for us to regard them as separate glacial stages of the Pleistocene. They seem rather to represent greater southward extensions of ice in the sea at the beginning and end of a single glacial episode.

According to the second interpretation, which postulates for the upper zones a single glacial stage marked by a moderate retreat of the ice between two greater extensions, the upper two glacial marine zones would correspond to the early and late substages of the Wisconsin.[28] (See fig. 3, B.) The lower two glacial marine zones in cores 4 to 7 might represent pre-Wisconsin stages, as they are separated from each other and from the upper glacial marine zones by foraminiferal marl, which contains pelagic Foraminifera that indicate surface water nearly or quite as warm as exists there today—in short, foraminiferal marl approaching the type now forming in that part of the North Atlantic. (See pp. 17–18.) The zones or layers of foraminiferal marl in the lower parts of cores 4 to 7 have approximately the same average thickness as the layer of postglacial

[27] Bradley, W. H., Bramlette, M. N., and others, Preliminary report on the North Atlantic deep-sea cores taken by the Geophysical Laboratory, Carnegie Institution: Am. Geophysical Union Trans., pp. 224–226, 1937; The Geological Survey's work on the Piggot North Atlantic deep-sea cores: Am. Philos. Soc. Proc., vol. 79, pp. 41–46, 1938

[28] Chamberlain, T. C., and Salisbury, R. D., Geology, vol. 3, pp. 392–394, New York, Henry Holt & Co., 1906.

foraminiferal marl at the tops of these same cores (see pl. 3), and it is assumed that they accumulated at approximately the same rate. This suggests that the intervals of time separating the two lower glacial marine zones from one another and from the next higher glacial marine zone were about equal in length to postglacial time and that during each interval the southern limit of the pack and berg ice in the sea retreated markedly, though probably not quite so far north as it now is. This hypothesis, if true, suggests that each of the lower two glacial marine zones represents a distinct glacial stage of the Pleistocene, but that each stage was set off by interglacial stages of no greater length than postglacial time. At the bottom of core 7 the number of Foraminifera and coccoliths and the quantity of calcium carbonate decrease markedly. In these same samples the percentage of sand increases conspicuously. Both these changes suggest proximity to the top of another glacial marine zone, yet the Foraminifera indicate that surface-water temperatures were quite as high as when the globigerina ooze just above was forming—that is, temperatures much like those that prevail today in that part of the North Atlantic. (See pl. 4.)

This second possible interpretation of the glacial marine zones seems to imply too short a time for the whole Pleistocene epoch, for each of the upper two interglacial zones indicates an interval of time about equal to postglacial time, whereas, the interglacial stage indicated in the lowest part of core 7 is evidently much longer than any of those above it, and may be even longer than this core seems to indicate. Moreover, the length of time represented by the glacial marine deposits must be considered. At present we have no means of estimating this, but the time represented by the glacial marine deposits might conceivably be much longer than that represented by the thicker foraminiferal marls between them.

The third possible interpretation is that all four glacial marine zones represent only substages of the Wisconsin stage (see fig. 3, C), though the latest two substages are not separated by a clearly defined nonglacial substage. For the greater part of the Wisconsin stage this interpretation apparently implies a greater latitudinal range of glacial phenomena both in the North Atlantic Ocean and in eastern North America than is evident in the record of continental glaciation. It implies that for periods of time measured in thousands of years the North Atlantic at approximately latitude 50° N. alternately contained an abundance of drift ice and then again for thousands of years was nearly or quite free of ice. This seems to indicate that, except in the intervals between the latest two glacial marine zones, the continental ice sheet not only withdrew from the coast but probably retreated well back toward its centers of dispersal so that the marine climate of the western North Atlantic was not greatly different from what it now is. Two observations on the deposits that lie between the glacial marine zones support this inference—the deposits contain Foraminifera and coccoliths that indicate surface-water temperatures about like those now prevailing, and they contain virtually no ice-borne material.

In the interval between the latest two substages, the drift ice in that part of the North Atlantic must have been only a little less plentiful than at the times of maxima, but the other glacial substages are set off from one another by intervals during which the surface-water temperature along the line of cores was nearly as warm as it is today. According to the third hypothesis, the thick unit of globigerina ooze in the lower part of core 7 may represent all or part of the interglacial stage that preceded the Wisconsin. Its foraminiferal fauna, which indicates surface water as warm, or perhaps warmer, than now prevails at that locality, is in accord with this inference.

Although the evidence available is insufficient to determine which of these interpretations of the glacial marine succession is the more nearly correct, we are inclined to favor the third interpretation—that all four glacial marine zones are substages of the Wisconsin stage. Only more and longer cores can provide adequate data for a completely satisfactory answer.

The speculation may serve a useful purpose in bringing to the attention of those interested not only the possible interpretations but also the factors involved. To pursue it further at this time seems fruitless. We do not know enough about the extent of the sea ice and its movements in the North Atlantic during the Pleistocene to correlate its advances and retreats with those recognized in the continental ice sheet and therefrom to give a valid interpretation of the glacial marine succession. These few cores do not give enough information on the areal extent and number of glacial marine zones to reveal their full significance. A series of similar but longer cores taken along a line running in a general southeast direction from Davis Strait through the vicinity of core stations 4 and 5 and on southward past the southern limit of the glacial marine deposits, would perhaps shed light on phases of the glacial epoch not decipherable on land. Such a marine record has the advantage of being continuous, and the mechanism that operated to bring about recognizable changes in the marine sediments probably was far more sensitive to climatic changes than a continental ice sheet. This sensitivity is suggested by Philippi's observations [29] in the south polar region. He observed there that lime-poor glacial marine deposits now forming within the limit of the pack ice are underlain at shallow depth by a thin layer of a more limy foraminiferal marl, which in turn overlies glacial marine deposits that contain almost no lime. This thin layer

[29] Philippi, E., Andeutungen von postglazialen Klimaschwankungen in der Südpolar-Region, in Die Veränderungen des Klimas: Eleventh Internat. Geol. Cong. Stockholm Ber., pp. 457–459, 1910.

of limy ooze he interpreted as the reflection of a brief postglacial amelioration of climate, during which the front of the pack ice was considerably farther south than it now is. Brooks [30] suggests that this warmer epoch which Philippi postulates may be the "climatic optimum."

It may be that the glacial marine history, when fully worked out, will provide the best means of testing Milankovitch's hypothesis [31] that the several glacial and interglacial stages of the Pleistocene were a function of solar radiation. Surely the expansion and contraction of areas in the sea that contain much drift ice would be more directly and immediately affected by changes in the sun's heat than would the advance and retreat of thick continental ice sheets. The relation between the drift ice and the glacial marine record is simple and direct, whereas the relation between the advance and retreat of continental ice sheets is indirect

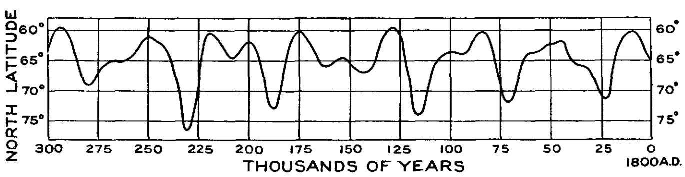


FIGURE 4.—Curve showing amplitudes of solar radiation changes at latitude 65° N. during the warm half of each year for the past 300,000 years. The variations in the amount of heat emitted are expressed in terms of an imaginary shift of geographic latitude. Time is reckoned from 1800 A. D. (After Milankovitch.)

and complicated. Yet, despite this apparent directness in the linkage between the sun's radiation and the glacial marine record, the expansion and contraction of drift-ice areas in the sea are influenced by other factors, some of whose effects, taken singly or in combination, may exceed those of solar radiation or be out of phase with the solar radiation. One of these factors, analyzed by Brooks,[32] is that there is a critical polar temperature below which a polar ice cap forms and expands rapidly to a maximum size. The great cooling effect of floating ice accounts for the rapid growth of ice caps and their stability.

Milankovitch, according to Zeuner,[33] calculated the variations in the solar radiation, which depend upon three periodical alterations of certain elements of the earth's orbit, as follows: (1) the eccentricity of the earth's orbit, with a period of 92,000 years, (2) the obliquity of the ecliptic, with a period of 40,000 years, and (3) the heliocentric longitude of the perihelion, with a period of 21,000 years. Milankovitch's [34] curve based on these calculations of solar radiation for the summer months is reproduced here as figure 4. The three radiation minima at 23,000, 72,000, and 115,000 years are regarded by Milankovitch, Zeuner,[35] and Blanc [36] as correlative with the three stages of the Würm glacial epoch in Europe.

Milankovitch's solar radiation curve, taken alone, does not seem to indicate four cold epochs corresponding to the four glacial marine zones which we think may be substages of the latest, or Wisconsin, glacial stage. No attempt, however, will be made here to explain this, or to relate the curve to the glacial marine record, because the glacial marine record is clearly fragmentary and the relationship is probably more complex than has been assumed by Milankovitch, Zeuner, and others.

POSTGLACIAL CLIMATIC CHANGES

Certain minor features of these cores may perhaps be explained by changes of climate that had either local or regional effects during the postglacial interval. In core 3, which we believe consists wholly of post-glacial sediment, there are three rather well-defined but thin layers that contain more clay, less calcium carbonate, and fewer Foraminifera and coccoliths than the rest of the core. These are indicated in plate 3 by sample numbers B–6, B–12, and B–18. They are also discernible in the photograph of the cores, plate 2. The physical character, together with the low surface-water temperature indicated by the Foraminifera in the upper two, suggests that these clay layers represent comparatively brief, cold episodes when sea ice containing no land-derived coarse detritus covered that part of the sea continuously; on the other hand, the Foraminifera in the third clay layer (at the bottom of the core) do not suggest surface-water temperatures lower than exist there today and thereby weaken the argument for this explanation. The sharp lower boundaries of at least the upper two clay layers (the base of the other clay layer was not penetrated by the core barrel) suggest that they may represent slumped material from the steep slopes of the adjacent Newfoundland banks. For further discussion of submarine slumping see pages 15–16.

The only other suggestions of postglacial climatic changes are the surface-water temperatures inferred from the pelagic Foraminifera by Cushman and Henbest. (See pl. 4.) The Formanifera in cores 3, 6, 9, and 12 (as shown in plate 4) indicate that during roughly the middle part of the postglacial interval the surface-water temperature in those areas in the North Atlantic was somewhat higher than prevails there today. This change is probably shown best in these particular cores because in them the zone of postglacial deposits is considerably thicker than in the other cores, where the postglacial record is compressed into much smaller compass.

[30] Brooks, C. E. P., Climate through the ages, pp. 411–412, New York, R. V. Coleman, 1926.

[31] Milankovitch, M., Théorie mathématique des phénomènes thermiques produits par la radiation solaire: Acad. Yougloslave Sci. Arts de Zagreb., pp. 246–291, Paris, 1920.

[32] Brooks, C. E. P., Climate through the ages, pp. 32–45, New York, R. V. Coleman, 1926.

[33] Zeuner, F. E., The Pleistocene chronology of central Europe: Geol. Mag., vol. 72, p. 361, 1935.

[34] Milankovitch, M., Mathematische Klimalehre und astronomische Theorie der Klimaschwankungen, Handbuch der Klimatologie. Band 1, Teil A, p. 141, Berlin, Gebrüder Borntraeger, 1936.

[35] Op. cit., pp. 362–372.

[36] Blanc, A. C., Low levels of the Mediterranean Sea during the Pleistocene glaciation: Geol. Soc. London. Quar. Jour., vol. 93, pp. 643–646, 1937.

A change to lower surface-water temperatures is indicated by the Foraminifera a little below the middle of core 9 (samples B–165 and 166, pl. 3). This change to colder conditions occurs at and a little below the base of the upper volcanic ash layer. It appears to have been a rather brief episode. Such brief episodes could not be revealed in the much more condensed sedimentary record of the other cores except by a larger number of thinner samples. Judging by the sparsity of ash in the lower part of core 3 this core did not reach the horizon represented by the cold zone in core 9. This temperature change shown in core 9 may, however, reflect only a local change in the fauna owing perhaps to some temporary change of currents.

RATE OF DEEP-SEA SEDIMENTATION

In order to estimate the rate of sedimentation as indicated by these cores it is necessary to make certain assumptions about the horizon in this oceanic stratigraphic sequence that corresponds most reasonably with a certain phase of the last glacial stage in North America. Only one horizon seems to us likely to have real meaning in this correlation, and this is the top of the uppermost glacial marine zone. This horizon is assumed to represent the beginning of the postglacial epoch as defined by Antevs, who says:

> The postglacial epoch is considered as having commenced when the temperature in the southern parts of the previously glaciated area had risen to equal that of the present time. In eastern North America the ice sheet was then probably confined to Labrador Peninsula. This was probably, in round figures, 9,000 years ago.[37]

The age of the horizon in the cores that we have adopted is, of course, subject to considerable error, because we do not know the rate at which the southern limit of the drift ice retreated. The drift ice, which contains the detritus-laden berg and shore ice, is much thinner than the ice of a continental glacier and has more surface exposed, so it would surely break up and disappear more quickly than the continental ice sheet, particularly in the North Atlantic, where the comparatively warm North Atlantic current tends continually to spread northward. Just as foraminiferal marl is now accumulating on the sea floor in latitudes farther north than the southern part of the Greenland ice sheet, so in the early waning phases of the last glacial stage the sea probably cleared of ice at latitudes farther north than that of the retreating front of the continental ice sheet.

Accordingly, the age of the top of the uppermost glacial marine zone in these cores is probably greater than 9,000 years; but, if we assume for the moment that it is 9,000 years, we can estimate the maximum rate of deposition for the postglacial deposits. The average thickness of the postglacial sediment in cores 4 to 7 is 34 centimeters. If this was deposited in 9,000 years, the rate of accumulation would have been about 265 years per centimeter. As pointed out above, however, 9,000 years is probably too short for the time elapsed since foraminiferal marl began to form at the sites of these cores after the last glacial marine deposits were laid down. The rate of accumulation of the foraminiferal marl near the tops of these cores may be nearer 1 centimeter in 500 years than 265, but a closer estimate based on these cores is hardly warranted.

A comparison of the thickness of the postglacial sediment in different cores shown graphically in plate 3 makes it plain that the rate of accumulation differs considerably from place to place even in the ocean abyss. The differences depend upon local conditions, as is illustrated by core 8, where currents have removed much of the normal fine sediment, with the result that the building up of the sea floor there has progressed at a comparatively slow rate. At the site of core 9, not far away, currents and perhaps other factors have caused an abnormally rapid rate of accumulation. The blue mud in core 3 evidently accumulated at least 10 times faster than the postglacial sediment in core 4.

Schott,[38] in his study of the stratification indicated by the Foraminifera in the cores taken by the *Meteor* in the equatorial region, assumed that the postglacial warm-water type of ooze began to accumulate there about 20,000 years ago. He calculated the average rate of accumulation of globigerina ooze in 48 cores to be approximately 1 centimeter in 415 years, and the range to be from 1 centimeter in 235 years to 1 in 950 years. For 6 blue muds he got an average rate of about 1 centimeter in 282 years, with a range from about 1 in 151 to 1 in 556 years. For 7 red clays the average was about 1 centimeter in 584 years.

It is interesting to compare these estimates with an estimate by H. Lohmann[39] based on the population and rate of growth of the Coccolithophoridae, published in 1909. Many assays of the plankton population showed that about 500 million of these minute calcareous plants grow under each square meter of open sea in the North Atlantic. These divide, on the average, about every 3 days, and as their total number, year in and year out, remains nearly constant, about one third of the population dies and sinks each day. From this rate and from the volume of the tiny plates or coccoliths into which the limy shells separate after the death of the organism he calculated that if the bottom deposits consisted of coccoliths alone they would accumulate at the rate of one millimeter in 1,000 years. But in the oozes he examined he estimated that coccoliths made up 30 to 70 percent of the sediment, which would mean that the sediment accumulated at something like 1 millimeter in 300 to 700

[37] Antevs, Ernst, Late glacial correlations and ice recession in Manitoba: Canada Geol. Survey Mem. 168, p. 6, 1931.

[38] Schott, W., Die foraminiferen in dem äquatorialen Teil des Atlantischen Ozeans: Wiss. Ergeb. Deutschen Atlantischen Exped. *Meteor*, 1925–27, Band 3, Teil 3, Lief. 1, p. 129, 1935.

[39] Lohmann, H., Plankton-Ablagerungen am Boden der Tiefsee: Naturwiss. Ver. Schleswig-Holstein Schr., Band 14, pp. 399–403, 1909.

years, or at an average rate of about 1 millimeter in 500 years. Although his samples came from depths of 2,400 to 4,800 meters in the North Atlantic, few of the samples from our cores contained more than 10 percent of coccoliths and most of them contained less. According to Correns,[40] Schott also estimated from the *Meteor* samples that the coccoliths, even where most abundant, made up not more than 13 percent of the total. If it be assumed the coccoliths make up 10 percent of the sediment now accumulating, Lohmann's figures would indicate a rate of about 1 millimeter in 100 years or 1 centimeter in 1,000 years. Probably a coccolith content of 3 percent would be nearer the average value for the sediment in the upper parts of cores 4 to 7, and this would indicate a rate of accumulation of about 1 centimeter in 300 years. This estimate, like the others, is obviously subject to considerable error, yet it is of the same order of magnitude as those given above, which were reached by a quite different line of reasoning.

The rate in the open ocean, as might be expected, is much slower than in inland seas or fjords, where more clastic material is supplied; for example, in the Clyde Sea[41] the varves in the mud indicate that the mud there accumulates at the rate of 1 centimeter in 2.1 years, whereas in Drammensfjord, Norway,[42] the varves indicate an accumulation rate of one centimeter in 6.7 years. In some of the larger inland seas the rate is apparently more nearly comparable with oceanic rates, as is illustrated by the deeper parts of the Black Sea, where, according to Archanguelsky,[43] the varves indicate an accumulation rate of about 1 centimeter in 50 years for the kind of ooze now being deposited.

EVIDENCE OF BOTTOM CURRENTS

The texture and structural features of the sediments in several parts of these cores seem to indicate rather plainly that, locally, currents move over the sea bottom with sufficient velocity to sweep the finer particles from the higher ridges and scatter them about over the bottom of the adjacent deeper parts of the ocean. The evidence for these currents is manifested most clearly in core 8, which was taken at a depth of 1,279 meters of water on the top of the Faraday Hills—a part of the mid-Atlantic ridge—and in core 13, taken at a depth of 1,955 meters on the continental slope off the Irish coast. (See fig. 1.) In these two cores the sediment contains an unusually large proportion of sand, the calcareous organisms are predominantly of sand size, and there is relatively so little binding matrix of clay-size material that the dry sediments are friable. These features are less obvious from the graphical illustration of the mechanical composition shown in plate 3 than they are when one examines the dry material under a binocular microscope, because a considerable proportion of the clay-size material is within the tests of the Foraminifera.

Evidently bottom currents move across these two core sites, winnow out most of the finer material, and carry it into deeper water. The evidence for this action is to be found not alone in the texture of the sediments of these two cores but more particularly in a comparison of the texture of core 8 with that of the next adjacent core 9, which, though relatively near, as shown in the profile (fig. 1), was taken at a depth of 3,745 meters of water. The postglacial zone in core 9 is more than 10 times as thick as it is in core 8, and it is made up predominantly of very fine grained material, as the data from the mechanical analyses plotted in plate 3 show. That much of this fine material came from the top of the mid-Atlantic ridge is suggested by the abnormal abundance of volcanic glass shards in core 9. These shards are mostly small and delicate, whereas the upper ash zone of core 8 contains but few shards and those are coarse and heavy. As the shards were brought to the ocean through the air, their distribution in the surface water was presumably uniform, therefore the sorting between cores 8 and 9 must have been subaqueous. Moreover, the scarcity of fine material in the sediment at the site of core 8 strongly suggests that the currents that did the winnowing were bottom currents.

Diatoms, coccoliths, and other minute organisms are rare in core 8, but they are abnormally abundant in core 9. These organisms are all minute and, like the volcanic ash shards, have large surface area with respect to their weight. Therefore, it seems probable that they also were removed from the Faraday Hills and concentrated in the deeper water by the same currents that brought the other fine material. The possibility has been suggested that for some ecological reason the surface waters just east of the Faraday Hills were particularly favorable for the growth of these organisms but it seems unnecessary to postulate such a special explanation to account for their concentration at the site of core 9.

The occurrence of coarser-grained sediment on the tops of ridges and mounds and fine-grained sediment in the deeper basins and depressions is apparently a common relationship.[44] Correns' work[45] on the many deep-sea samples of the *Meteor* expedition also showed that the coarser-grained sediment was found on the ridges

[40] Correns, C. W., Die Sedimente des äquatorialen Atlantischen Ozeans: Wiss. Ergeb. Deutschen Atlantischen Exped. *Meteor*, 1925–27, Band 3, Teil 3, Lief. 2, pp. 208–209, 1937.

[41] Moore, H. B., The muds of the Clyde Sea area: Jour. Marine Biol. Assoc., Plymouth, vol. 17, No. 2, new ser., pp. 348–351, 1931.

[42] Strøm, K. M., Land-locked waters: Norske vidensk.-akad. Oslo, Skr., 1936, No. 1, fig. 41, 1937.

[43] Archanguelsky, A. D., On the Black Sea sediments and their importance for the study of sedimentary rocks: Soc. naturalistes Moscou Bull., sec. Géol. new ser., tome 35, pp. 276–277, 1927.

[44] Trask, P. D., Origin and environment of source sediments of petroleum, pp. 87–94, Houston, The Gulf Publishing Co., 1932.

[45] Correns, C. W., Anzeichen von Beziehungen zwischen Strömungen und Bildung kustenferner (eupelagischer) Sedimente: Neues Jahrb., Beilage-Band 57, Abt. A, pp. 1113–1117, 1928.

and swells of the ocean floor, and this relationship was interpreted by him as a result of deep-sea bottom currents. He also showed that in areas where Foraminifera made up most of the sediment the deposits on ridges and mounds were richer in lime than those deposited in the adjacent basins, because the currents swept away the less calcareous clay fraction from the ridges.

The depth of 1,280 meters on the top of the mid-Atlantic ridge, where core 8 was taken, is almost surely too great for any surface wave effects, and the deep circulation of polar water southward is estimated [46] to be too slow to have much effect on the bottom. The effects of tidal currents, however, at these depths may be considerable, and deserve further investigation. Murray and Hjort [47] wrote "We now know that tidal currents prevent the formation of muddy deposits on the top of the Wyville-Thompson Ridge in depths of 250 to 300 fathoms, while just below the summit of the ridge on both sides mud is deposited." Tidal currents might be significant at even great ocean depths where ridges constrict the cross section of a large volume of slowly moving water.

The material in cores 8 and 13 is considerably more oxidized than in the other cores. They are stained with hydrous iron oxides and some manganese oxide, and they contain no iron sulphide. This relatively greater degree of oxidation apparently reflects the continual supply of oxygen from the water that circulates freely over these parts of the sea floor. Near the site of core 13 the *Michael Sars* dredged cobbles and boulders that appeared to have been only partly buried in the globigerina ooze.[48] Above a well-defined line these cobbles are stained with iron and manganese oxides, and to them are attached siliceous sponges, serpulae, horny worm tubes, and hydroids. These cobbles were dropped there from floating ice. Peach thought they probably fell into a flocculent ooze and sank until they reached a more tenaceous layer. Results of the present study suggest that it is perhaps more probable that they fell into glacial marine deposits and were subsequently covered, or partly covered, with globigerina ooze. That part of the interpretation is, however, much less pertinent than how they continue to remain partly emergent. Peach wrote: [49] "Their presence at the surface is probably due to a current that is just strong enough not only to sweep away the falling pelagic organisms that mainly go to form the ooze, but also to denude some of the looser top deposit and partially to expose the stones." The thinness of the postglacial deposits in core 13 and the conspicuous amount of sand and pebbles that are mixed with the postglacial types of Foraminifera support Peach's interpretation that currents of appreciable velocity sweep the bottom close to the edge of the continental shelf.

Currents of sufficient velocity to move silt and sand sized particles may not be restricted to these more exposed parts of the sea floor but may also operate to an appreciable extent even at depths exceeding 4,820 meters. The distribution of the shards of volcanic glass in both ash zones of these cores presents evidence that may be interpreted as the result of such currents. The shards that are scattered through a considerable thickness of sediment above the base of each ash zone may be so distributed because, for a long time, gentle currents continued to remove them from the tops of low mounds or ridges on the ocean floor and scatter them about over the adjacent flatter areas while the foraminiferal ooze continued to be deposited. This implies that, by reason of the currents, parts of an ash zone remain exposed for a long time on the mounds and ridges to supply shards to the adjacent areas. Such a hypothesis to account for the distribution of the shards in the ash zones might be tested conclusively in some particular locality by a group of cores that sampled the sediment on the top of a low ridge and on the adjacent flatter parts of the ocean floor.

Another and perhaps more plausible explanation of the distribution of the shards in the ash zones is given on pages 22–23 under the heading "Role of mud-feeding organisms."

SUBMARINE SLUMPING

Several layers of sediment in these cores that are rather sharply set off from the adjacent material by distinctive textural changes suggest submarine slumps. Two of these are in core 5 (samples B–53 and B–55) and another in core 12 (bottom part of sample B–214). Sample B–53 consists of a mixture of sand and Foraminifera which contains so little fine-grained material that it is decidedly friable. It contrasts markedly with the underlying homogeneous clayey sediment, which contains very few Foraminifera. The contact between them is sharp, but the most distinctive feature of sample B–53 is its gradation in grain size from coarsest at the base to fine at the top, as is shown in table 2.

TABLE 2.—*Grain-size distribution in sample B–53 from core 5 and approximate composition*

Distance above base of sample (centimeters)	Average diameter (millimeters)			Composition (percent, estimated)			Other constituents
	Clastic grains	Foraminifera	Mud pellets	Foraminifera	Clastic grains	Clay pellets	
8	0.06	0.24		30	45		Finely comminuted foraminiferal shells, 25 percent.
7	.09	.25		30	70		
6	.11	.24		40	60		
5	.13	.23		65	35		
4	.14	.25	Small	60	40	Rare	
3	.18	.27	Small	60	40	Rare	
2	.28	.27	0.4	55	42	2	Basaltic glass scoria, 1 percent.
1	.46	.32	.9	75	3	20	Basaltic glass scoria, 2 percent.
0	.45	.39	.8	55	40	5	

[46] Defant, A., Über die wissenschaftlichen Aufgaben und Ergebnisse der Expedition; die deutsche atlantische Expedition auf dem Forschungs- und Vermissungsschiff *Meteor:* Gesell. Erdkunde Berlin Zeitschr., pp. 362–366, fig. 53, 1927.

[47] Murray J., and Hjort, J., The depths of the ocean, p. 170, London, Macmillan Co., 1912.

[48] Peach, B. N., Report on rock specimens dredged by the *Michael Sars* in 1910, by H. M. S. *Triton* in 1882, and by H. M. S. *Knight Errant* in 1880: Royal Soc. Edinburgh Proc., vol. 32, pp. 267–275, 1913.

[49] Idem, p. 272.

The regular gradation in size of this material, the sharp boundary at the base, the irregular occurrence of clay pellets, and the gradation into material of yet finer grain above suggest that this sample consists of material thrown into suspension by a submarine slump, carried beyond the slide itself, and deposited rapidly. Material thus thrown into suspension would be expected to settle according to the respective settling velocities of the various constituents. Clouds of suspended sediment are known to have travelled far beyond the outermost limit of subaqueous slides in lakes.[50] The average slope of the lake bottom over which one of these slides moved was a little less than 5 percent. Archanguelsky [51] describes numerous subaqueous slides in the sediments of the Black Sea and says they "seem to exist wherever the inclination of the bottom attains 2° to 3°, but at places occur even there, where the angle of the slope does not exceed 1°." Schaffer [52] cites apparently good reasons for believing that submarine slides have occurred off the Spanish and Portuguese coasts. Stetson and Smith [53] have recently referred to a large submarine slide which broke the Western Union Telegraph Co's. cable off the Newfoundland Banks following the earthquake of November 1929.

Another reason for thinking that the material in sample B–53 was derived from a submarine slide is the anomalous temperature indicated by its Foraminifera. The analysis of these Foraminifera by Cushman and Henbest indicates surface water temperatures warmer than prevail there today; whereas the Foraminifera in all other samples from the zone between the uppermost two glacial marine zones in cores 4 to 7 indicate temperatures nearly, or quite, as cold as in the glacial marine zones. (See pl. 4.) The presence of these warmer-water Foraminifera at this place in the core suggests that the sliding segment of mud—perhaps from a steeper part of the slope between cores 4 and 5 (see fig. 1)—was thick enough when it broke away from the slope to include at its base part of a layer of warm-water sediment similar to, or perhaps actually correlative with, that which makes up the lowest parts of cores 4 and 5.

Sample B–55, also in core 5, is sharply set off from the adjacent mud by its coarser grain and friability, by its greater abundance of Foraminifera, Radiolaria, coccoliths, and alkalic volcanic glass shards, and by its ill-defined lamination. This layer is as sharply defined at the top as at the base and has no discernible upward gradation in grain size. These features suggest that it resulted from a slump comparatively nearby, the finer-grained particles of which were carried beyond the site of this core. The presence in this layer, about midway between the upper and lower ash zones, of more shards of alkalic volcanic glass than in the adjacent sediment suggests that this slump, at its source, may have cut down into the lower ash zone. Such a layer might also be explained as a product of a local bottom current which, for some unknown reason, flowed more rapidly for a time and then either shifted its course or ceased to flow; but the abruptness of the change from one kind of sediment to another at both top and bottom of this layer makes this explanation less plausible. Near the bottom of core 3 is a sharply defined silty layer with obscure lamination which, though it consists largely of terrigenous silt, is similar in texture to B–55 in core 5 and presumably had the same origin. (See pl. 2.)

A very thin layer in the bottom part of sample, B–214, which was taken from a thick glacial marine zone in core 12, is like sample B–55 in being sharply defined at top and bottom and in showing no obvious upward gradation in grain size, though the material is somewhat coarser grained than the sediments immediately above and below. This layer at the base of sample B–214 contains more calcium carbonate, more coccoliths, and more shards of alkalic volcanic glass than the rest of the sample. Its Foraminifera indicate warmer water than the adjacent samples in the glacial marine zone within which it lies. (See pl. 4.) These facts, together with the distinctive texture and sharp boundaries of the layer, suggest either material that settled out from the suspended material of a submarine slump or perhaps material sorted by local and temporary currents. The presence of the alkalic glass shards suggests, as in B–55, that if it is the result of slumping, the slump may have carried down in its basal part material from a lower ash zone. But no matter how the shards got into sample B–214 it is plausible to assume that they provide evidence that the lower alkalic ash zone is present east of the mid-Atlantic ridge though none of these cores reached it.

Lower in core 12 the material from the general horizon of sample B–223 nearly to the bottom has a somewhat lumpy appearance and is sandy and friable. This part also contains small granules, some rather cleanly sorted fine reddish sand, and at least one red sandstone pebble more than a centimeter across. The texture and composition of the material in this part of the core and the fact that the core was taken on the lower part of the continental slope (see fig. 1) suggests that this lumpy material may have slid from a position higher on the banks and that the slide included some glacial marine material. An alternative interpretation was given on page 7.

[50] Heim, Arnold, Über rezente und fossile subaquatische Rutschungen und deren lithologische Bedeutung: Neues Jahrb., 1908, Band 2, pp. 137–140. Nipkow, F., Über das Verhalten der Skellete planktischer Kieselalgen und geschichteten Tiefenschlamm des Zürich—und Baldeggersees: Rev. Hydrologie, 4 année, pl. 1, pp. 114–115, 1927.

[51] Archanguelsky, A. D., Slides of sediments on the Black Sea bottom and the importance of this phenomenon for geology: Soc. naturalistes Moscou Bull., Sci. Géol. new ser., tome 38, p. 80, 1930.

[52] Schaffer, F. X., Über subaquatische Rutschungen: Centralbl. Mineralogie 1916, Abt. A, p. 24.

[53] Stetson, H. C., and Smith, J. F., Behavior of suspension currents and mud slides on the continental slope: Am Jour. Sci., 5th ser., vol. 35, p. 12, 1938.

CARBONATE CONTENT OF THE SEDIMENTS

The total amount of carbonate in these samples was determined by treating the material with hot dilute hydrochloric acid until the solution was slightly acid as indicated by methyl orange. The amounts of total carbonate plotted in plate 3 are therefore only approximate determinations, subject to errors of several percent. Among the variety of factors that introduce errors are the partial solubility and the base exchange of the clay minerals and the incomplete solution of carbonate particles by reason of clay films that protect them from the acid. The figures given for total carbonate include both calcium and magnesium carbonates, and in the following discussion "carbonate" refers to these amounts of total carbonate unless stated otherwise. Actually, the magnesium-carbonate content of the 31 samples in which it was determined averages only 2.19 percent, which is probably within the range of uncertainty of the total carbonate determinations, so that it may be neglected in the following consideration, and the total carbonate may be considered as all calcium carbonate. In support of this suggestion K. J. Murata of the Geological Survey's chemical laboratory has pointed out to us how closely the relationship of the CaO and CO_2 in the 20 precise analyses given by Edgington and Byers in the chapter "Selenium content and chemical analyses" agree with the relations of CaO to CO_2 in pure calcite. This relationship is shown in figure 5. Many of the points in this figure lie above the line of pure calcium carbonate. This suggests that a small part of the total calcium in the samples is present in a noncarbonate form. The points that fall below the line apparently represent magnesian calcite or mixtures of calcium and magnesium carbonate. Sample 5A12, for example, contains 4.14 percent of $MgCO_3$, and samples 10A5, 3A9, and 13A3 each contain several percent of $MgCO_3$. Sample 10A4, which contains comparatively little carbonate, owes its anomalous position with respect to the line representing the composition of calcite to the abundance of basaltic debris in the mud. The rest of the samples approximate rather closely the composition of calcite.

Before considering the distribution of the carbonate it is desirable to consider briefly the terminology of carbonate-rich sediments. Murray and Chumley [54] defined globigerina ooze as deep-sea sediment that has a carbonate content of 30 percent or more. The average carbonate content of all their samples is 64.72. Correns [55] points out that this means of defining globigerina ooze on the basis of carbonate content is unsatisfactory, because many deep-sea sediments contain 30 percent or more of carbonate, yet only a few *Globigerina* or any other Foraminifera. As a substitute he proposes to define globigerina ooze by the foraminiferal number, which is the number of Foraminifera per gram within the size range 0.2 to 2.0 millimeters. Samples with a foraminiferal number of 6,000 or more he calls globigerina ooze. This would mean that certainly more than a quarter and generally about half of the sediment would consist of foraminiferal shells. He found that most of the *Meteor* samples had a carbonate content of 60 percent or more. According to this definition many of our samples should not be classed as globigerina ooze, but the Foraminifera in our samples have not been counted, and it is not possible to compare them directly with the *Meteor* samples. In this report the term globigerina ooze is used loosely to designate the sediment in which roughly half or more of the sediment, by weight, consists of Foraminifera. By bulk, these hollow shells are obviously the predominant constituent. Limy muds containing a lesser but still conspicuous number of Foraminifera are referred to by the more qualitative term "foraminiferal marl."

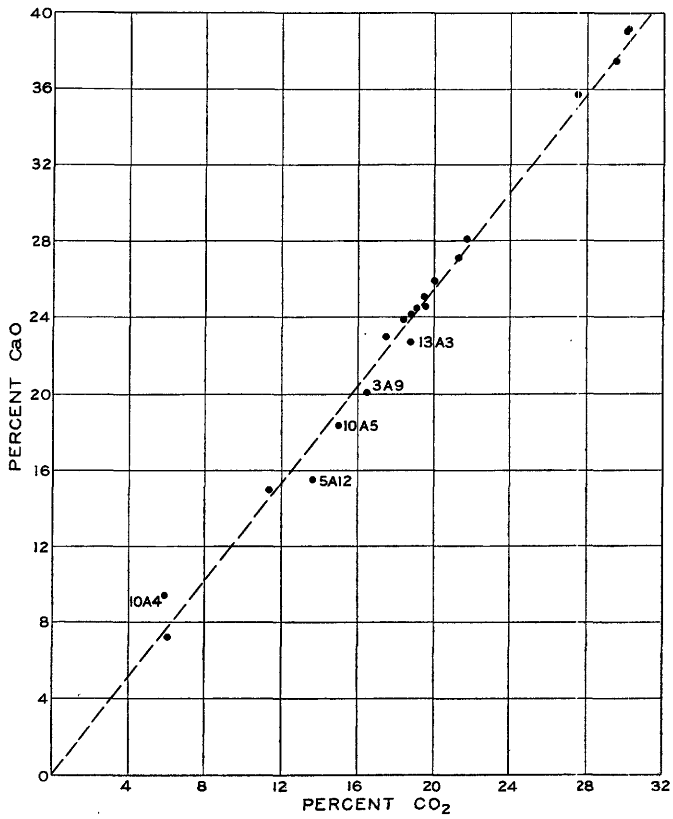


FIGURE 5.—Graph showing the CaO-CO_2 ratios of core samples (represented by dots) in relation to the CaO-CO_2 ratio of pure calcite (represented by the diagonal line). All data are from analyses made by Edgington and Byers, and the numbers by some of the dots are sample numbers given in their table of analyses.

The tests of Foraminifera, most of which are nearly whole and thus easily recognizable, were estimated to make up approximately 47 percent, by weight, of the carbonate of the sediment that is classed as globigerina ooze in these cores, whereas in the globigerina ooze collected by the *Challenger* the Foraminifera (pelagic

[54] Murray, J., and Chumley, J., The deep sea deposits of the Atlantic Ocean: Royal Soc. Edinburg Trans., vol. 54, pt. 1, p. 217, 1924.

[55] Correns, C. W., Die Sedimente des äquatorialen Atlantischen Ozeans: Wiss. Ergeb. Deutschen Atlantischen Exped. *Meteor*, 1925-27, Band 3, Teil 3, Lief. 2, pp. 206-208, 1937.

and bottom-dwelling) make up 61 percent.[56] For the North Atlantic samples the percentages of Foraminifera shown in plate 3 are rough estimates. In making these estimates there is a tendency to overestimate the percentage by weight, owing to the relatively large volume of the shells in proportion to their weight. A correction for this difference was attempted while making the estimates under a binocular microscope, and the fact that the small comminuted fragments of Foraminifera were not included in the estimates tends further to compensate for any overestimate of the weight of the whole shells. We believe, therefore, that these estimates, though subject to rather large errors, give a fairly reliable picture of the distribution of the Foraminifera in the cores.

Globigerina ooze blankets the sea floor in all parts of the North Atlantic where all these cores were taken except at core station 3, which is in the blue mud zone, and at core station 9 where the mud is very limy but contains relatively few Foraminifera. Similar globigerina ooze makes up the lower parts of cores 5, 6, and 7, below the lowest glacial marine zone. The carbonate content of the globigerina ooze at the tops of the cores and in the lower parts of cores 5 to 7 ranges from 46.6 percent to 90.3 percent by weight and averages 68.2 percent. In the foraminiferal marl the average carbonate content is generally somewhat lower, but the range is large; for example, sample B–60 in core 5, contains 25.7 percent carbonate, and at the other extreme are samples B–152 to 156 in core 9, which have an average carbonate content of 78 percent.

The only other calcareous organisms that commonly form a quantitatively significant part of the calcium carbonate in these cores, are the minute algae belonging to the Coccolithophoridae. These are flagellate brown algae, the commonest of which have globular coatings or shells of calcium carbonate made up of plates. These plates, the coccoliths, separate readily when the plant dies, and in the sediment only these minute plates of various shapes are commonly found. The smallest of these coccoliths are only about 0.002 millimeter in diameter, and few of the largest exceed 0.015 millimeter in diameter. They belong to several different types among the many genera and species that have been described by Schiller.[57] We have made no attempt to differentiate the various genera and species.

In the more calcareous sediments the coccoliths are usually common, but because of their small size they rarely constitute more than a few percent by weight of the total carbonate. Where they reach their maximum abundance in the upper parts of cores 9 and 3, they were estimated to make up about 10 percent of the sediment by weight. They can be recognized only at high magnifications, and as many hundred coccoliths would equal only one of the smaller Foraminifera, a careful separation into grade sizes and determination of the percentages within these fractions would be necessary to obtain satisfactory estimates. Therefore, only the relative abundance of the coccoliths, based on rough estimates, is shown in plate 3.

Rhabdoliths represent a type of calcareous algae living in warmer water, but none were observed in any of the samples.

A small number of echinoid spines and plates of their tests were noted in samples from most of the cores. Ostracodes are about equally rare, and shells and fragments of mollusks are still more rare. These are discussed further in the chapters on "Echinodermata," "Mollusca," "Ostracoda," and "Miscellaneous fossils." Pteropods constitute a few percent of the calcareous material in some samples, notably B–131 near the top of core 8, between samples B–225 and 226 in core 12, and B–231 in core 13. Calcareous organisms other than Foraminifera and coccoliths occur so sparingly that in most samples they are quantitively insignificant.

In the more highly calcareous samples, most of which are to be classed as globigerina ooze, it is obvious that the calcium carbonate consists predominantly of the tests and comminuted fragments of calcareous organisms, but the particles of calcite of fine silt size and smaller are only in part recognizable. The irregular shape and range in size of these indeterminate particles of calcite suggest that they are largely the finest debris of the comminuted organisms rather than a chemical precipitate of calcium carbonate. Particles resembling the aragonite needles described by Vaughan [58] from the Bahama Banks region, if present, are too rare to have been noted. The large percentage of calcium carbonate in some of the finer-grained sediment, such as that making up most of cores 3 and 9, is mostly of indeterminate origin. It seems probable that these fine-grained sediments would contain the largest amount of chemically precipitated calcium carbonate if any were to be found, but no adequate criteria for recognizing such a chemical deposit have been noted. The presumption is, therefore, that the greater part of this finely divided carbonate of irregular shapes and sizes consists of the most finely comminuted particles of calcareous organisms that have been winnowed out, along with other fine particles, from the Newfoundland Banks (core 3) and the mid-Atlantic ridge (core 9).

Well-formed crystals of calcite, commonly intergrown so as to form clusters or rosettes, have been noted in many of the samples, but in no sample are they abundant. Some of these calcite crystals are distinctly zoned. These obviously inorganic calcite grains are generally 0.1 to 0.2 millimeter in diameter. Because of their comparatively large size, crystal form, and

[56] Murray, J., and Chumley, J., op. cit., pp. 222–223.

[57] Schiller, J., Coccolithineae: Rabenhorst's Kryptogamen-Flora, Band 10, Ab. 2, 1930.

[58] Vaughan, T. W., Chemical and organic deposits of the sea: Geol. Soc. America Bull., vol. 28, pp. 933–944, 1917.

habit, it seems more probable that they are the result of growth within the mud than of chemical precipitate in the water above the mud or in the surface water. They form only a negligible portion of the carbonate content of the cores but seem to be more common in the glacial marine zones than elsewhere.

The large amount of chemical data on ocean water obtained by the *Meteor* expedition and discussed by Wattenberg [59] indicates that much of the water is approximately saturated with calcium carbonate under existing conditions of equilibrium, and a slight departure from these conditions may therefore cause precipitation. Revelle [60] has pointed out the possibility that Wattenberg's figure for the solubility-product constant of calcium carbonate in sea water may be somewhat too low and that, in consequence, less of the ocean water is saturated with calcium carbonate than Wattenberg believes. It is generally agreed, however, that the water at greater depths is not saturated and tends to dissolve carbonates. Accordingly, even though carbonates were precipitated at the surface of the ocean as tiny needles of aragonite, they would probably be redissolved before reaching the bottom, because this form of calcium carbonate is relatively unstable, particularly in minute particles. The high alkalinity determined by Wattenberg [61] for the water close to the bottom suggests solution of calcium carbonate, probably of the more finely divided particles and particularly those in the form of aragonite. The dissolved carbonates in these waters near the deep ocean bottom may thus reach a concentration sufficient to cause some reprecipitation of calcite crystals within the bottom sediments. It is noteworthy in this connection that shells of pteropods, which are composed of aragonite, are seldom found below a depth of 2,740 meters and are generally restricted to deposits formed in water shallower than that containing the remains of other pelagic organisms whose shells are composed of calcite.[62] Pteropods were found only in cores 8, 13, and the lower part of 12, which are the cores from the shallowest water of the series. In cores 8 and 12 these pteropods occur in parts of the cores classed by Cushman and Henbest as warmer-water deposits. (See pl. 4.) The pteropod shells are well preserved in several samples of core 13, but in sample B–235 and between samples B–240 and B–241 their former presence is revealed only by clay casts of the shells. These samples from which the shells have been dissolved were taken from glacial marine zones, and it therefore appears that, like the present polar waters, the cold water of the glacial marine epochs was a more effective solvent of calcium carbonate than the warmer water of nonglacial epochs.

Among the pebbles and granules of the glacial marine deposits, the most common rock types are limestone and dolomitic limestone. Grains of these types are likewise recognizable in the sediments of coarse and medium sand sizes, in some of which they are estimated to make up 10 to 15 percent. If there is a similar or greater proportion of clastic limestone grains, in the grains of finer sand and silt size, as may be expected from the relative softness of limestone, it seems probable that clastic carbonate constitutes the major part of the carbonate content of the glacial marine deposits in which Foraminifera are few and coccoliths absent.

The amounts of MgO and CaO in the acid-soluble portions of 31 samples selected from the top, middle,and bottom of each core were determined quantitatively. The CO^2 was not determined, but it was assumed that all the MgO was present in the form of carbonate. A small but unknown amount of the MgO calculated here as carbonate is doubtless present as exchangeable base obtained from the acid treatment of the sediment. Lacking the CO_2 determinations it is impossible to say how much is exchangeable base.

The percentages of magnesium carbonate in these 31 samples are given in table 3. The percentage of magnesium carbonate in the 20 samples of foraminiferal marl in which magnesia was determined ranges from 0.63 to 2.66, and the average is 1.32 percent. In the blue mud of core 3 the average magnesium carbonate content is 3.46 percent, and the average for the 6 samples of glacial marine deposits in which magnesia was determined is 4.01 percent.

TABLE 3.—*Distribution of magnesium carbonate within cores 3 to 13, percent*

Position of sample in core (approximate)	3	4	5	6	7	8	9	10	11	12	13	Average [1]
Top	2.59	1.25	0.9	1.33	0.94	1.17	1.75	[2] 4.08	1.34	0.73	1.09	1.31
Middle	3.11	[3] 4.85	[3] 4.14	[3] 5.19	1.38	1.36	2.15	[3] 6.48	-----	[3] .79	1.25	1.85
Bottom	4.67	1.55	1.8	2.66	.63	1.25	[3] 2.61	[2] 1.46	-----	.88	.90	1.79

[1] Exclusive of the glacial marine deposits and the peculiar mud in core 10.
[2] For peculiarities of this mud see pp. 32–34.
[3] Glacial marine deposits.

The distribution of the magnesium carbonate with respect to depth in each core is shown in table 3. It is evident from this table that the blue mud of core 3, the glacial marine deposits of all the cores, and at least part of the peculiar mud in core 10 (see pp. 32–34), contain, on the average, considerably more magnesium carbonate than the rest of the sediment in the cores. The greater quantity of magnesium carbonate in the glacial marine deposits probably can be accounted for by the recognizable grains of dolomite and dolomitic limestone, though a part may perhaps be ascribed to

[59] Wattenberg, H., Kalciumkarbonate-und Kohlensäuregehalt des Meerwassers: Wiss. Ergeb. Deutschen Atlantischen Exped. *Meteor*, 1925–27, Band 8, Teil 2, pp. 206–227, 1933.
[60] Revelle, Roger, Physico-chemical factors affecting the solubility of calcium carbonate in sea water: Jour. Sedimentary Petrology, vol. 4, pp. 105–106, 1934.
[61] Op. cit., pp. 165–172.
[62] Murray, J., and Chumley, J., Deep sea deposits of the Atlantic Ocean: Royal Soc. Edinburg Trans., vol. 54, pt. 1, p. 234, 1924.

differential solution of fine-grained calcite with respect to fine-grained dolomite by the colder water of the glacial epochs. (See p. 9.) The greater content of magnesium calculated as carbonate in the upper and lower clayey mud zones of core 10 may be due to partial solution of the basaltic constituents that they contain in addition to the scattered shards of alkalic glass. (See pp. 32–34.) If we exclude from consideration the glacial marine deposits and the peculiar muds of core 10, we find that cores 3, 4, 5, 6, 8, and 12, which have top and bottom sediments that are comparable in type, all show a slightly greater percentage of magnesium carbonate at the bottom than at the top. But in cores 7, 8, and 13 the middle samples contain more magnesium carbonate than the samples above or below them, and in cores 7 and 13 the bottom samples contain the lowest percentage for those cores.

Perhaps the uniformity in composition and texture of the sediment in core 3 makes the progressive increase of magnesium with depth in that core considerably more significant than the distribution of magnesium in any of the other cores. The magnesium content in core 3 is not complicated by glacial marine deposits nor by zones of either alkalic or basaltic volcanic material. Further investigation of the distribution of magnesium in depth in the oceanic blue muds is certainly warranted for what light it may throw on the tendency toward dolomitization with age and depth of burial.

The analyses showing MgO are so few, however, that averages of the figures given in table 3 can hardly be conclusive as indicators of a possible tendency to diagenetic dolomitization with increasing depth below the sea floor, as was suggested by the increasing magnesium carbonate content of the reef limestone in the deep boring at Funafuti.[63] The Funafuti boring, of course, represented a much greater range of depth than these cores.

The relation between magnesia and lime in these samples is not wholly consistent, yet it is generally true that the greater the percentage of total carbonates in the sediment the smaller the percentage of magnesia. This is in part, at least, an accidental relationship that depends upon the presence of clastic grains of dolomite and dolomitic limestone in the glacial marine deposits, which are relatively poor in total carbonates. Had some transporting agent dropped the clastic dolomite and dolomitic limestone grains into globigerina ooze the relationship would have been different. In part also the concentration of magnesia in the samples having relatively low percentages of total carbonates is due to the zones of peculiar mud in core 10. These muds contain less carbonate than any other samples in the series, yet by reason of their basaltic debris, they are relatively rich in magnesia. Analyses of the carbonates in core 3 illustrate the reciprocal relation of CaO to MgO in some of these core sediments. The uppermost sample in core 3 contains 40 percent $CaCO_3$ and 2.59 percent $MgCO_3$, the middle sample contains 37.8 percent $CaCO_3$ and 3.11 percent $MgCO_3$, and the bottom sample contains 29.1 percent $CaCO_3$, and 4.67 percent $MgCO_3$.

The *Challenger* samples also contained a larger percentage of magnesia in those samples that contained relatively small percentages of total carbonates. This relationship was interpreted by Murray and Hjort[64] as probably due to preferential solution of calcium carbonate over magnesium carbonate.

As much of the carbonate in these samples was derived from foraminiferal shells it is interesting to compare the CaO–MgO ratios of the samples given in table 4 with the CaO–MgO ratios of analyzed foraminiferal shells. According to Clarke and Wheeler,[65] the average lime-magnesia ratio of two samples each consisting of a single species of pelagic Foraminifera dredged from the ocean is about 35. These particular Foraminifera evidently contain much more magnesium carbonate than some of the globigerina ooze of the North Atlantic cores, as for example in the upper and lower parts of core 7, which consist predominantly of pelagic Foraminifera. (See table 4.) Murray and Hjort[66] in commenting on the fact that magnesium carbonate makes up only a small percentage of the total carbonate on the sea floor wrote: "Since the proportion of Mg to Ca, primarily in rocks and secondarily in river-waters, is much larger than this, it is clear that dissolved magnesium is accumulating in the ocean." Recent experiments in base exchange by A. C. Spencer and K. J. Murata[67] have shown that for certain pure clays each 100 grams of clay brought into the ocean by rivers adsorbs nearly 0.2 gram of Mg from the sea water. This amount of Mg abstracted from the sea water is added to that which the fine clastic particles had already adsorbed when they were constituents of soils and which they held while in transit. Thus, as most of these particles are deposited in the zone of terrigenous deposits relatively near the coast, they fix therein whatever adsorbed Mg they brought with them from the land and also an additional amount which they adsorbed from the sea water. This may explain in part why there is relatively more Mg in the blue mud of core 3 than in the other limy sediments more remote from the coast. The base-exchange experiments also showed that when this same clay was transferred from normal river water to sea water it released about 0.9 gram of Ca for each 100 grams of clay. Thus more Ca and less Mg is delivered to the ocean water

[63] Judd, J. W., the chemical examination of the materials from Funafuti, in The atoll of Funafuti, pp. 364–365, London, Royal Soc., 1904.

[64] Murray, J., and Hjort, J., The depths of the ocean, p. 181, London, Macmillan Co., 1912.

[65] Clarke, F. W., and Wheeler, W. C., The inorganic constituents of marine invertebrates: U. S. Geol. Survey Prof. Paper 124, p. 2, 1922.

[66] Op. cit., p. 181.

[67] Spencer, A. C., and Murata, K. J., oral communication.

than chemical analyses of river water alone indicate. If this additional Ca brought into the ocean is precipitated as carbonate, for example, it may account, in part, for the greater excess of Ca over Mg in the deep-sea sediments. As noted above, because we lack the CO_2 determinations, it is impossible to say how much of the Mg and Ca are present in these samples as carbonates and how much as exchangeable base obtained from the acid treatment of the samples.

TABLE 4.—*Lime-magnesia ratios (to the nearest whole number of the samples shown in table 3)*

Position of sample in core (approximate)	3	4	5	6	7	8	9	10	11	12	13
Top	18	59	14	60	100	51	44	[1] 3	49	118	60
Middle	14	[2] 5	[2] 6	[2] 5	32	34	34	[2] 7	-----	[2] 28	52
Bottom	7	23	34	27	106	26	[2] 8	[1] 7	-----	44	52

[1] For peculiarities of this mud see pp. 32–34.
[2] Glacial marine deposits.

SULPHATES

K. J. Murata called our attention to the fact that the SO_3 reported by Edgington and Byers (see chapter on "Selenium content and chemical analyses") is roughly twice as much as would be expected from the amounts of Cl if the SO_3/Cl ratio were the same in the entrained sea salts as it is in sea water. Abnormally large quantities of SO_3 were also found in another core sample analyzed by E. T. Erickson in the Geological Survey's chemical laboratory. A number of corals, echinoderms, bryozoa, and other calcareous marine organisms contain appreciable quantities of sulphate [68] and Mr. Murata suggested that the excess sulphate in these core samples might be a part of the normal composition of the calcareous foraminiferal shells and coccolith tests. As a result of this suggestion, J. J. Fahey, of the Geological Survey's chemical laboratory, determined the SO_3 in three fractions of a sample of globigerina ooze (W–17, core 10; see pl. 3). Two fractions consisted almost wholly of foraminiferal shells, but the third fraction consisted of the material that had passed through a 200-mesh screen. All three fractions contained SO_3 but definitely less than 0.01 percent. In preparing this sample (W–17) for mechanical analysis the entrained sea salts had been thoroughly leached out with large volumes of distilled water. Analyses of the leachate of several other samples from various cores contained, like the fusion analyses of Edgington and Byers, nearly double the amount of SO_3 that would be expected. These facts suggest that the sediments contain small quantities of a soluble sulphate, possibly gypsum. Bannister [69] reported euhedral gypsum crystals from the Weddell Sea sediments, but we did not recognize any during the microscopic examination of the North Atlantic sediments. To be sure, there remains the possibility that calcium sulphate makes up a small part of the calcareous shells and that the long leaching removed it from them.

SILICEOUS ORGANISMS

The remains of siliceous organisms generally form less than 1 percent of the sediment of the cores. Diatoms, Radiolaria, and sponge spicules are the most common forms, and any one or another of them may be the most numerous in a given sample. In cores 8 and 13 sponge spicules are the only siliceous remains, but these spicules are relatively coarse and heavy as compared with the diatoms. The presence in these two cores of only the spicules—the heavier forms—is apparently to be explained as a residual enrichment, the lighter diatoms, Radiolaria, and other small particles having apparently been swept away by the currents that move over these sites. (See pp. 14–15.) In contrast with the rarity of diatoms in core 8, these delicate siliceous tests are unusually abundant in core 9, only a little farther to the east. Indeed, the sediment in some of the middle part of core 9 may properly be classed as diatom ooze, as diatom frustules make up 50 percent or more of it. This most diatomaceous part of core 9 is in the lower part of the upper volcanic ash zone. In core 10, the upper volcanic ash zone also contains thin beds in which diatoms are unusually abundant. West of the mid-Atlantic ridge diatoms are rather more common in the upper ash zone than in other parts of the cores, though much less common than in the ash zone of cores 9 and 10. This is another illustration of the common association of diatom remains and pyroclastics which has been pointed out by Taliaferro [70] and others.

Lohman's systematic work on the diatoms in these cores (see chapter on "Diatomaceae") shows that these bottom deposits contain no remains of the very delicate forms that constitute a large element of open-sea pelagic diatom flora. This agrees with the findings of Brockmann [71] and with his interpretation that the tests of the more delicately silicated diatoms are dissolved before reaching the bottom, even in relatively shallow water, such as that of the North Sea. In the lower parts of several of the cores some of the diatoms had apparently been leached out after burial on the sea floor, for shallow cavities that appeared to be molds of frustules were observed in the clayey matrix. More study is required, however, to establish definitely that the silica of the diatoms was removed after burial. In certain samples also the central canals of sponge spicules appeared to be corroded. Enlargement of sponge-spicule canals by solution on the sea floor has been described by Schulze.[72]

[68] Clarke, F. W., and Wheeler, W. C., The inorganic constituents of marine invertebrates: U. S. Geol. Survey Prof. Paper 124, pp. 7–56, 1922.

[69] Bannister, F. A., Report on some crystalline components of the Weddell Sea deposits: *Discovery* Repts., vol. 13, p. 66, 1936.

[70] Taliaferro, N. L., The relations of volcanism to diatomaceous and associated siliceous sediments: California Univ. Pub., vol. 23, No. 1, pp. 1–55, 1933.

[71] Brockmann, Chr., Diatomeen und Schlick im Jade-Gebiet: Senckenberg, naturf. Gesell. Abh. 430, p. 6, 1935.

[72] Schulze, F. E., Report on the Hexactinellidae: *Challenger* Rept., Zoology, vol. 21, pp. 26–27, 1887.

ROLE OF MUD-FEEDING ORGANISMS

Apparently mud-feeding animals have played a significant part in reworking the sediment, even on the floor of the abyssal parts of the ocean. This seems to be best illustrated by the distribution of the volcanic ash shards in both ash zones, although an alternative explanation for the distribution of the shards was suggested on page 15. We know that explosive eruptions of volcanoes are brief episodes and that when the ash from them falls into quiet water it accumulates in thin, sharply defined layers, as indicated in figure 6, *A*. The glass shards in the deposits of the North Atlantic, however, are not so concentrated in thin layers; instead, they are distributed as shown in figure 6, *B*, with the greatest concentration at the base in one or several ill-defined layers and the remainder scattered at random up through a considerable thickness of sediment above. One might think that this distribution is due to differential settling of the shards through several thousand meters of water. This seems improbable, however, as many of the shards are half a millimeter or more across, and they show no size gradation upward in the sediment but are apparently quite unsorted. A more conclusive argument against differential settling is as follows: The columns in figure 6 are so drawn that the interval through which the shards are scattered represents nearly all postglacial time, that is, thousands of years. A calculation based on Stokes' law shows that the shards in these ash zones would have reached the bottom in less than 5 years.

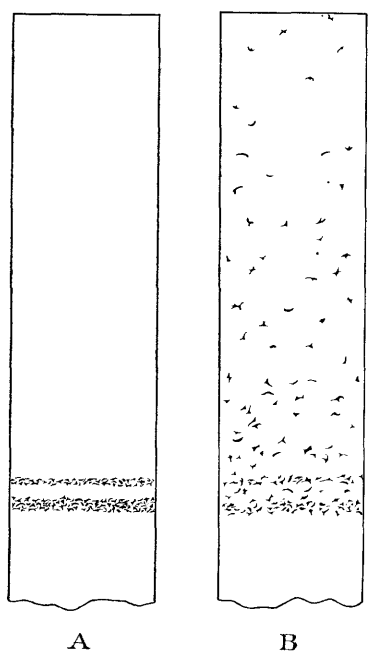


FIGURE 6.—Diagram showing distribution of volcanic ash shards in sediments. *A*, Ash shards that accumulated in quiet water from two explosive eruptions; *B*, ash shards from two similar explosive eruptions that accumulated in water where mud-feeding animals continually worked over the sediment while ash-free sediment continued to accumulate so that the shards were incorporated in successively younger deposits. For an alternative explanation of this distribution of the shards, see p. 15.

We infer that mud-feeding animals living on the sea floor at the time the ash layer was newly formed must have passed through their intestines mud consisting largely of ash shards and that succeeding generations of these animals picked up progressively fewer shards as the sediment became more and more diluted by the continual influx of the normal constituents of foraminiferal marl. Each time an animal scooped up mud and later excreted it on the sea floor, most of the mud particles must have been deposited at a level a little above their original position. Apparently it was this raising by successive small increments that eventually resulted in the distribution of the shards through a considerable thickness of overlying sediment. Grains of fine sand and even some coarse grains are scattered through the zones of foraminiferal marl between and above the layers of glacial marine sediment. Presumably these grains were originally deposited in the glacial sediment but, like the ash shards, have been reworked into younger sediments. Probably detritus of other kinds, including the shells and spicules of animals, has been similarly reworked, but it is difficult or impossible to tell how much their positions have been shifted.

The animals that are supposed to have performed this work are, of course, not known, but it seems probable from what is known of the abyssal fauna today that holothurians were largely responsible, though echinoids, annelids, and ophiurids doubtless also contributed. Théel [73] wrote:

> But the first inspection [of the Holothuroidea dredged by the *Challenger*] made it evident that the forms from great depths, now displayed for the first time, were of the greatest interest by making it manifest that holothurians are living there not merely in great numbers but belonging to many species, and that a large majority of them present certain peculiarities that render them strikingly different from the littoral forms hitherto known, and make them constitute perhaps the most characteristic group of the whole abyssal fauna.

All of these deep sea forms belong to one order, the Elasipoda, of which he wrote further:[74]

> It is evident that some of the Elasipoda, living together in great multitudes, pass along the bottom of the sea; this seems especially to be the case with *Laetmogone wyville-thomsoni* and *L. violacea*, *Oneirophanta mutabilis*, several species of the genus *Benthodytes*, *Kolga nana*, *Scotoplanes globosa*, etc., of which great numbers have sometimes been dredged at the same station. But numerous different species were also found together; thus, no less than ten forms were obtained from station 157, five from station 158, six from station 160, six from station 298, etc. The nature of the bottom of the sea is doubtless of great importance in regulating the distribution of the Holothuroidea, and they are found most numerous and in greatest abundance on a bottom of red clay, globigerina ooze, or diatom ooze.

Most of these came from depths ranging between 1,825 and 5,300 meters.

[73] Théel, Hjalmar: Report on the Holothurioidea dredged by H. M. S. *Challenger* during the years 1873–1876, Part 1: *Challenger* Rept., Zoology vol. 4, p. 1, 1882.

[74] Idem, p. 9.

The calcareous plates of holothurians were found in the cores but they were much less numerous than fragments of echinoids and ossicles of ophiurids. It may be that the large surface per unit volume of the limy plates, wheels, and spicules of the deep-sea holothurians has been responsible for their disappearance by solution rather than that the animals themselves were scarce. Murray and Renard,[75] in discussing the occurrence of organic remains in deep-sea deposits said:

> Representatives of the various orders of Echinodermata are widespread over the sea bottom at all depths, and one would expect to find their remains somewhat abundant in the deposits now forming in the ocean; like Crustacea, however, the areolar nature of the shells seems to determine the removal of the hard parts in solution shortly after the death of the animal. It is seldom that a large sample of Globigerina ooze or Pteropod ooze can be examined without some fragments of Echini spines being observed, but it is the exception to meet with any other remains in the deep-sea deposits.

If the sediments in these cores have been as much reworked by mud-feeding animals as we infer from the distribution of volcanic ash shards and sand grains, we might expect them to have a more or less well-defined coprolitic structure. Ellipsoidal and elongate or cylindrical pellets that appear to be fecal pellets are plentiful in the mud at the top of cores 10 and 12. (See pl. 5, *A* and *B*.) They were not found elsewhere. Some of the elongate forms shown in plate 5 may be filled borings. Considerably larger ellipsoidal and somewhat irregularly shaped pellets are rather characteristic of the sediment in the glacial marine zones. Whether these are fecal pellets or filled borings is not clear. No attempt was made to identify any of these pellets with the fecal pellets described by Moore[76] and Galliher.[77]

Inasmuch as these pellets that appear to be of fecal origin are restricted to parts of the cores that contain a rather large percentage of clay it suggests that only excreted pellets containing enough clay to act as a binder persisted long enough to be preserved. It seems probable that fecal matter bound only by mucous or other organic substances that could serve as nutriants for bacteria would be entirely disaggregated before they could be buried on the ocean floor, where sedimentation is so slow. This might account for the absence of coprolitic structure in the foraminiferal marl.

In addition to the work done in redistributing various constituents of the sediments, mud-feeding animals probably also are responsible, along with free-swimming animals in the water above, for the comminuted particles of foraminiferal shells and other small shells found in the foraminiferal marl.

[75] Murray, J., and Renard, A. F., Deep-sea deposits, *Challenger* Rept., p. 265, 1891.

[76] Moore, H. B., The specific identification of faecal pellets: Marine Biol. Assoc. United Kingdom Jour., vol. 17, No. 2, pp. 359–365, 1931; The faecal pellets of the Anomura: Royal Soc. Edinburgh Proc., vol. 52, pt. 3, pp. 296–308, 1932.

[77] Galliher, E. W., Organic structures in sediments: Jour. Sedimentary Petrology, vol. 2, pp. 46–47, 1932.

MINERALOGY OF THE CLASTIC SEDIMENTS

No systematic study of the mineralogy of the clastic grains was made, but notes were taken on the mineral components of the sand in many samples. The examination of the sand-size material was sufficient to show that the mineralogy of the clastic grains did not differ markedly from one horizon to another within individual cores and also that it did not differ conspicuously from core to core. More detailed study, however, would probably show a greater difference in the mineral content of sediments from the eastern and western parts of the North Atlantic than was evident in the examination given them. Casual examination, for example, showed that grains and pebbles of red sandstone are rather common in cores 12 and 13, whereas they are rare or absent from the cores in the middle and western parts of the North Atlantic.

In general, quartz is more plentiful than the feldspars. The feldspars include orthoclase, microcline, sanidine, and plagioclase feldspars ranging from albite to labradorite. The mineral grains in the sand-size portions of the samples were not separated into light and heavy fractions. However, simple inspection showed that grains of heavy minerals are rather common in the glacial marine deposits. In many samples of the glacial marine deposits the content of heavy minerals was estimated to be 5 to 10 percent, but in the sand between and above the glacial marine deposits it seemed to be generally less. Quantitative data on this relationship might indicate whether or not the sand in the nonglacial deposits was material that had been reworked from glacial marine deposits.

Green hornblende is the most plentiful heavy mineral, particularly in samples west of the mid-Atlantic ridge. Augite, hypersthene, and diopside are fairly common. Black opaque minerals consisting largely of magnetite and ilmenite are plentiful, as are also micas. Epidote, apatite, and garnet are less common but were found in all samples examined. Olivine was found in some samples, but it is rare, particularly in the cores from the western part of the North Atlantic. The rarer minerals, whose relative abundance in different samples could not be even roughly compared without first separating and concentrating the heavy minerals, include sillimanite, kyanite, zircon, rutile, titanite, and tourmaline. Nevertheless, the relatively small proportion of such common heavy minerals as zircon and tourmaline is noteworthy.

Throughout the cores, but especially in the glacial marine deposits, well-rounded sand grains, mostly of quartz though in part of feldspar (usually microcline), are rather common. These range from about 0.1 to 1.0 millimeter in diameter, but those with diameters of about 0.5 millimeter are most plentiful. The rounded grains generally have a more or less distinctly frosted surface common to grains that have been rounded by either wind or water. The proportion of well-rounded sand grains seems to vary only a little either vertically within the cores or laterally from one core to another.

Stetson [78] has recently described a remarkable concentration on the outer edge of the continental shelf off New England of very well-rounded quartz grains that have a mat surface and that range in diameter from a little less than 0.3 millimeter to a little more than 1.0 millimeter. These grains decrease in abundance both seaward and landward but were found in cores taken as far down as the bottom of the continental shelf, at depths exceeding 6,000 meters. They are virtually absent, however, from a wide strip of the continental shelf adjacent to the coast and also from the beach sands and even the dunes on Cape Cod. Stetson interprets these deposits of well-rounded sand as remnants of an area of dunes formed during one or more times in the Pleistocene when the sea had retreated from the continental shelf and when periglacial winds were exceptionally strong.

Although the well-rounded, mat-surfaced sand grains in our cores are similar to those found on the edge of the continental shelf off the New England coast and although they may have come from the places where Stetson found them or from similar sites around the margin of the North Atlantic, they may quite as well have come from other kinds of deposits of rounded sand grains. The means by which these grains were distributed all across the North Atlantic and scattered through the glacial and nonglacial zones of sediment are not evident.

Although these grains may have been frosted, or both rounded and frosted, by wind action, it seems improbable to us that even large storms of exceptional violence could carry quartz grains of such size for great distances. Morover, if the rounded sand in our cores had been formed on the emerged continental shelves during glacial maxima and transported to the sites of the cores by great wind storms, by shore ice, or even by drifting seaweeds, it should now be restricted to the glacial marine zones. The fact that these rounded grains are scattered through both the glacial and nonglacial sediments suggests that they, along with other sand grains of similar size, were derived from reworking glacial marine deposits by mud-feeding animals. If, on the other hand, the rounded and frosted grains were not derived from deposits on the outer edge of the continental shelves but from some place nearer the present coast when the ocean level was higher than in glacial maxima, then there remains the possibility that they (and perhaps also the isolated pebbles found in deposits other than those of the glacial marine zones) were carried out to sea by drifting seaweeds, such as *Fucus*. It would be interesting to see if similar clastic material is common in the sediments of the Sargasso Sea, where seaweeds of this type are plentiful and glacial marine deposits are probably absent.

[78] Stetson, H. C., The sediments of the continental shelf off the eastern coast of the United States: Massachusetts Inst. Technology and Woods Hole Oceanogr. Inst., Papers in Physical Oceanography and Meteorology, vol. 5, No. 4, pp. 14–20, 34–36, 1938.

Little has been done with the clay minerals in the sediment of these cores other than to note that the minute flaky particles of the clay minerals commonly have the optical properties of the beidellite or hydrous mica groups. For one sample of the peculiar mud from the upper part of core 10 (sample W–15) P. G. Nutting of the Geological Survey determined a dehydration curve. This curve is shown in figure 7, with

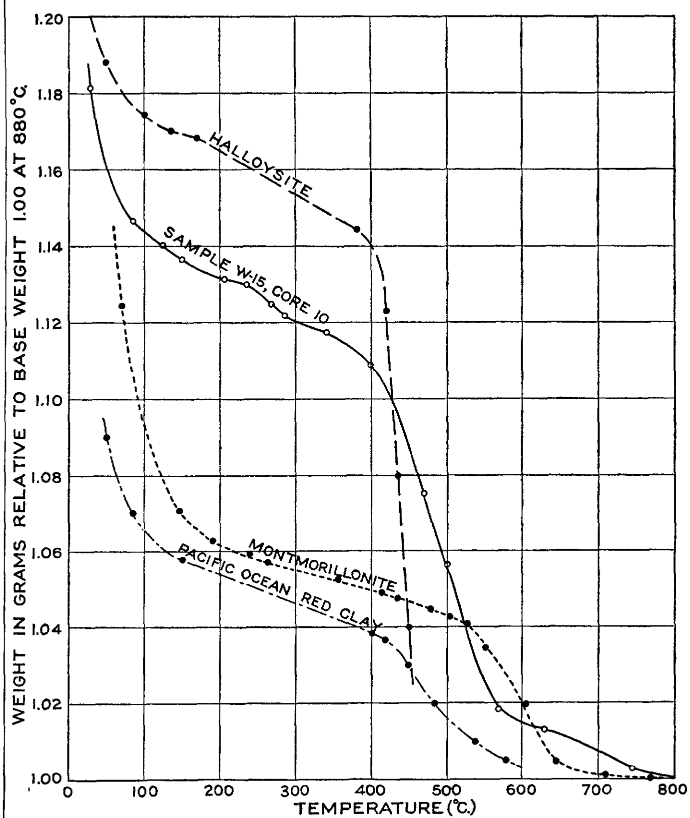


FIGURE 7.—Dehydration curves of basaltic mud from core 10 (sample W–15), a red clay from the Pacific Ocean (lat. 32°27′ N., long. 145°30′ W., depth 5,584 meters), and typical halloysite and montmorillonite from clay deposits in the United States. Data by P. G. Nutting.

the dehydration curves of typical samples of halloysite, montmorillonite, and a red clay from the Pacific Ocean. The steep uppermost parts of these curves represent adsorbed water, most of which is driven off at relatively low temperatures. The steep portions of the curves between 400° and 600° C. represent loss of water that was held within the crystal lattice of the mineral particles. Inspection of these curves shows that the halloysite type of clay contains much more crystal lattice water than the montmorillonite clay and also that the mud from the North Atlantic core 10 contains a quantity of crystal lattice water more nearly like that of halloysite than montmorillonite. That the bench between 100° and 400° C. on the curve of sample W–15 is lower than the comparable bench on the curve for halloysite, Nutting[79] believes to be due probably to the mixture of the silt- and clay-size particles of basaltic minerals and glass with the clay minerals. The form of the curve, although determined largely by the clay minerals, is probably modified by the dehydration of the basaltic glass. The moderate slope between 400° and 570° C. may also be due to the dehydration of the basaltic glass, but it may be due in part to the minute size of the clay flakes—indeed, some of the clay appears even at high magnification to be gel-like and virtually isotropic. This gel-like material, however, is filled with distinct but very small crystalline flakes. Most of these flakes are so thin that they appear to have a very feeble birefringence, but larger and thicker flakes show the higher birefringence that characterizes a beidellite or hydrous mica type of clay. Adequate discussion of the clay minerals in these sediments must await more study than we were able to give them.

In the Atlantic bottom samples collected by the *Meteor*, montmorillonite, halloysite, and kaolinite were reported.[80] These identifications were based partly on petrographic methods and partly on X-ray analyses by V. Leinz and O. E. Radczewski.

Glauconite is present in most samples, but it is rare and generally forms a very small fraction of 1 percent of the sediment. It occurs as tiny pellets that range in color from bright green to brownish green. Most of this glauconite may have been carried into the ocean along with the other clastic constituents, for similar glauconite grains were observed in some of the sandy limestone and limy sandstone pebbles of the glacial marine deposits. However, glauconite grains are somewhat more common in cores 12 and 13, and at least some of them may have formed in place on the sea floor.

Iron sulphide, the nearly black, probably hydrous form, was found in small amounts throughout cores 3 and 9, but even in these cores it seems to make up only a small fraction of 1 percent of the sediment. It commonly occurs as aggregates of minute spherules lining the borings of small organisms such as worms. Small amounts of this iron sulphide also occur in much of core 12, but not in the uppermost or lowermost parts. It was not found in any of the other cores. A considerable amount of iron oxide coats the clastic grains and foraminiferal tests in cores 8 and 13, giving the sediment as a whole a rusty-buff color. This brown iron oxide was found in parts of some other cores, also, but less plentifully. The distribution of the sulphide and oxides of iron in the cores suggests that in the deeper depressions on the ocean floor, where the finest sediment accumulates in quiet water at a comparatively rapid rate, reducing conditions exist and the iron accumulates as the sulphide, whereas on ridges and mounds where the water circulates more freely and the sediment accumulates more slowly, the iron is converted to the oxide. (See the positions of cores 3, 8, 9, and 13 with respect to the submarine topography in the profile, fig. 1.)

A coating of brownish-black manganese oxide was found on some grains of sediment and is particularly common on the granules of fine-grained basalt, tachylite, and altered basic glass. As is discussed more fully on page 32, the volcanic rock penetrated by core 11 contains a large amount of manganese oxide. The MnO soluble in hot dilute hydrochloric acid was determined in the 31 samples listed in table 3 (p. 19) and ranges from a trace to a maximum of 0.03 precent. In the fusion analyses by Edgington and Byers (see ch. on "Selenium content and chemical analyses") the MnO ranges from 0.04 to 0.28 percent, but in neither series of determinations does the amount of MnO show any discernible relationship to the composition or the stratigraphic units of the sediments in the cores. Correns[81] found that in the *Meteor* samples the MnO varied with the content of $CaCO_3$, but in the Edgington and Byers analyses the MnO shows only a random distribution when plotted against the CO_2.

Metallic beads of extra-terrestrial origin, which Murray[82] called cosmic spherules, are rare in oceanic deposits but somewhat less rare in the red clay. Only one minute cosmic spherule was noted in these North Atlantic core samples and that only incidentally, as no special attempt was made to concentrate these rare grains. It had a brilliant metallic luster and the characteristic circular pit. Correns[83] reported only two cosmic spherules in the *Meteor* cores.

SPECTROSCOPIC TESTS

At our request, George Steiger, of the Geological Survey, made spectrographic tests for 12 of the less common or rare elements whose presence was not tested for in any other way in these investigations. The samples tested are as follows: W–2 from core 3, W–9 from core 5, W–13 from core 8, B–181 from core 10, B–211 from core 12, and B–232 from core 13. The positions of these samples in their respective cores are indicated in plate 3. The specimens were tested by placing a small portion directly in the carbon arc. Each sample gave distinct evidence of barium and rather weak evidence of boron. All samples were tested for antimony, beryllium, bismuth, cadmium, germanium, lead, silver, tin, and zinc, but if present they were in quantities too small to be revealed by a 10-inch spectrograph.

[79] Oral communication.

[80] Correns, C. W., Die Sedimente des äquatorialen Atlantischen Ozeans; Auswertung der Ergebnisse: Wiss. Ergeb. Deutschen Atlantischen Exped. *Meteor*, 1925–27, Band 3, Teil 3, Lief. 2, pp. 247–248, 263, 281–285, 1937.

[81] Correns, C. W., op. cit., pp. 223–224.

[82] Murray, John, and Hjort, Johan, The depths of the Ocean, pp. 154–155, London, Macmillan Co., 1912.

[83] Correns, C. W., Die Sedimente des äquatorialen Atlantischen Ozeans; Auswertung der Ergebnisse: Wiss. Ergeb. Deutschen Atlantischen Exped. *Meteor*, 1925–27, Band 3, Teil 3, Lief. 2, p. 287, 1937.

Goldschmidt and Peters [84] analyzed many substances spectrographically and found that igneous rocks are generally poor in boron but that sea salts contain approximately 0.1 percent and recent marine clays contain on the average about 0.03 percent. They found that globigerina oozes collected by the *Challenger* contained 0.05 percent. The sediments that Mr. Steiger tested for us included both clayey muds and globigerina ooze.

POROSITY OF THE SEDIMENTS

The original porosity of some of these sea-bottom deposits can be calculated approximately from the porosity of the air-dried core and the known amount of shrinkage that has occurred upon drying. Because the texture and composition of the sediment in core 3 was nearly homogeneous, samples from it were selected for porosity determinations. Fine-grained calcareous mud makes up 82 percent of this core. At depths of 60, 185, and 279 centimeters below the top of the core, however, are layers of less calcareous clay, and near the bottom there is one thin layer of rather cleanly sorted silt. Of the seven samples whose porosity was determined, five (W–1, W–2, W–4, W–5, and W–6) came from the calcareous mud and two (W–3 and W–7) came from clay layers. The positions of these samples are shown in plate 3.

The amount that a wet mud shrinks depends not only on the grain size but also upon the size distribution and the relative proportions of granular and flakelike mineral particles. Uniform shrinkage of a core of sediment, therefore, implies uniform physical constitution of the sediment. Core 3 shrank with remarkable uniformity. Exclusive of the clay layers, the thin silt layer, and the uppermost piece of the core (which is discussed separately below), the dried calcareous mud core has an average width of 4.165 centimeters, but the maximum width is only 0.125 centimeter greater than the average, and the minimum width only 0.145 centimeter less than the average. These figures are based on 34 measurements. In all the other cores the range of differential shrinkage is many times greater, except in core 8, which is uniformly coarse-grained. The apparent homogeneity of the calcareous mud in core 3 makes it seem well-suited for investigation of the question of whether or not the pore space decreases progressively with depth of burial even in the uppermost few meters.

Because the sediment may have been compacted somewhat as the core barrel was driven into it an attempt was made to evaluate this factor before computing the original porosity. The experiments recently made by Wrath [85] in cooperation with H. C. Stetson at the Woods Hole Oceanographic Institution suggest that the sediment in our cores may be considerably compacted, especially in the upper part, as a result of friction along the walls of the core barrel. Wrath coated the outer surface of the coring tube with shellac just before taking each sample and so was able to measure the penetration of the tube. In soft mud the average length of the recovered cores was a little less than 50 percent of the depth of penetration, in sandy silt about 50 percent, and in sand nearly 68 percent. The coring device was a simple weighted tube.

Similar results were obtained by the *Meteor* expedition with a comparable type of core sampler, but after they adopted a core bit whose cutting edge had an inside diameter a little smaller than the core tube, the cores recovered were almost exactly equal in length to the distance penetrated by the coring device.[86]

In the Piggot coring device used to take these North Atlantic cores, the inside diameter of the core bit is a little smaller than the inside diameter of the barrel of the sample tube.[87] Judged by the experience reported by the *Meteor* expedition, this feature should have been conducive to the recovery of full-length cores. The greater diameter of the sample tube of the Piggot sampler (4.9 centimeters as compared with 2.2 centimeters in the *Meteor* sample tube) should also have reduced the amount of compaction. The core bit of the Piggot sampler entered the sediments at high velocity and this makes it seem unlikely that much water could have been squeezed from so fine grained a mud as that in core 3. Then too, the mud core at this station is 2.92 meters (9 feet 7 inches) long, which is very nearly the full length of the core barrel, 3.05 meters (10 feet). The device may have penetrated 32 centimeters more than the full length of the core barrel—that is up to the water-exit ports—but it seems improbable that it penetrated more deeply than that because no mud was found in the water-exit ports, where it surely would have lodged if these ports had been submerged in mud as they were at station 10. (See p. 6.) The sediment in core 3, therefore, may have been compacted by the operation of coring as much as 14 percent but probably not more than that. If the mud was compacted to this degree, the computed original porosities may be a few percent too low.

The original porosity of the mud just after the core was taken can be calculated from the volume and porosity of the dried mud and the volume of the core barrel. P. G. Nutting of the Geological Survey determined for us the mean grain and lump densities and the porosities of seven dried samples from core 3 and one sample from core 10. These data, together with the calculated original porosities, are given in

[84] Goldschmidt, V. M., and Peters, Cl., Zur Geochemie des Bors: Gesell. Wiss. Göttinggen, Math.-phys. Kl. Nachr., No. 31, pp. 535–544, 1932.

[85] Wrath, W. F., Contamination and compaction in core sampling: Science, vol. 84, pp. 537–538, 1936.

[86] Pratje, Otto, Gewinnung und Bearbeitung der Bodenproben: Wiss. Ergeb. Deutschen Atlantischen Exped. *Meteor*, 1925–27, Band 3, Teil 2, Lief. 1, p. 26, 1935.

[87] Piggot, C. S., oral communication.

table 5. The densities and percent voids refer to material dried at 160° C. for 18 hours. The procedure used in calculating the porosity is outlined here briefly.

TABLE 5.—*Grain and lump density and porosity of dried mud from cores 3 and 10, and calculated original porosity*

[Data by P. G. Nutting, except calculated original porosity]

	Core 3							Core 10
	W-1	W-2	W-4	W-5	W-6	W-3	W-7	W-15
Mean grain density	2.51	2.57	2.51	2.56	2.61	2.59	2.54	2.54
Mean lump density	1.23	1.19	1.21	1.23	1.34	1.38	1.47	1.14
Percent voids	51.83	53.76	51.85	51.82	48.64	46.77	42.17	54.97
Calculated original porosity	76.4	73.8	70.2	71.6	65.8	76.6	75.6	81.0

The volume of each dried core segment whose original porosity was to be calculated was determined as follows: The area of the irregular cross section of half of the dried core (A_2) was determined by comparing the weight of its replica traced on paper with the weight of a paper replica of half the cross section of the inside of the brass core barrel, the area of which (A_1) was calculated. The volume of 1 centimeter length of the dried core (V_2) is then A_2 cubic centimeters. The average longitudinal shrinkage per centimeter (S_a) was estimated from the average width of the transverse cracks that divide the core into segments (in the uppermost part of the core the longitudinal shrinkage was greater than in the rest of the core (see pl. 2). The original undried volume (V_1) of the selected dry sample of 1 centimeter in length was therefore (1 cm.$+S_a$) A_1.

The difference between the original volume and the volume of the dried segment is the volume of water lost in shrinking down to the size of the dried segment. As the water occupied the pores in the wet mud, the volume of water lost in that shrinkage equals the volume of pore space lost. Then the total volume of pore space or voids in the original wet mud was the volume of the water lost in drying down to the size of the dried segment plus the pore space (P) of the dried segment. The percentage of pores, or the porosity, of the original wet mud therefore was $\frac{V_1-V_2+P}{V_1}$.

The calculated original porosities for samples W-3, W-4, and W-7 are somewhat less reliable than the others because the area of the cross section of the dried samples was calculated from the diameter of the dried segment and an assumed semicircular outline rather than a traced outline.

In figure 8 the calculated original porosities of the samples from core 3 (W-1 to W-7) are plotted against the distance below the top of the core. The decrease in porosity with depth for the calcareous mud is fairly regular, but the calculated porosities for samples W-3 and W-7 suggest that the clay is compacted less rapidly than the calcareous mud. The amount of total carbonate shown in plate 3 for sample W-3 is greater than that for sample W-7, which suggests that these two clays are not strictly comparable. However, two samples are not enough to be significant and, as noted above, the calculated original porosities for samples W-3, W-4, and W-7 are somewhat less reliable than the others.

H. B. Moore [88] in his studies of the Clyde Sea muds found that the water content by volume (=porosity) of the fresh muds within 2.5 centimeters of the mud surface at 17 stations ranged from 50.7 to 84.6 percent and averaged 77.1 percent. At a depth of 25 to 27.5 centimeters the muds at 12 of these same stations

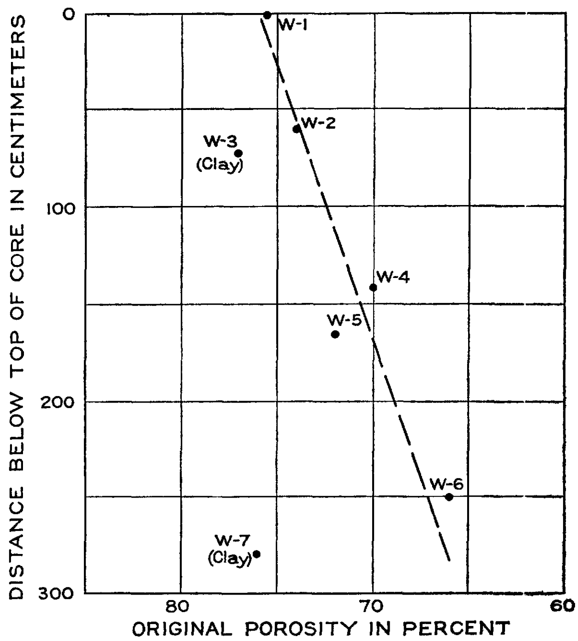


FIGURE 8.—Relation of calculated original porosity of blue mud in core 3 to depth below top of core.

(figures for the other 5 lacking) had an average water content of 74.3 percent. These figures are comparable with the porosities calculated for the sediment in cores 3 and 10 (see table 5). Moore [89] found also that the water content of the Clyde Sea muds decreased much more rapidly in the top 5 or 10 centimeters of the mud columns than in the lower parts.

The marked upward narrowing of the dried mud at the top of the left half of core 3 (see pl. 2) suggests that the sediment at the top of this core was considerably more watery than that lower down. Although the calculated porosities given in figure 8 show that the top sample has a greater porosity than in the others, it is not so disproportionately large as the marked shrinkage of the sample would lead one to expect. The sediment at the top of this core, however, apparently was modified somewhat after the core was taken. The evidence for this modification is shown in figure 9, which shows that the right-half of the dried core at

[88] Moore, H. B., The muds of the Clyde Sea area, part 3: Marine Biol. Assoc. United Kingdom Jour., vol. 17, new ser., pp. 331-332, 1931.

[89] Idem, pp. 333-335.

the top is as wide as the left-half at the first transverse shrinkage crack, 13 centimeters below the top. At about 6 centimeters down from the top the two are about equal. For these two halves of a core of originally homogeneous wet mud to shrink so differently upon drying to the shrinkage limit implies that the average grain size of the part on the right side is considerably coarser than that on the left side. The inference seems to be that this core lay with the right half down for a considerable time after the core was taken and that during that time the coarser and heavier particles settled to that side leaving chiefly the finer clayey particles in the upper (now left) half of the core. This inference is strengthened by the fact that this core barrel came up from the sea floor slightly bent, and the

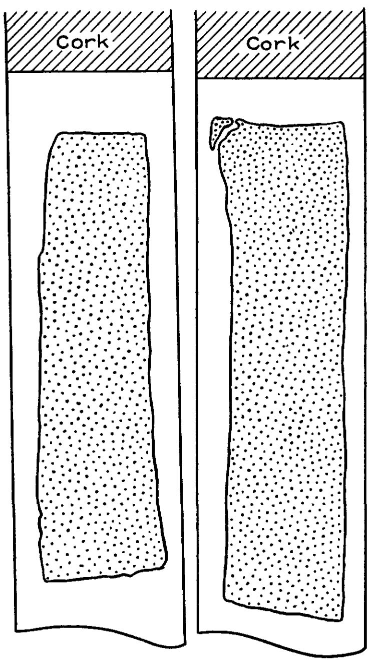


FIGURE 9.—Sketch of the two halves of the top part of core 3 showing differential shrinkage.

bend is such that when the core barrel was placed on deck it must have lain so that what is now the bottom of either the left or right half of the core barrel was down. (See pl. 2.) The average width of the two halves of the dried core in this uppermost 13 centimeters is 3.44 centimeters, as compared with 4.17 centimeters for the average width of this kind of material in the rest of the core, which also suggests that this upper part was more watery.

MECHANICAL ANALYSES

The preparation for complete mechanical analysis of fine-grained sediments is time-consuming, particularly of those which are not in their original wet state. Only four samples were analyzed, therefore, but these samples were selected so as to represent four types of sediment found in these cores. They include a blue mud (sample W–2) from core 3; a gravelly foraminiferal deposit (sample W–13) from the top of the mid-Atlantic ridge, core 8; a fine-grained globigerina ooze (sample W–17), taken from the anchor flukes at the site of core 10; and a distinctive clay (sample W–18) like that in the upper part of core 10 but taken from the water-exit ports of the coring device when core 10 was hauled inboard. The coring device buried itself deeply at the site of core 10, and an unknown amount of mud passed upward through the water-exit ports and was lost. Samples W–17 and W–18 had been kept moist but the other two were thoroughly air-dried. Unfortunately no complete mechanical analysis of a sample of a glacial marine deposit was made, but the size distribution of sample W–13 is somewhat similar except that this sample contains an abundance of Foraminifera, whereas the glacial marine deposits probably contain a greater quantity of silt-size clastic material.

All the samples contained either sea water or salts left from the evaporation of sea water, and they were therefore first leached in large volumes of distilled water on a steam bath. The sediment was stirred frequently, and after long settling the clear water above the sediment was siphoned off. This was repeated until the leach water showed no reaction for chloride with acidulated silver nitrate. The leaching required a month or more. Next, enough dilute sodium-oxalate solution was added to each sample to bring the whole suspension to a concentration of approximately N/100, following Krumbein's [90] dispersing procedure. The samples were then stirred until the dispersion seemed to be at a maximum. Thereafter they were analyzed by the pipette method according to the technique outlined by Krumbein.[91] After the pipette samples had been taken, the remainder of each sample was wet-screened to obtain the size distribution of the constituents larger than would pass a 200-mesh sieve.

The results obtained by Grippenberg [92] indicated that better dispersion of the finest particles probably would have been obtained if the sea salts had been removed by electrodialysis.[93] Indeed, better dispersion probably would have been obtained had the suspensions been analyzed immediately after leaching and before the sodium oxalate was added. This was shown by two other samples, which were leached and finally brought into a high state of dispersion but which quickly coagulated when the sodium oxalate solution was added. These samples were discarded. More experimentation should have been carried out to find the most effective means of dispersing these carbonate-rich sediments, but the time available precluded it. In fact, these complete

[90] Krumbein, W. C., The dispersion of fine-grained sediments for mechanical analysis: Jour. Sedimentary Petrology, vol. 3, pp. 126–127, 1933.

[91] Krumbein, W. C., The mechanical analysis of fine-grained sediments: Jour. Sedimentary Petrology, vol. 2, pp. 144–146, 1932.

[92] Grippenberg, Stina, Sediments of the North Baltic and adjoining seas: Fennia, vol. 60, No. 3, pp. 60–70, 1934.

[93] According to C. S. Ross (personal communication), electrodialysis definitely breaks down some clay minerals and is, therefore, not satisfactory for dispersing fine-grained sediments.

mechanical analyses suffered throughout by reason of the press of other work that had to be done simultaneously.

Many minute crystals of calcium oxalate were found in most of the pipette samples, although none were ever found in the sediment [94] not treated with sodium oxalate. After the globigerina ooze (sample W–17) had been mechanically analyzed, the fine fraction that had passed through a 200-mesh sieve was analyzed for calcium oxalate by K. J. Murata of the Geological Survey chemical laboratory. He found that 5 percent by weight of this dried material consisted of calcium oxalate. Almost precisely 50 percent of the oxalate that had been introduced as sodium oxalate had been precipitated as calcium oxalate. As these calcium oxalate crystals are only a few microns across, they are concentrated in the fraction of sediment made up of the finest particles, which is correspondingly 5 percent heavier than in the original sediment.

The sample of blue mud (W–2) from core 3 was not properly dispersed, and of the sieved fraction made up of grains that range in size from 0.074 to 0.15 millimeter, 45 percent consists of clay aggregates. (See pl. 6.) The diatoms in this sample were coated with a thin film of clay, and clay flocs probably account for some other irregularities. (See fig. 10.)

In presenting the results of these mechanical analyses two methods have been used—pyramidal diagrams (pl. 6) and cumulative curves (fig. 10). In both, the size of particles less than 0.074 millimeter is calculated by Stokes law from the settling velocity. The sizes shown, therefore, are the sizes of ideal spheres that have the same mean density and the same settling velocity as those observed; they do not represent the true particle size, but they probably approximate it closely enough for this purpose. In calculating the sizes allowance was made for the mean grain density of the particles and the density and viscosity of the liquid at the time each pipette sample was taken. The mean grain densities were determined by P. G. Nutting of the Geological Survey.

In the pyramidal diagrams given in plate 6 the abcissae represent percentages by weight of each size group and the ordinates represent a logarithmic scale of the size ranges. Descriptive notes, with some estimates of proportions, have been added for each block or group of blocks in order to show, at least in a rough way, how the various constituents are distributed with respect to size. A few blocks will serve to illustrate how the characteristic features of certain sediments are revealed by these diagrams. The graph for sample W–13 from the top of the mid-Atlantic ridge shows that there is an abundance of sand concentrated in the size range 0.15 to 0.30 millimeter and that Foraminifera are also abundant but that their size range extends

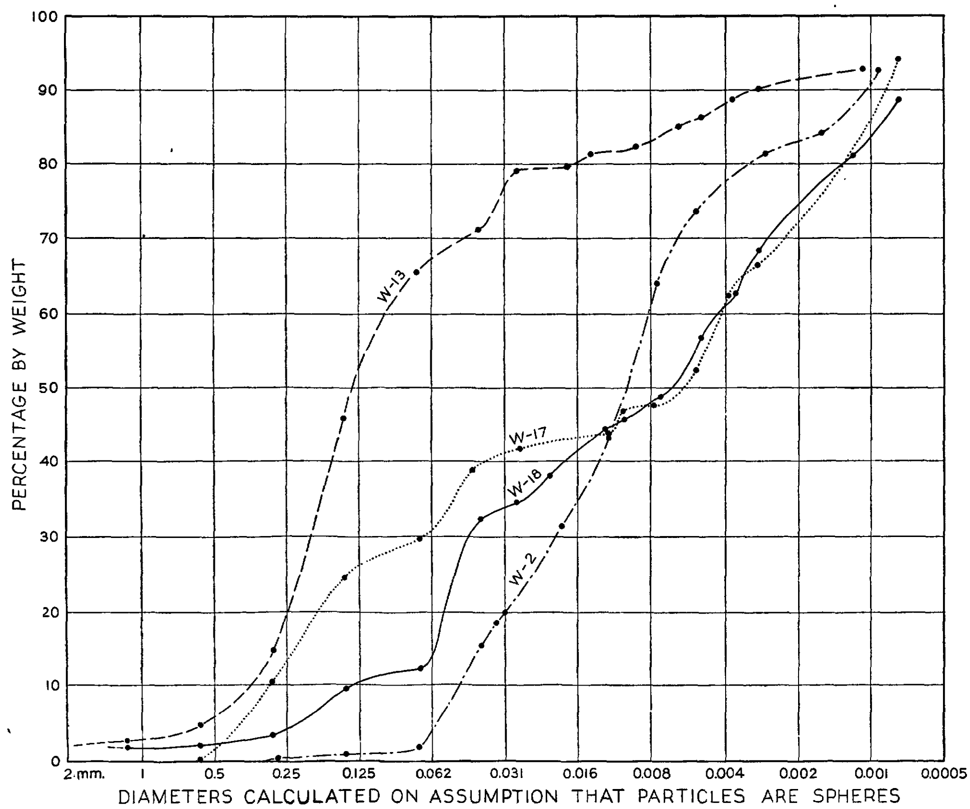


FIGURE 10.—Cumulative curves showing the size distribution of the organisms and mineral particles in samples representing sediments of four types. W–2, Blue mud (core 3); W–13, gravelly foraminiferal marl (core 8); W–17, globigerina ooze, and W–18, clay (site of core 10).

[94] Crystals of both calcium oxalate and citrate were found in the bottom deposits of the Weddell Sea by F. A. Bannister (Report on some crystalline components of the Weddell Sea deposits: *Discovery* Repts., vol. 13, pp. 60–69, Cambridge, 1936).

from 0.074 to 0.6 millimeter. The graph for sample W–18 shows a highly anomalous feature for a marine mud. Concentrated in the coarse silt range (between 0.04 and 0.74 millimeter) is an abundance of magnetite, augite, labradorite, and basaltic glass. This type of mud is discussed more fully on pages 32–34, where a complete chemical analysis of a similar sample (W–15) is also given. (See also dehydration curve, fig. 6.) Sample 18 also has a considerable number of coarse sand grains and pebbles, the presence of which seems explicable only on the assumption that they were dropped from an erratic iceberg that went far beyond the normal range of drift ice. (See pl. 1.) Consequently this sample is less satisfactory than one taken from the core itself, but this particular sample was chosen because it had been kept wet and was therefore easier to disperse. The mud that makes up the top of core 10, and is in all other respects identical with sample W–18, contains no particles larger than silt size. (See the gross mechanical composition as plotted in pl. 3, samples B–179 and B–180.) In the graph for sample W–17 (the globigerina ooze) the height of the blocks spanning the size range 0.001 to 0.003 millimeter should be reduced by about 5 percent because, as pointed out on page 29, they contain about 5 percent by weight of calcium oxalate, which is not a normal constituent of the sediment. Probably the other pyramidal diagrams should have a similar correction.

The cumulative curves of figure 10 also show that in sample W–13 a much larger percentage of the constituents are relatively coarse-grained, whereas in sample W–2 the dominant constituents are concentrated in the finer silt and clay sizes. These curves are markedly irregular, and although some of the irregularities are due to faulty dispersion of the sediment and to errors in size of the pipette samples, others are clearly due to concentrations of various constituents within fairly narrow ranges of size. For example, the high hump between sizes 0.031 and 0.062 millimeter on the curve for sample W–18 reflects the concentration of coarse silt-size grains of magnetite, augite, labradorite, and basaltic glass, already noted. So also the two humps on the curve for sample W–17, one at about 0.150 millimeter and the other between 0.031 and 0.062 millimeter evidently reflect the abundance of foraminiferal shells in the two size groups.

BASALTIC PYROCLASTICS AND THEIR ALTERATION

As pointed out earlier in the report, pumiceous fragments and smaller shards of basaltic volcanic glass are scattered throughout all the cores, but are somewhat more common east of the mid-Atlantic ridge than west of it. Rarely do these fragments make up as much as 1 percent of a sample. Notable exceptions to the general distribution of the basaltic glass are core 3, which contains very few pieces, and the unusual basaltic mud in core 10, which contains an abundance of basaltic glass. Although some samples contain more than others, this basaltic volcanic glass shows no conspicuous concentration either in distinct beds or in zones, as does the alkalic volcanic glass.

The basaltic glass generally appears to be homogeneous, is clear in thin slivers, and in transmitted light has a brown or greenish-brown color. In reflected light it is almost black. The index of refraction of the unaltered glass is between 1.59 and 1.60, and most of it is nearer 1.60. Basaltic glass of this type has been named sideromelane by Von Waltershausen.[95] According to Peacock and Fuller's terminology,[96] the less clear and less homogeneous basaltic glass containing many microlites would be termed tachylite. Tachylite is distinctly less common in these cores, but gradations from this type to granules of fine-grained basalt consisting of labradorite, magnetite, augite, and in some, olivine were found. Some of the clear basaltic glass contains minute phenocrysts of labradorite and augite. Larger pieces of the basaltic glass, a few of which are as much as a centimeter across, are vesicular and about as "frothy" as a pumice formed from more alkalic glass. Like the basaltic glass pumice noted by Murray,[97] it tends to have cavities that are more nearly spherical than those in most alkalic glass, which are generally elongate.

In many samples the basaltic glass has a thin surface film of an alteration product that may be classed under the broad term palagonite. (See pl. 7,*C*). This alteration product shows a considerable variation in properties, and although two distinct and common types were distinguished in the material studied, both are classed here as palagonite. One of these is nearly colorless and has a refractive index ranging from 1.49 to 1.52. The other, probably richer in iron, is yellow to amber-colored and its refractive index is much higher, ranging from 1.57 to 1.59. In the alteration film on some of the basaltic glass these two types of palagonite alternate with an agatelike interbanding, and in some of these alteration films not only are the two types of palagonite interbanded, but with them are equally thin laminae consisting of radiate needles of a birefringent mineral, apparently one of the clay minerals or possibly a chlorite mineral.

In the samples from core 9 the pieces of basaltic glass are generally fresh, with only a few showing very thin alteration films of the colorless palagonite that has the low index of refraction. The pieces of basaltic glass from cores 4, 5, 6, and 7 generally have alteration films. Some of these alteration films include both types of palagonite, and a few, on the more deeply altered pieces, include also laminae of the claylike mineral. But in cores 8 and 13 the pieces of basaltic

[95] Von Waltershausen, Sartorius, Über die vulkanische Gesteine in Sicilien und Island und ihre submarine Umbildung, pp. 202–204, Göttingen, 1853.

[96] Peacock, M. A., and Fuller, R. E., Chlorophaeite, sideromelane, and palagonite from the Columbia River Plateau: Am. Mineralogist, vol. 13, pp. 360–383, 1928.

[97] Murray, J., and Renard, A. F., Deep-sea deposits, *Challenger* Rept., p. 296, 1891.

glass are most conspicuously altered. Indeed, most of the grains and pieces are completely altered or contain only a small central nucleus of the basaltic glass. The alteration products in these more completely altered fragments are largely palagonite and a clay mineral resembling beidellite, but they commonly include minute prismatic crystals of a zeolite which, according to H. E. Merwin [98] of the Geophysical Laboratory, is probably phillipsite. (See pl. 7, A.) Lozenge-shaped crystals of an unidentified mineral were also found in the alteration product. Some of these minute crystals were isolated and submitted to Charles Milton, of the Geological Survey's chemical laboratory, who reported the following properties:

> The refractive indices range from 1.56 to 1.57, optically positive, strong dispersion both of bisectrices and optic axes ($\rho > \nu$). The crystals are flat, tabular parallel to 010 and have good development of 100, 201, and 001. The optic angle is medium-sized, and an axis emerges not far from the normal to 010. The crystals have excellent basal cleavage, indicating 001. The crushed fragments almost invariably show albite twinning, the fragments resting on the 001 cleavage; Carlsbad twinning was also observed. Good microchemical tests for calcium and aluminum were obtained. The crystals are insoluble in HCl and float in bromoform (density 2.80).
>
> Were it not that these crystals are apparently secondary, that they seem to be very much more fragile than feldspars, and that the optic angle is only moderate, they would unhesitatingly be called labradorite.

The degree of alteration of the basaltic glass in cores 8 and 13 is obviously greater than in core 9. This appears to be significant, as cores 8 and 9 are rather close together, and the difference in alteration is consistent throughout the length of these two cores. The sediment of core 9 evidently accumulated more rapidly and under less oxidizing conditions than that of cores 8 and 13 (see pp. 14–15), which suggests that perhaps the dominant factors in the alteration of basaltic glass on the ocean floor are the amount of oxygen in the water and the length of time the particles are exposed to the oxidizing water. The relation between alteration and oxidation is suggested by the composition of the basaltic glass and of the palagonitic alteration product given by Murray,[99] which show that most of the iron was changed from the ferrous to ferric form in the alteration from basaltic glass to palagonite. The same sort of thing is shown by Correns' analyses [1] of the light-brown glass rind of a basalt fragment dredged from the mid-Atlantic ridge. The iron determinations, in percent, from the analyses of Murray and Renard and of Correns are given in table 6.

TABLE 6.—*Relative oxidation of iron in fresh basaltic glass and in basaltic glass altered on the sea floor*

	Challenger analyses		*Meteor* analyses	
	Fresh glass (percent)	Altered rim (percent)	Fresh glass (percent)	Altered rim (percent)
Fe_2O_3	1.73	14.57	2.30	16.56
FeO	10.92	----------	7.55	.93

The oxygen in the bottom waters is derived from the cold polar surface water, which sinks in the higher latitudes and flows generally equatorward below the warmer, and therefore lighter, surface water of the middle latitudes. The amount of dissolved oxygen that is available for oxidizing particles on the ocean floor is therefore a function of the distance from the polar seas, the speed of the bottom current, and of the environmental conditions of the abyssal organisms that consume oxygen. Correns [2] has pointed out that in the deep parts of the ocean the constriction in the cross section of large, slow-moving currents where they flow across ridges on the ocean floor increases their velocity enough to winnow out the finest particles and thereby increase the proportion of coarse grain-size in the sediments accumulating on the ridges. Thus, in such sites where the bottom water moves relatively fast, oxygen-rich water is continuously in contact with the sediment, and the carbon dioxide formed by oxidation of organic matter in the sediment is continually swept away. But where the bottom water moves more slowly and in places sheltered by ridges, the oxygen content of the water close to the bottom decreases, and its carbon dioxide content increases. Wattenberg's [3] abundant data on the relation between oxygen content and depth in the equatorial Atlantic show clearly this oxygen diminution within a few hundred meters of the bottom, particularly in the western Atlantic.

On the other hand, not all the alteration of the basaltic glass occurred while the glass was exposed on the sea floor. Some of the alteration was a diagenetic change that occurred after the glass was buried in the sediment, as is indicated by a piece of vesicular basaltic glass from the lower part of core 5. This piece of basaltic glass scoria, which was nearly a centimeter in diameter, was embedded in a foraminiferal marl. The glass had a thin surficial film of the colorless palagonitic material of low refractive index, and a zone of the sediment surrounding the glass was stained buff with iron oxide. This stain faded out rather abruptly in all directions away from the nucleus of basaltic scoria.

[98] Oral communication.

[99] Murray, John, and Renard, A. F., Deep-sea deposits, *Challenger* Rept., p. 307, 1891.

[1] Correns, C. W., Die Sedimente des äquatorialen Atlantischen Ozeans: Auswertung der Ergebnisse: Wiss. Ergeb. Duetschen Atlantischen Exped. *Meteor*, 1925–27, Band, 3, Teil 3, Lief. 2, pp. 288–289, 1937.

[2] Correns, C. W., Anzeichen von Beziehungen zwischen Strömungen und Bildung küstenferner (eupelagischer) Sedimente: Neues Jahrb., Beilage-Band 57, Abt. A., pp. 1109–1117, 1928.

[3] Wattenberg, H., Die deutsche atlantische Exped. *Meteor;* Bericht über die chemischen Arbeiten: Gesell. Erdkunde Berlin Zeitschr., pp. 309–314, 1927.

The depth of alteration and the variety of alteration products derived from the basaltic glass contrast sharply with the freshness of the alkalic volcanic glass in the upper and lower ash zones of these cores.

VOLCANIC ROCK IN CORE 11

Core 11 represents only 34 centimeters of the sea floor because of the hard rock encountered at this depth. The hardest rock at the base of this core is an olivine basalt, according to Dr. H. E. Merwin,[4] of the Geophysical Laboratory, who examined a thin section of it. The upper 15 centimeters of the core is a globigerina ooze, which rests on and within irregular cavities of the upper surface of a clayey rock illustrated in plate 7, *B*. This clayey rock grades downward through closely similar rock that is strongly impregnated with manganese oxide and that contains nodular lumps of much altered basalt. Below the manganiferous part the clayey rock grades into the hard, more nearly fresh basalt at the base. The lower part of this core is described in some detail because it suggests that the material represents an altered rock which may be a submarine lava flow, though the evidence is inadequate and additional cores in that area are necessary to test this possibility.

The material immediately beneath the globigerina ooze (see pl. 7, *B*) is composed largely of a clay mineral resembling beidellite. Within this clay are scattered grains of more or less rounded sand and foraminiferal shells. The Foraminifera include globigerinas and other calcareous types like those that occur in the overlying ooze, but their original calcium carbonate tests have been replaced by a zeolite resembling phillipsite. (See pl. 7, *C*.) Some of the lozenge-shaped crystals of the unidentified mineral described on page 31 are also present in the clay matrix. In places this clay matrix contains brown films that outline "ghost" areas of shapes resembling shards and pumiceous fragments. The similarity of this clayey rock in form and mineral composition to the small altered fragments of basaltic glass in cores 8 and 13 suggests that this clayey part of the rock is altered basaltic glass. The gradation downward from clay that has a vesicular upper surface (see pl. 7, *B*) through manganese-stained clay that contains lumps of deeply altered basalt into comparatively fresh olivine basalt at the base suggest the possibility of a submarine lava flow which, in moving over the bottom, incorporated some of the sand, Foraminifera, and other bottom sediments in its more brecciated and apparently glassy surface part. The alteration of this glassy surface part is obviously much more complete and deep than the alteration rims of the small fragments of basic volcanic rock scattered through the sediment of the other cores. The greater depth of alteration of this rock may have been due to the heat supplied by a large mass of lava. This heat may also have accounted for the replacement of the calcium carbonate of the foraminiferal tests by the zeolite—a reaction not found elsewhere in these sediments. Much of the manganese in the lower part of this core is in the form of small, ellipsoidal pellets separated more or less distinctly from one another by thin lenses or irregular layers of clay-like material. This is very closely similar to the manganese-impregnated zone around the basalt pieces dredged by the *Discovery* from the Carlsberg Ridge.[5] The presence of hard and nearly unaltered basalt at the base of this core would not necessarily indicate that all the brecciated and altered zone of the supposed flow rock had been penetrated, for this fresh rock may be only a larger and therefore not completely altered fragment similar to the smaller, more deeply altered, but nevertheless crystalline lumps of basalt in the clay matrix above.

If this rock in core 11 represents an unusually large boulder of basaltic rock of ice-rafted origin, it must have been altered after it reached the sea floor, because the soft, clayey zone of altered material could hardly have been preserved during the plucking and transportation by ice. If it is a transported boulder whose alteration occurred on the sea floor, it is peculiar that the alteration should be so much more extensive than is found on the small pieces of basaltic glass and other basic rock scattered through the cores; furthermore, such a hypothesis would leave quite unexplained the conversion of the tests of pelagic Foraminifera to the zeolite. The possibility that the rock represents a volcanic island which subsided so recently that only 15 centimeters of globigerina ooze has accumulated on it seems rather improbable and also leaves unexplained the type of alteration and the replacement of the tests of the pelagic Foraminifera.

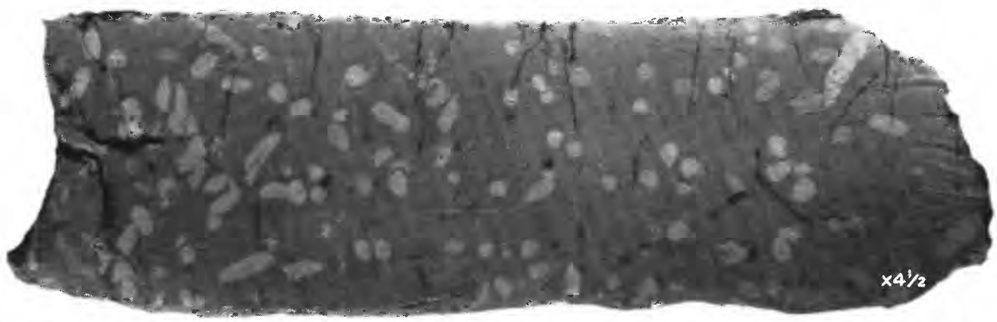
The globigerina ooze overlying the altered volcanic rock in core 11 does not contain shards of alkalic volcanic glass of the upper ash zone, as do the tops of all the other cores. This absence of shards may not be of much significance, for in the other cores the shards decrease in abundance upward and are rather sparse at the top. On the other hand, the absence of shards from the upper part of core 11 might mean that a submarine lava flow had been extruded on the sea floor above the upper ash zone, which it covered and partly incorporated. According to this hypothesis, no ash-bearing sediment is accessible so that it can be reworked into the uppermost layer of globigerina ooze.

BASALTIC MUD IN CORE 10

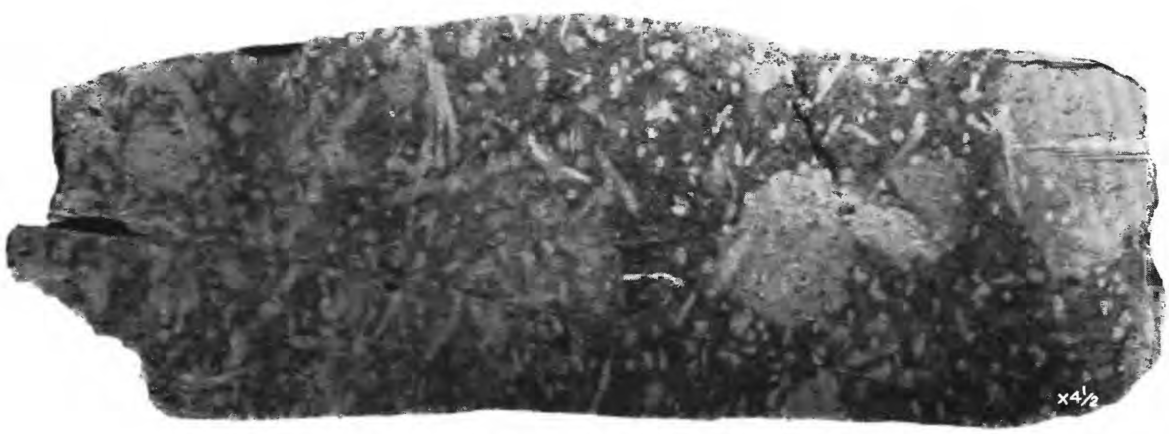
The sediment in core 10 differs from all the others by reason of a large proportion of highly distinctive clayey mud. As noted on page 6, the coring device buried itself in the soft mud at this station. From the glo-

[4] Oral communication.

[5] Wiseman, J. D. H., Basalts from the Carlsberg Ridge, Indian Ocean: British Mus. (Nat. Hist.), John Murray Exped., Sci. Rept., vol. 3, No. 1, pp. 4-5, fig. 2-A, 1937.

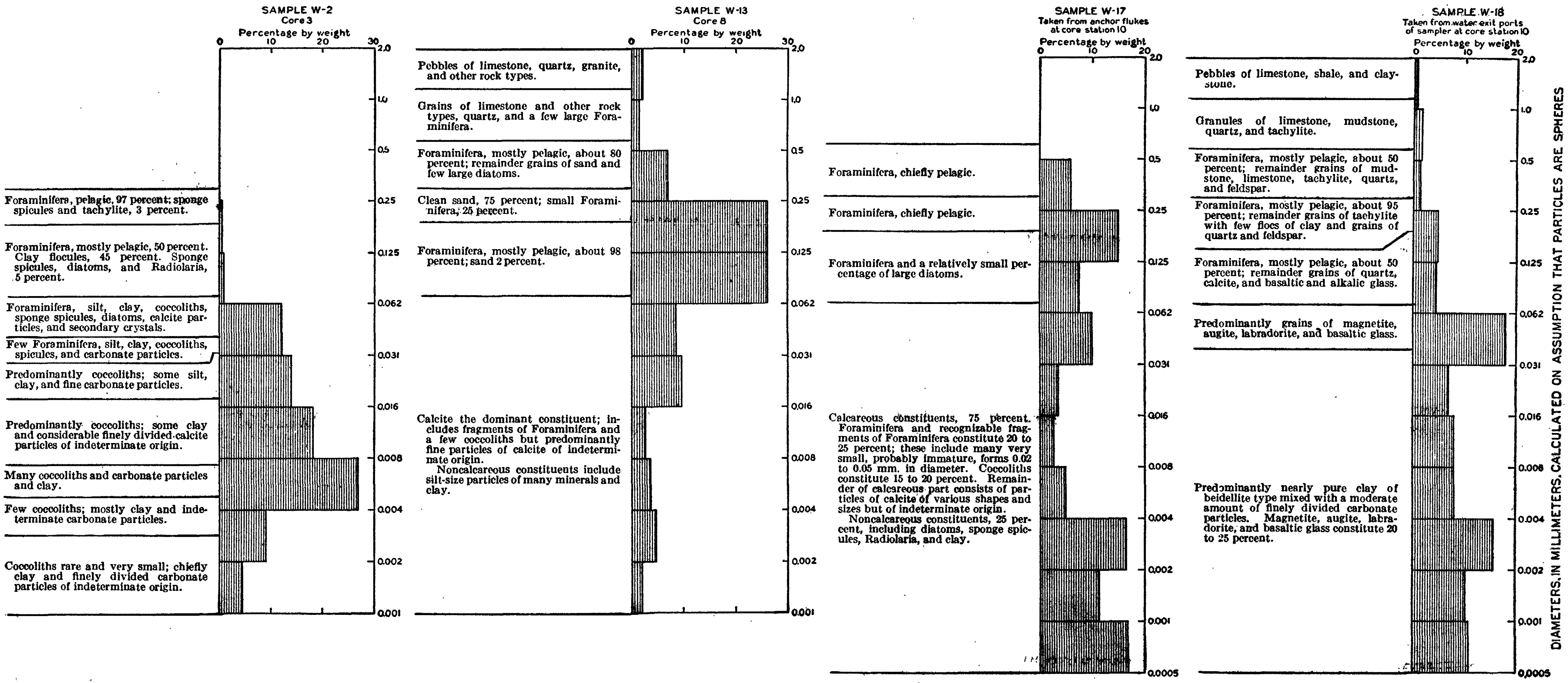


A. FECAL PELLETS OR FILLED BORINGS IN THE BASALTIC MUD AT THE TOP OF CORE 10. SAMPLE B-179.



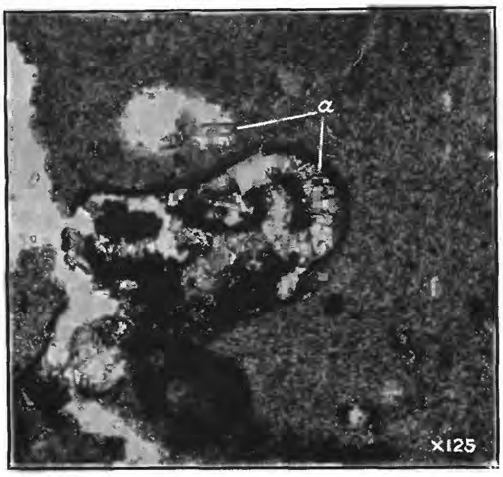
B. FECAL PELLETS IN MUDDY FORAMINIFERAL MARL NEAR THE TOP OF CORE 12.

Some of the long tubular bodies may perhaps be filled borings. The large, irregular, roundish pellets or lumps are rather common in the glacial marine deposits, but their origin is unknown. Sample B-207.

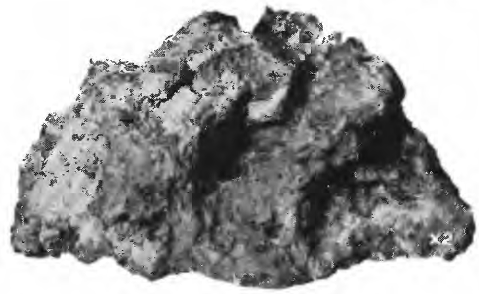


STANDARD PYRAMID DIAGRAM SHOWING THE SIZE DISTRIBUTION, KINDS OF ORGANISMS, AND MINERAL PARTICLES IN SEDIMENTS OF FOUR TYPES FROM THE NORTH ATLANTIC.

Sample W-2, blue mud from core 3; sample W-13, a gravelly foraminiferal marl from core 8, top of mid-Atlantic ridge; sample W-17, a fine-grained globigerina ooze taken from anchor flukes at site of core 10; sample W-18, a distinctive clay like that in the upper part of core 10, taken from water-exit ports of coring device when core 10 was hauled aboard.

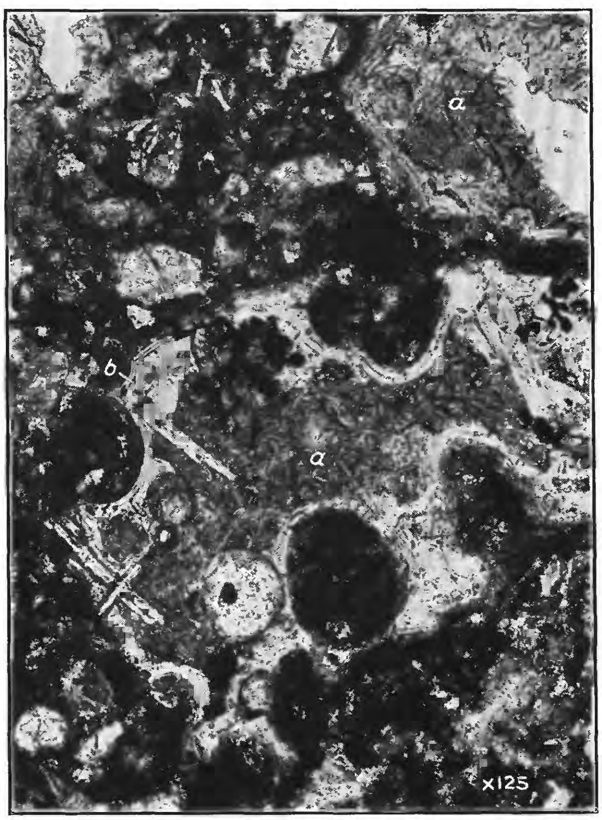


A. ZEOLITE CRYSTALS (*a*) PROBABLY PHILLIPSITE, IN THIN SECTION OF THE CLAYEY ROCK SHOWN IN 7, *B.*



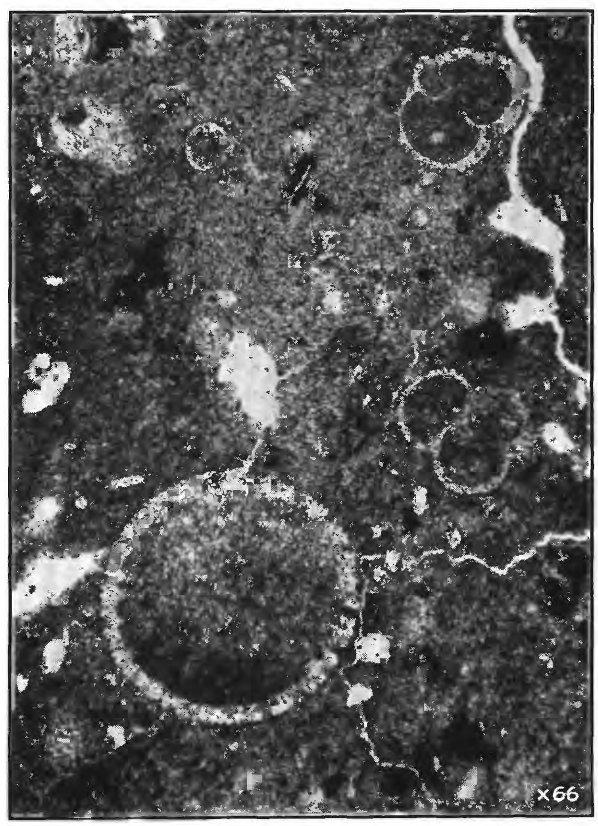
B. VESICULAR UPPER SURFACE OF CLAYEY ROCK THAT IS INTERPRETED AS AN ALTERATION PRODUCT OF THE BASALTIC LAVA AT THE BOTTOM OF CORE 11.

The surface of this clayey rock appears to have retained the vesicular form of a lava.



C. PALAGONITE RIMS SURROUNDING FRAGMENTS OF UNALTERED BASALTIC GLASS.

Basaltic glass at *a*. Delicate concentric banding within the palagonite rims is visible at *b*.



D. FORAMINIFERA SHELLS REPLACED BY A ZEOLITE RESEMBLING PHILLIPSITE.

These are embedded in the clayey rock shown in 7, *B*.

bigerina ooze collected from the anchor flukes we know that the floor of the sea is covered with normal globigerina ooze, and from the presence of mud in the water-exit ports 32 centimeters above the top of the core we know that the peculiar mud at the top of the core was at least a little thicker than is represented in the core. Approximately 1 meter at the bottom of this core and 80 centimeters at the top consist of the distinctive mud—a homogeneous, dark-gray sediment that shrank greatly upon drying. (See pl. 2.) Although about 50 percent of this mud is made up of silt-sized particles of basaltic glass, magnetite, augite, and calcic plagioclase, it contains but little quartz sand or other common clastic material, and exceedingly few Foraminifera. The remainder of this mud consists predominantly of clay minerals resembling beidellite or hydromica. The distribution of these constituents is shown in the diagram, plate 6 (sample W–18), which is based on a complete mechanical analysis of this same type of mud that was collected from the water-exit ports of the coring device. As noted on page 30, however, that particular sample was abnormal because it contained some coarse sand and pebbles.

A few normal and common types of pelagic and bottom-dwelling Foraminifera were found in the uppermost part of core 10 (sample H–95). In sample W–18, which came from the water-exit ports of the coring device, above the top of the core, pelagic Foraminifera are rather common (see pl. 6), but, as Foraminifera are virtually absent from the lower part of the upper clayey mud zone and increase in abundance at the top, it is suggested that this mud may grade upward into the overlying globigerina ooze, just as the lower clayey mud zone grades into the foraminiferal marl between the mud zones. The basal part of the upper mud zone (B–182) is somewhat more silty and has a sharp contact with the underlying foraminiferal marl. (See pl. 2.)

A sample of this basaltic mud (W–15), taken 67 centimeters below the top of core 10, was analyzed by E. T. Erickson in the chemical laboratory of the Geological Survey. Before analysis this sample was leached of its sea salts in distilled water, as is shown by the small amount of Cl reported. This analysis is given here as reported and also recalculated to 100 percent without calcium-magnesium carbonate. In this recalculation it was assumed that all the carbon dioxide was present in the form of carbonates and that the CaO and MgO were combined with it in the same proportions that they were found to be present in the fraction of the sample soluble in hot dilute HCl. This analysis was recalculated on a carbonate-free basis so as to compare it with analyses of other sediments on a carbonate-free basis. The analysis of this basaltic mud is not much like those of the common sediments, shale, mudstone, or clay; nor, on the other hand, is it like the analyses of basalt. It is surprisingly similar, however, to the analysis of a large group of oceanic red clays, despite the fact that the basaltic mud is quite unlike the red clays in appearance and mineral composition. (See table 7, B and C.) The most striking difference between these two analyses is the state of oxidation of the iron. More than half the iron in the mud from core 10 is in the ferrous state, whereas less than one tenth of that in the red clays is ferrous iron.

TABLE 7.—*Analyses of mud from core 10 (Sample W–15) and oceanic red clays*

	A	B	C
SiO_2	44.14	52.27	54.48
Al_2O_3	12.44	14.73	15.94
Fe_2O_3	5.74	6.80	8.66
FeO	3.22	3.81	.84
MnO_2	Not det.	--	1.21
MgO	3.94	2.65	3.31
CaO	10.32	2.76	1.96
Na_2O	1.31	1.55	2.05
K_2O	2.19	2.59	2.85
H_2O-	3.66	4.33	7.04
H_2O+	5.48	6.49	
TiO_2	1.52	1.80	.98
CO_2	6.28	--	--
P_2O_5	.05	.06	.30
SO_3	.12	.14	--
Cl	.02	.02	--
BaO, Cr_2O_3, CuO, and other rare constituents	Not det.	--	.38
	100.43	100.00	100.00

A. Sample taken 67 centimeters below top of core. Analysed by E. T. Erickson.
B. Analysis A recalculated as free from $CaCO_3$, $MgCO_3$.
C. Composite of fifty-one samples of "red clay." Analyzed by G. Steiger, with special determinations by W. F. Hillebrand and E. C. Sullivan.

Although the chemical composition of the basaltic mud in core 10 is similar to that of the red clays we believe the basaltic mud probably had a quite different origin and history. The abundance of basaltic minerals and fresh basaltic glass points to a volcanic source, and the extreme scarcity of Foraminifera and coccoliths suggests deposition so rapid that they were masked out by the bulk of the other material.

Basaltic particles comparable with those found in the basaltic mud zones of core 10 presumably were discharged into the water of the Mediterranean over the Nerita Bank off the coast of Sicily during the submarine eruption of 1831, for according to Washington's [6] account "* * * the surface of the sea was seen to rise to a height of 80 feet, the column maintaining itself for 10 minutes, and then again sinking down. This was repeated every quarter to half an hour, and was accompanied by a dense cloud of black smoke and loud rumblings." The black smoke presumably consisted of basaltic dust particles.

It is perhaps futile to speculate further upon the possible origin of the volcanic muds in core 10. Nevertheless, the basaltic composition, the restriction to core 10, and the fact that the upper mud zone has, at least approximately, the same stratigraphic position as the volcanic rock in core 11 suggests a genetic relationship with deeply altered volcanic rock like that found in core 11.

The clay particles and basaltic grains in the greater part of this upper mud zone make up a homogeneous

[6] Washington, H. S., The submarine eruptions of 1831 and 1891 near Pantelleria: Am. Jour. Sci., 4th ser., vol. 27, pp. 133–134, 1909.

mixture in which there is no discernible tendency (other than the comparatively thin basal silty layer) toward size gradation according to different settling velocities. This suggests that the bulk of the material did not settle at the site of this core from a cloud of particles thrown into suspension. Had the material been diffused upward even a few meters in such a suspension, most of the dense, silt-sized mineral and glass particles would have settled out from the cloud of minute particles of flaky clay minerals. A submarine volcanic eruption, perhaps in the vicinity of core 11, may have discharged into the sea finely divided basaltic particles and at the same time have thrown into suspension much clay, derived largely from the deeply altered surface of earlier submarine lava flows. Such a mixture of material, having settled to the bottom, would, by reason of its fine grain, make a quite labile sediment that would tend to collect in the deeper depressions or areas on the sea floor. It might move into these lower places either as mud flows on gentle slopes or by reworking under the influence of bottom currents, perhaps set up by the eruption. The homogeneity of the basaltic mud zones in core 10, with the sharply defined base (of the upper one) and gradational upper parts, suggests that most of the material reached its present site as mud flows and that mud-feeding animals reworked the uppermost material long thereafter, so that it grades upward into the overlying sediment. That mud-feeding animals were effective in reworking the upper part of the basaltic mud is indicated by the abundance of coprolitic pellets and mud-filled borings in the mud at the top of core 10. (See pl. 5, *A*.)

Additional cores in the part of the North Atlantic where cores 10, 11, and 12 were taken should prove to be of exceptional interest, for it is only in this way that submarine volcanic activity and its extent can be definitely established. Such information might also reveal the time of the postulated volcanic activity and perhaps, as suggested on page 7, relate it to foundering of a part of the Thulean basaltic province, which includes part of northwestern Scotland, northern Ireland, Iceland, Jan Mayen, and southwestern Greenland.

As with so many phases of this work, only with additional and longer cores can the questions raised in this investigation be satisfactorily answered.

Part 2. FORAMINIFERA

By Joseph A. Cushman and Lloyd G. Henbest

PREPARATION OF SAMPLES

The procedure followed in sampling the cores from the North Atlantic was essentially the same as that described in the report on a deep-sea core collected in 1935 southeast of New York City.[1] The cores were split longitudinally into two parts and allowed to dry before they were sampled. With drying, most of the sediments became hard enough to be handled more or less like indurated rock, so that it was possible to remove with a hacksaw segments from any part of a core desired. Several of the globigerina oozes, however, remained friable, and required a different method of sampling.

At the outset it was decided that to examine thoroughly every centimeter of the cores would require more time and assistance than we could devote to this study; so, it was necessary either to take long samples and thereby run the risk of combining different facies, or to take short but representative samples from every lithologic zone. Inasmuch as such zones were recognizable by differences in texture, color, composition, manner of contracting on drying, or other peculiarities, the latter plan was not only feasible but gave opportunity to obtain data that are more significant. In addition to some supplementary sampling for studies not recorded separately, 184 samples were taken from the cores. These are indicated as the "H" series of samples, except three which are indicated as belonging to the "B" series.

To avoid contamination, constant care was exercised in all operations. Each zone of friable sediment was cleared as far as possible of extraneous material, and the sample was scooped out with a small spoon shaped from thin sheet iron. The difficulty of avoiding contamination can easily be appreciated, yet it is almost certain that whatever contamination existed was insufficient to change the results of the paleontologic studies. Fortunately, only a few zones of very friable sediment were encountered. Most of the sediment was hard enough after drying to be handled and to withstand without breakage the trimming away of the thin layers of dragged material that were formed on the outside of the core by the core barrel and through the center of the core by the band saw used for splitting the cores. Generally it was easy to distinguish the layer of extraneous material from the undisturbed sediment. The zone of drag on the outside of the cores was, in most places, only 2 to 4 millimeters deep, but locally this depth was increased by the presence of pebbles.

The samples were very carefully washed through 200-mesh bolting silk, constant care being taken to avoid contamination. After drying, each sample was searched for metazoan fossils as well as for unusual foraminifers and lithologic specimens. The sample was then divided and about three-fifths of it, along with foraminifers that were picked out during the search for metazoan fossils, was sent to the Cushman Laboratory, where Miss Frances L. Parker thoroughly searched the samples for Foraminifera and arranged and mounted the specimens.

[1] Cushman, J. A., Henbest, L. G., and Lohman, K. E., Notes on a core sample from the Atlantic Ocean bottom southeast of New York City: Geol. Soc. America Bull., vol. 48, p. 1298, 1937.

ACKNOWLEDGMENTS

The samples were washed by F. S. MacNeil of the Geological Survey. The authors are especially indebted to Miss Frances L. Parker of the Cushman Laboratory, who searched the samples for Foraminifera and made a preliminary classification of the specimens, and to W. H. Bradley of the Geological Survey for a very careful criticism of the text. The illustrations on plates 8–10 were drawn by Miss Patricia G. Edwards of the Cushman Laboratory.

DISTRIBUTION IN THE CORES AND LIST OF SPECIES

The species of Foraminifera found in the cores are divided into two groups, according as they are of pelagic or bottom-living habit, and their distribution in each core is plotted on a separate chart. (See figs. 11–21.) The numbers in the following list of species correspond with those appearing on the charts (figs. 11–21). Some of these Foraminifera listed have not been specifically identified, because specific identification would involve considerably more detailed work than has been attempted for this paper.

PELAGIC SPECIES

1. *Globigerina pachyderma* Ehrenberg. (Living habits are not definitely known, but despite the fact that it is apparently bottom-dwelling during a part if not all of its life history, it has been included with the other globigerinids among the pelagic forms.)
2. *Globigerina bulloides* D'Orbigny.
3. *Globigerina inflata* D'Orbigny.

4. *Globorotalia scitula* (H. B. Brady). (Not definitely known to be pelagic.)
5. *Globorotalia hirsuta* (D'Orbigny).
6. *Globorotalia truncatulinoides* (D'Orbigny).
7. *Globorotalia menardii* (D'Orbigny).
8. *Orbulina universa* D'Orbigny.
9. *Globigerinoides rubra* (D'Orbigny).
10. *Globigerinoides conglobata* (H. B. Brady).
11. *Globigerinella aequilateralis* (H. B. Brady).

BOTTOM-DWELLING SPECIES

12. *Karreriella bradyi* (Cushman).
13. *Quinqueloculina oblonga* (Montagu).
14. *Quinqueloculina venusta* (Karrer).
15. *Massilina tenuis* (Czjzek).
16. *Sigmoilina schlumbergeri* A. Silvestri.
17. *Triloculina tricarinata* D'Orbigny.
18. *Pyrgo murrhina* (Schwager).
19. *Pyrgo serrata* (L. W. Bailey).
20. *Pyrgo irregularis* (D'Orbigny).
21. *Ophthalmidium acutimargo* (H. B. Brady).
22. *Ophthalmidium inconstans* (H. B. Brady).
23. *Nonion barleeanum* (Williamson).
24. *Nonion pompilioides* (Fichtel and Moll).
25. *Nonion* sp. (?).
26. *Bolivinita* ?, n. sp. (?).
27. *Bulimina aculeata* D'Orbigny.
28. *Bulimina inflata* Seguenza.
29. *Bulimina rostrata* H. B. Brady.
30. *Buliminella elegantissima* (D'Orbigny).
31. *Virgulina subdepressa* H. B. Brady.
32. *Virgulina advena* Cushman.
33. *Virgulina campanulata* Egger.
34. *Bolivina* sp. (?).
35. *Bolivina subspinescens* Cushaman.
36. *Uvigerina* sp. *A*.
37. *Uvigerina* sp. *B*.
38. *Uvigerina* sp. *C*.
39. *Uvigerina* sp. *D*.
40. *Eponides umbonata* (Reuss).
41. *Gyroidina soldanii* D'Orbigny.
42. *Patellina corrugata* Williamson.
43. *Epistomina elegans* (D'Orbigny).
44. *Pulvinulinella* sp. *A*.
45. *Pulvinulinella* sp. *B*.
46. *Cassidulina subglobosa* H. B. Brady.
47. *Cassidulina crassa* D'Orbigny.
48. *Cassidulina laevigata* D'Orbigny.

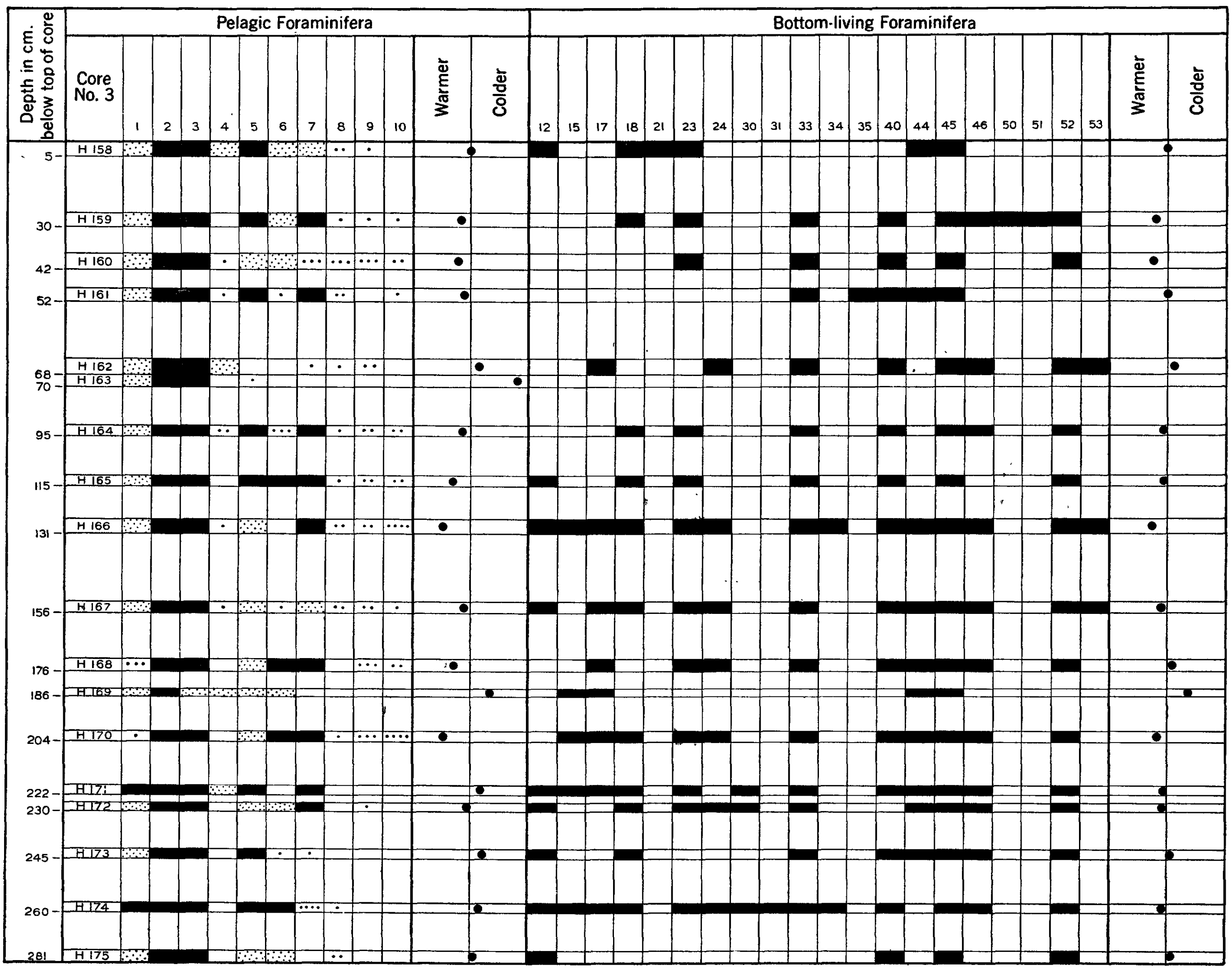


FIGURE 11.—Distribution and temperature significance of Foraminifera in core 3.

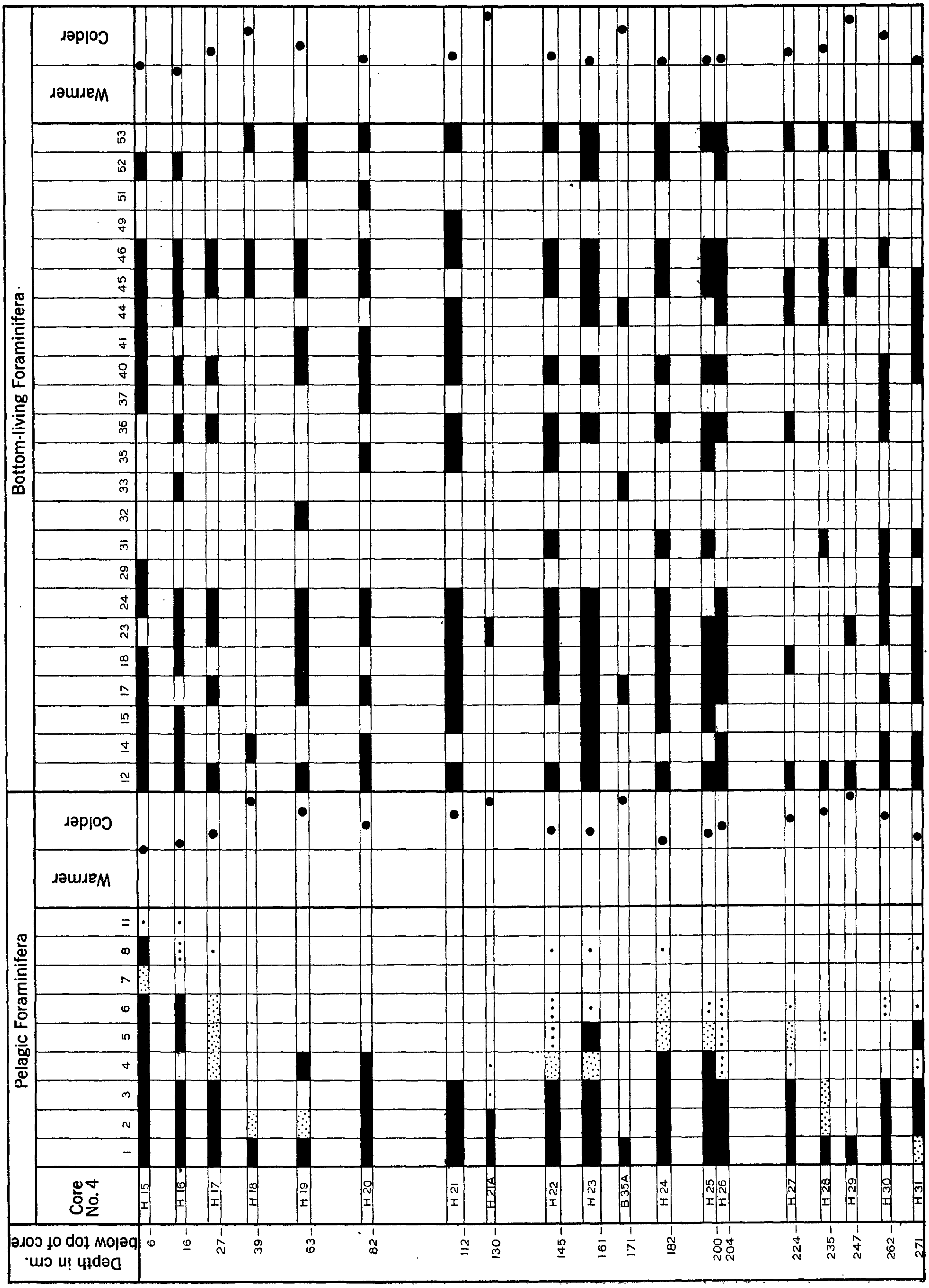


FIGURE 12.—Distribution and temperature significance of Foraminifera in core 4.

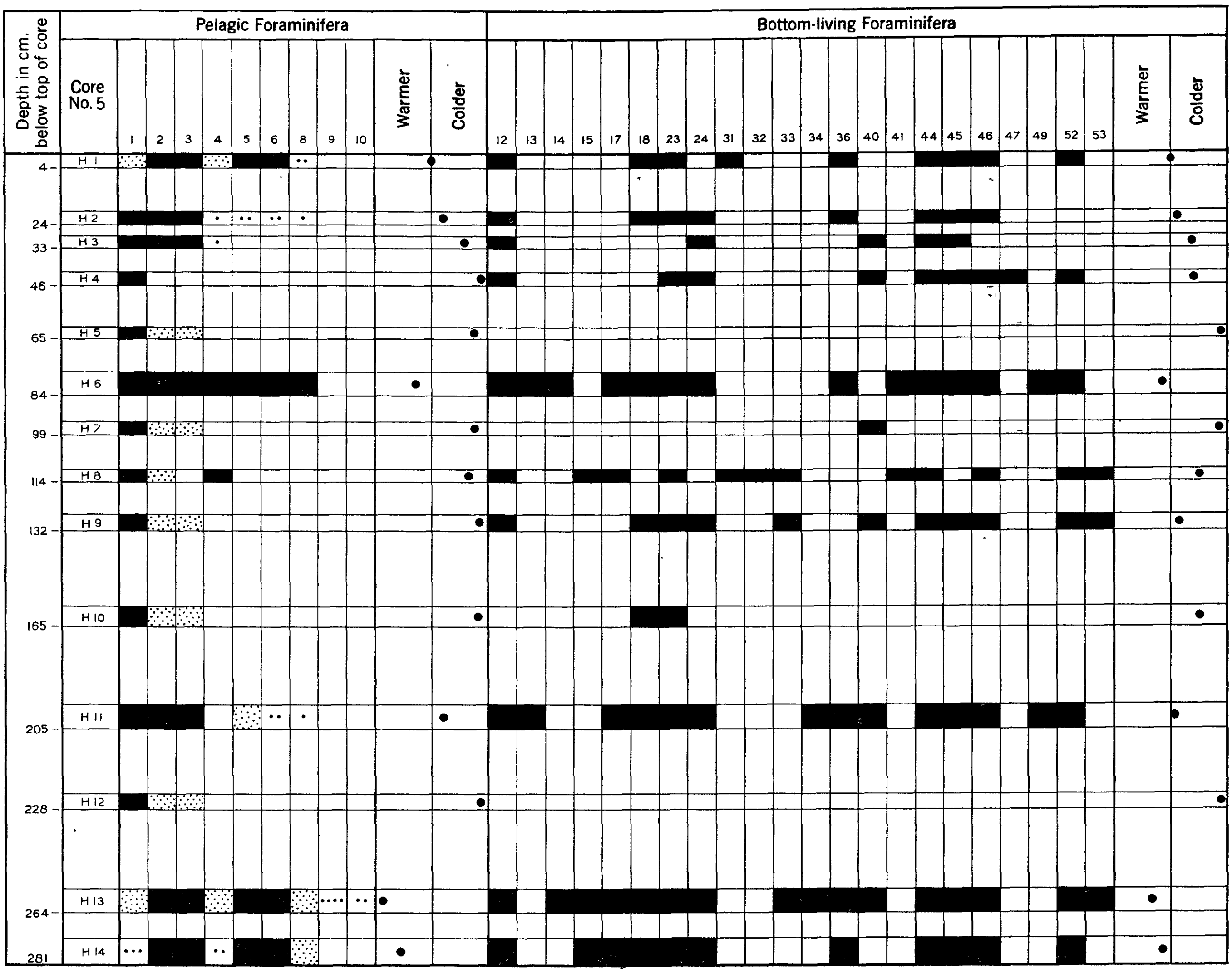


FIGURE 13.—Distribution and temperature significance of Foraminifera in core 5.

49. *Ehrenbergina serrata* Reuss.
50. *Chilostomella ovoidea* Reuss.
51. *Sphaeroidina bulloides* D'Orbigny.
52. *Pullenia sphaeroides* D'Orbigny.
53. *Pullenia quinqueloba* (Reuss).
54. *Rupertia stabilis* Wallich.
55. *Laticarinina pauperata* (Parker and Jones)
56. *Elphidium* sp. (?).

The specimens illustrated on plates 8–10 represent the character of the species used in this work for temperature determinations even though their exact nomenclature or classification cannot now be presented. The specimens illustrated were taken, wherever possible, from the surface or topmost sample of a core.

On the charts (figs. 11–21) the first two columns show the number and depth of each sample. The vertical length of the sample and its position in centimeters below the top of the core are plotted as nearly as possible to scale. Three of the samples have the letter B before the number (B–35A in core 4; B–108 and B–109½ in core 8). All others have prefixed the letter H.

For the pelagic forms a black rectangle indicates that the particular species is abundant or common; a stippled rectangle indicates 6 to 25 specimens; and 1 to 5 dots in a rectangle represent the exact number of specimens found.

For the bottom-dwelling forms a black rectangle indicates merely the presence of one or more specimens. Not all bottom-living species were plotted, because lack of time for an exhaustive study prevented giving attention to rare specimens, to species found in only one core, or to species that otherwise appeared to have little significance. For this reason the relative abundance of bottom-living species was not estimated.

The temperature significance was determined and plotted separately for the pelagic and the bottom-living Foraminifera. Relative temperature is indicated in the columns headed "warmer" and "colder" by large black dots so plotted as to show departures from the norm (represented by the vertical line separating the two columns), which is based on the temperature conditions exhibited by the Foraminifera in the top sample of each core and thus represents the present-day temperature of the water at that collecting station.

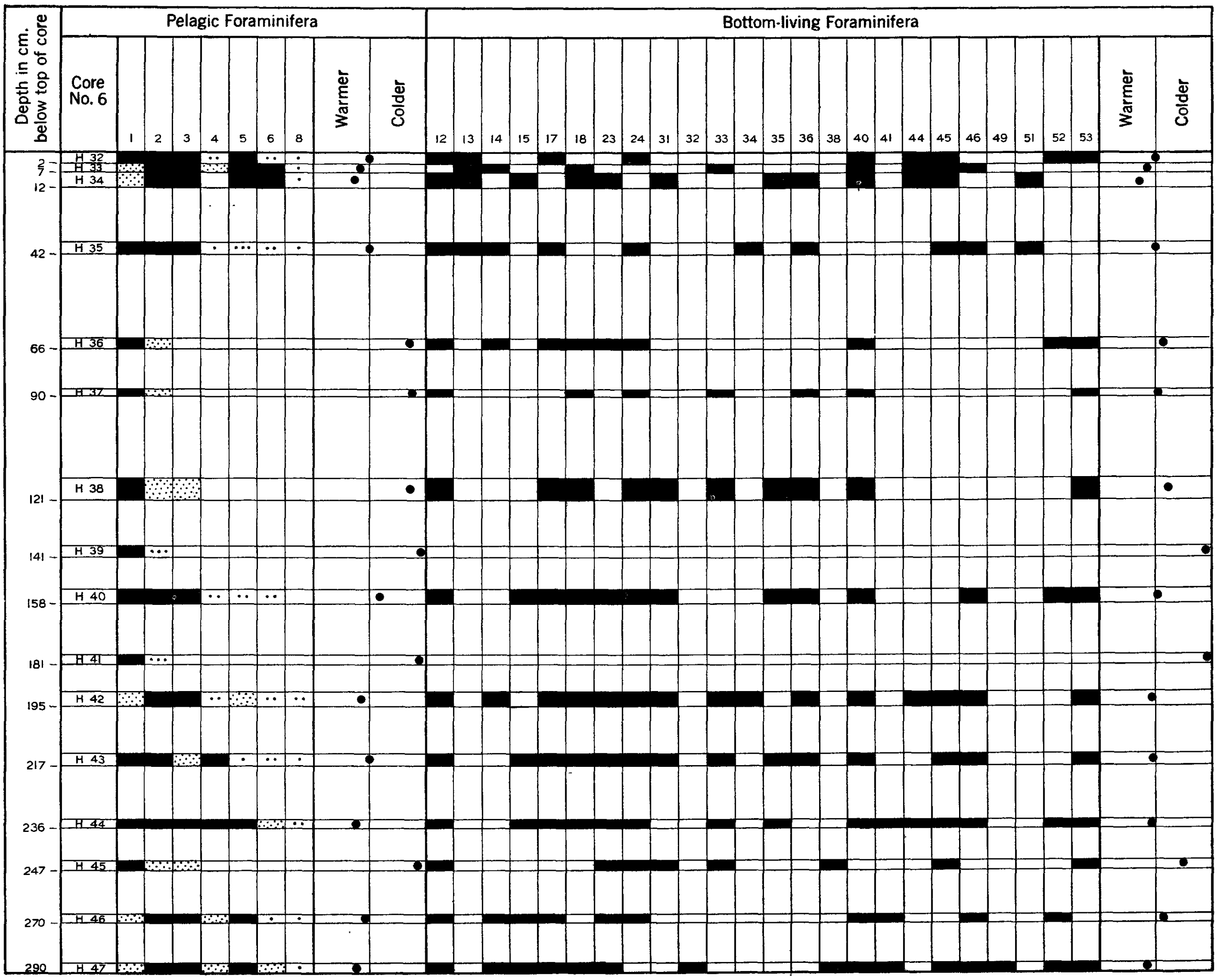


FIGURE 14.—Distribution and temperature significance of Foraminifera in core 6.

PELAGIC FORAMINIFERA

Although the record of foraminifers that have a pelagic habit is probably incomplete, enough townet samples have been taken from the seas to demonstrate that comparatively few genera and species occupy the pelagic realm.

The pelagic species of the world belong to the genera *Globigerina, Globigerinoides, Globigerinella, Orbulina, Hastigerina, Hastigerinella, Pulleniatina, Sphaeroidinella*, and *Candeina*, all of which are members of the family Globigerinidae, and to the globorotalid genera *Globotruncana* and *Globorotalia*. *Tretomphalus* is free swimming during the later part of its life but is normally restricted to near-shore or shallow-water areas.

Approximately 26 species of pelagic habit have been described. This small number of species and genera and their general similarity of shell morphology and moderate size may make them appear, from the standpoint of taxonomy, as insignificant members of the order Foraminifera, but the principal pelagic species produce an enormous number of individuals. They have been in the first rank of recognizable lime-precipitating agents during and since the middle of the Mesozoic. The small number of pelagic species and their comparatively simple taxonomy, their independence of local bottom conditions that do not disturb the chemical and physical stratification of the water, and their exceptionally broad distribution within their marine climatic realms make them a valuable source of information on paleoecology.

All the globigerinids in the core samples except *Globigerina pachyderma*, an Arctic species, are supposed to be pelagic. The globigerinids characteristic of very warm surface water were not found in abundance in the top samples of the cores, but in some of the lower zones in several cores warm-water species are present in great abundance, thus indicating that at the time when the sediments of these zones were deposited the Gulf Stream must have extended farther north than it does at the present time.

The fauna at the top of each core reflects the temperature of the present time and may, therefore, be

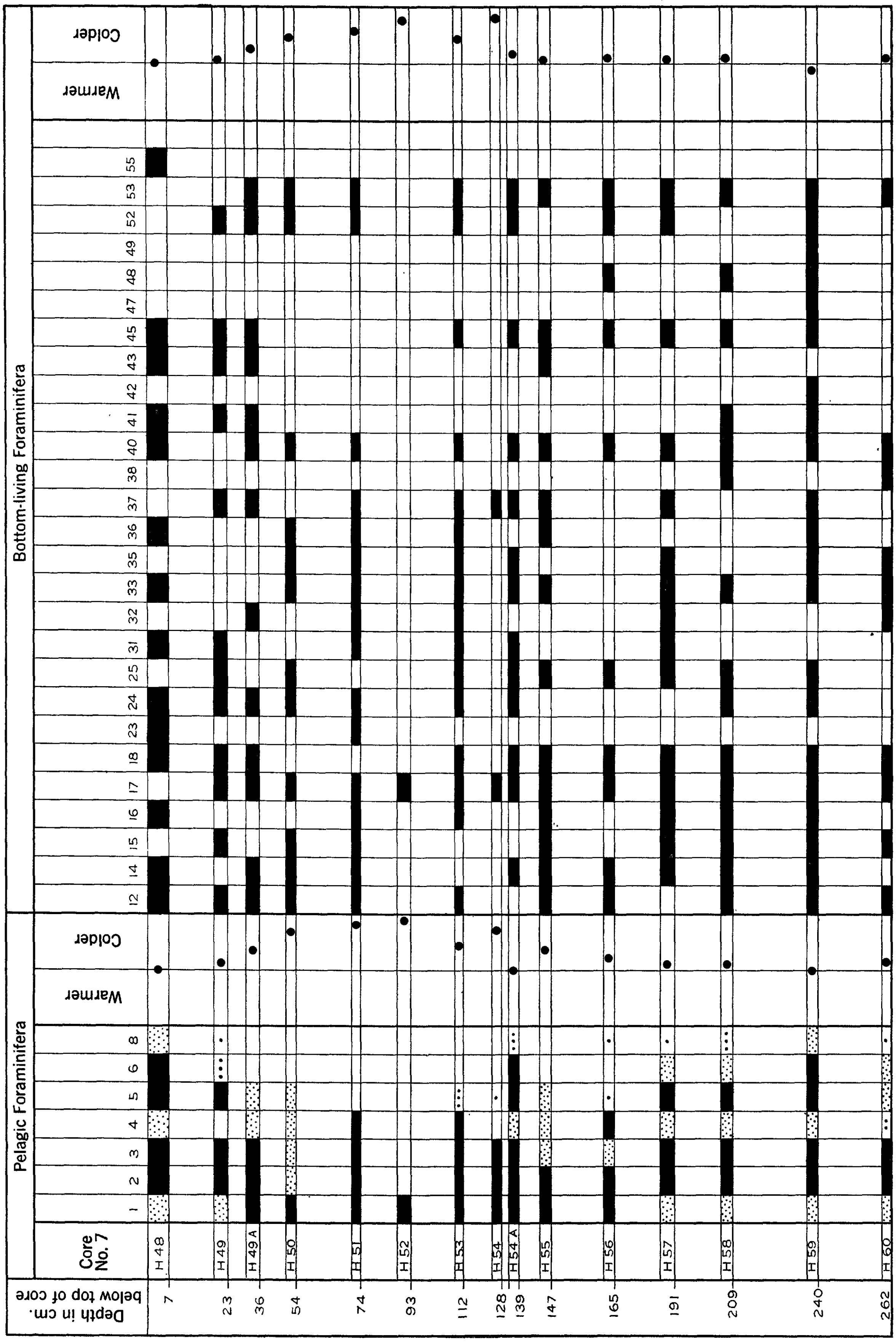


FIGURE 15.—Distribution and temperature significance of Foraminifera in core 7.

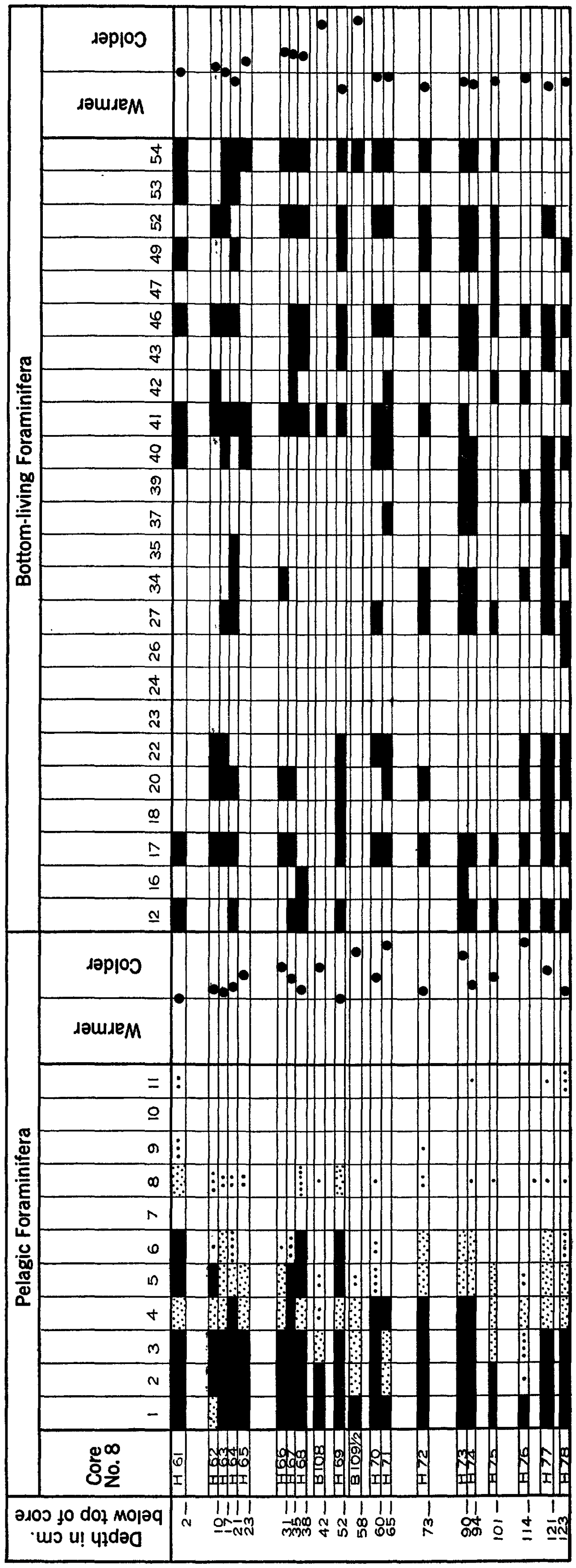


FIGURE 16.—Distribution and temperature significance of Foraminifera in core 8.

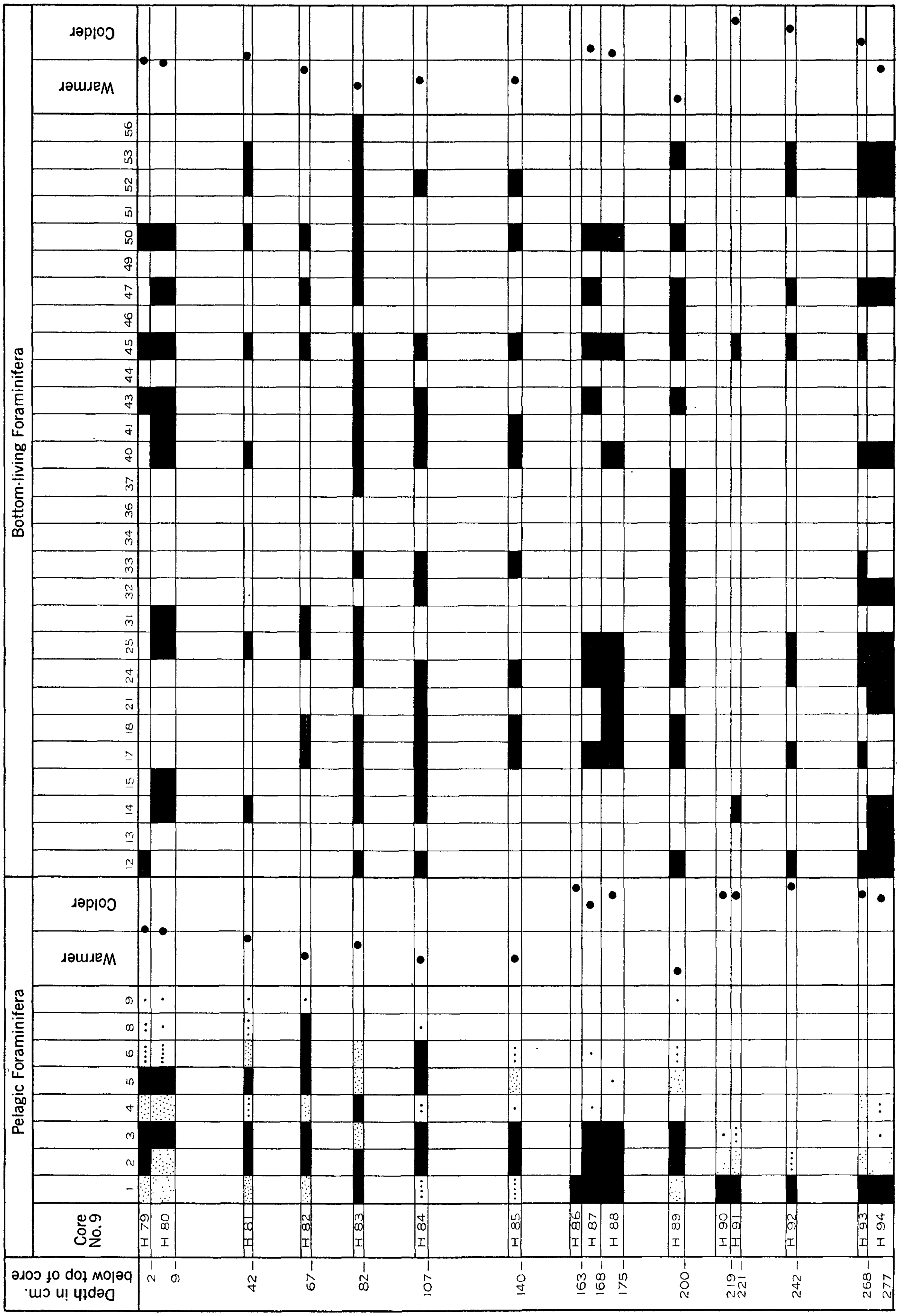


FIGURE 17.—Distribution and temperature significance of Foraminifera in core 9.

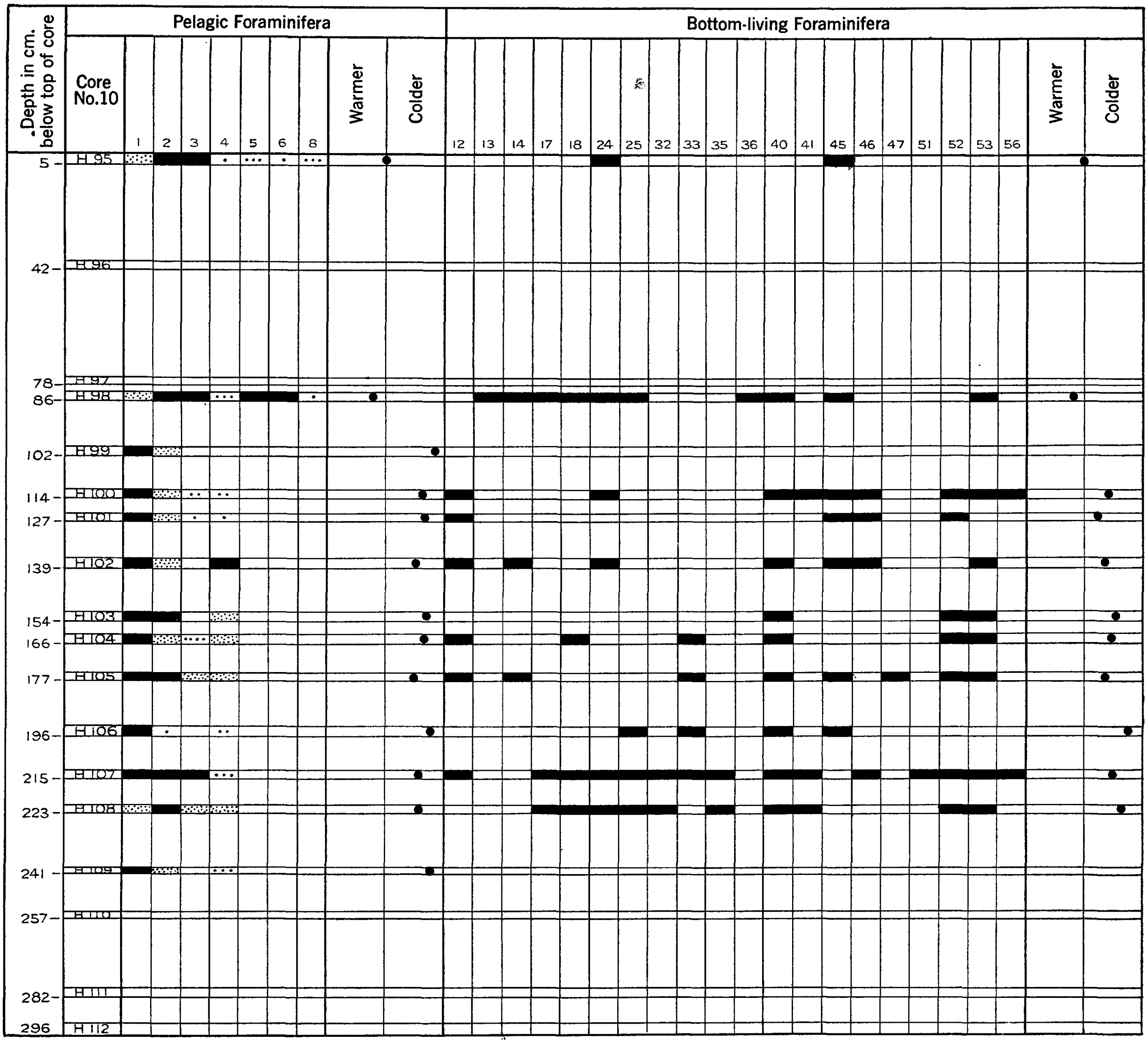


FIGURE 18.—Distribution and temperature significance of Foraminifera in core 10.

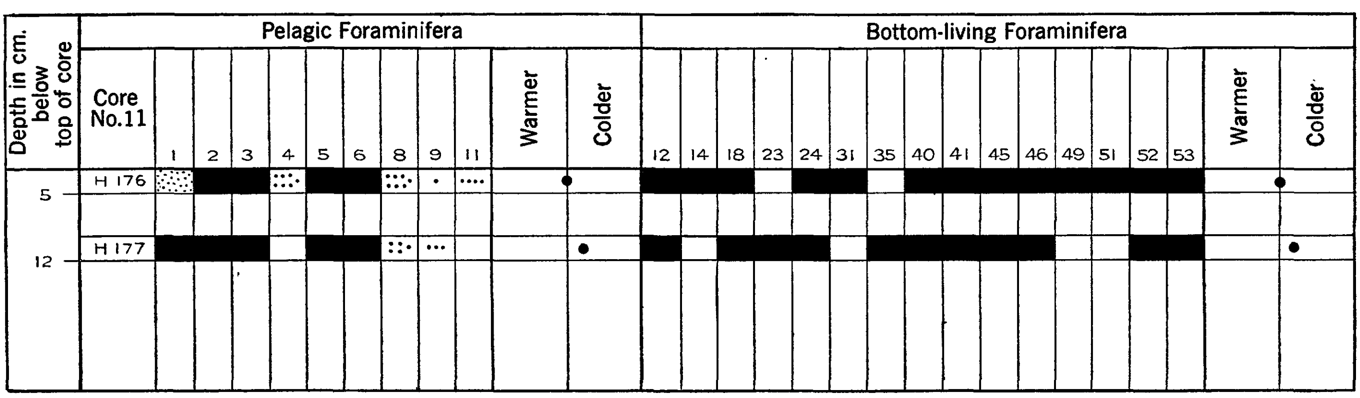


FIGURE 19.—Distribution and temperature significance of Foraminifera in core 11.

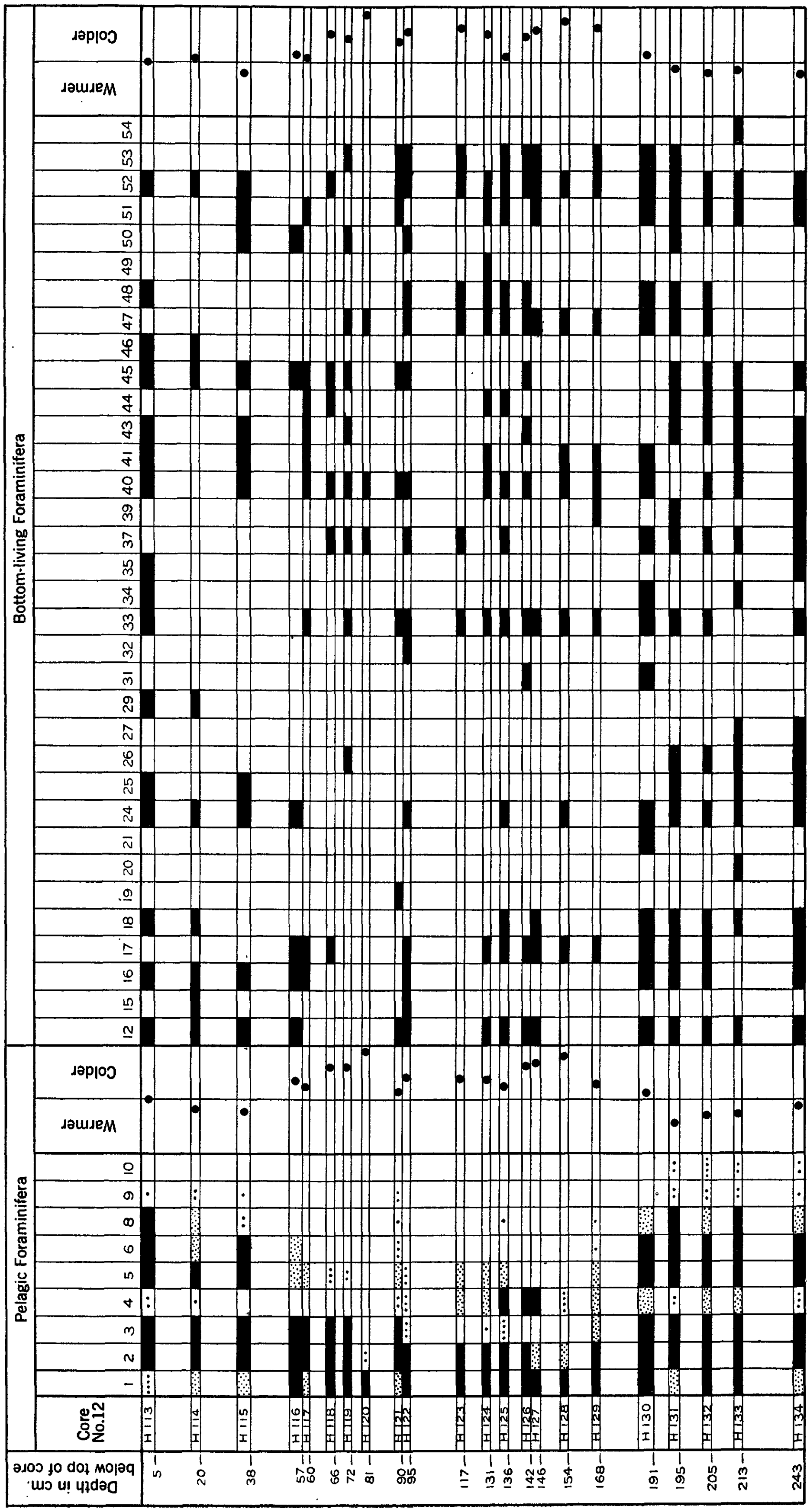


FIGURE 20.—Distribution and temperature significance of Foraminifera in core 12.

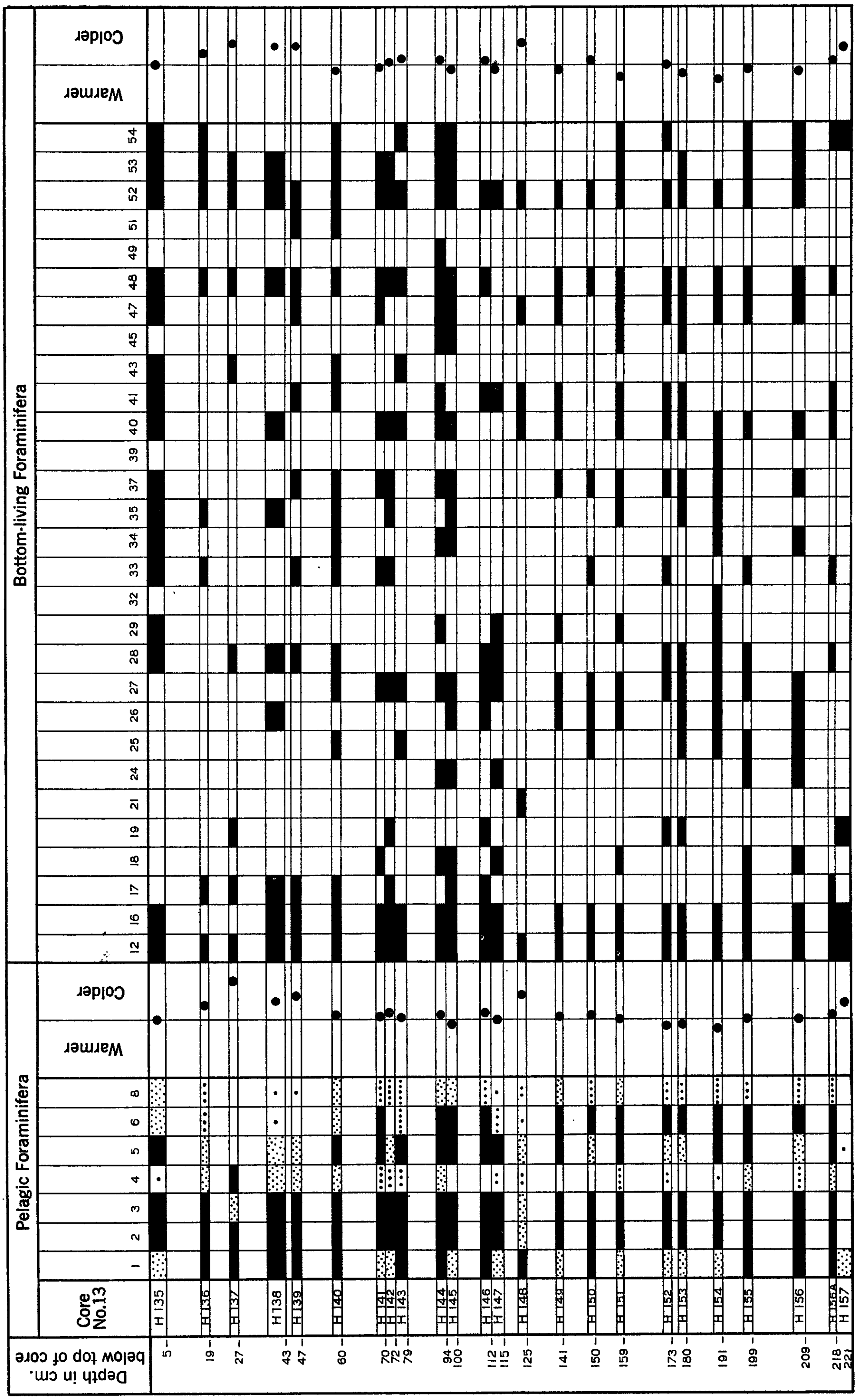


FIGURE 21.—Distribution and temperature significance of Foraminifera in core 13.

used as a convenient norm with which the temperatures indicated by the faunas below can be compared and plotted. The departures from the temperature norms as indicated by the foraminifers have been plotted in figures 11 to 21. It is evident from these charts that several alternations of periods colder and warmer than the present have occurred during the time represented by the sediments in these cores. The zones containing Foraminifera of a more tropical or a more arctic facies than that represented by the top of the core will be referred to respectively as warm or cold, whereas those of an intermediate aspect or resembling present-day temperatures will be referred to as normal.

Globigerina bulloides D'Orbigny (pl. 8, figs. 2a, b, c.) is one of the most generally distributed globigerinids in the core samples. It is abundant in all warm and normal temperature zones, and though abundant in a few of the cold zones it is commonly subordinate, rare, or absent in the coldest ones. The distribution of this species in the present oceans is somewhat uncertain, because the taxonomic limits of the form are under question. Brady and others have considered it almost universal, but they may have used too much latitude in its taxonomy. In the tropical Atlantic its occurrence is spotty, though locally very abundant according to Schott.[2] Heron-Allen and Earland [3] report it as abundant in the New Zealand area and very widely distributed elsewhere.

Globigerinoides rubra (D'Orbigny) (pl. 8, fig. 9) is extensively distributed in the tropical and warm-temperate waters of the North and South Atlantic, Pacific, and Indian Oceans, and in the Mediterranean Sea. The species was originally described from the West Indies, where it seems to be more prolific and more typical than elsewhere. Schott [4] indicates in the *Meteor* report that *G. rubra* is one of the more prolific species collected in net hauls from the tropical Atlantic. In core 3 it is rare throughout and absent from the cold zones. It is present in the lower warm zone of core 5 (H–13). It is rare in samples H–61 (top) and H–72 of core 8, rare in 5 samples of core 9, rare in the globigerina ooze of core 11, rare in the warmer zones of core 12, and absent from all of the other samples.

Globigerinoides conglobata (H. B. Brady) (pl. 8, fig. 10) is a characteristic tropical Gulf Stream form. Brady [5] reports its range in the Atlantic as from latitude 40° north to 35° south; he found its distribution in the Pacific to be more restricted. Later investigators have extended somewhat its range in the Pacific region. This species was observed in several of the net hauls of the *Meteor* expedition in the tropical Atlantic. It appears to be most characteristic and most numerous in the tropical part of the Gulf Stream. *G. conglobata* is found sparingly in only the warm zones in core 3, and in the lowest warm zone in cores 5 and 12. Elsewhere, it is absent.

Globorotalia menardii (D'Orbigny) (pl. 8, fig. 3) is a very prolific species in the pelagic fauna of the tropical and temperate waters of the North and South Atlantic. It is reported as abundant in the Pacific around the Hawaiian and Philippine Islands, where the shells are a prominent constituent of the globigerina oozes. It has been reported elsewhere in the tropical Indian and Pacific Oceans and off the Juan Fernandez Islands. Heron-Allen and Earland [6] failed to find the species in the Antarctic Ocean, even at stations where preceding investigators had reported its occurrence. Brady [7] reports that its northern limit in the Atlantic Ocean is 55°11′ north latitude and its southern limit 50° 36′ south latitude. As now recognized, the species has a worldwide distribution in the tropical and warm-temperate zones. *G. menardii* is present in all samples in core 3, except those from two cold zones. Only a few specimens were found in two moderately cold zones. The remaining zones in core 3 are near normal or warmer than normal. In core 4 it is present only in the top sample. The climate represented by the other samples in core 4, as indicated by the pelagic foraminifers, was colder than that represented by the top sample. *G. menardii* is absent from the other cores.

In analyzing the significance of the Foraminifera in the cores taken by the *Meteor*, Schott [8] used *G. menardii* as an indicator of surface water temperatures comparable to those now prevailing in the tropical part of the Atlantic. *G. menardii* is a common constituent of the globigerina ooze now accumulating in that region. The cores taken by the *Meteor*, however, revealed a zone of sediment 20 to 30 centimeters below the sea floor that does not contain *G. menardii.* Schott interpreted this zone as representing a period of cold water belonging to the last glacial stage of the Pleistocene. The sediment underlying this zone of colder water contains *G. menardii* and was thought by Schott to represent the last interglacial epoch.

BOTTOM-LIVING FORAMINIFERA

Information on the distribution of bottom-dwelling Foraminifera relative to temperature is less detailed and definite than that for the pelagic forms. The pelagic foraminiferal faunas are comparatively simple in composition, for they contain relatively few but very prolific species that generally have a very broad geographic distribution. On the contrary, many bottom-

[2] Schott, W., Die Foraminiferen in dem aquatorialen Teil des Atlantischen Ozeans: Wiss. Ergeb. Deutschen Atlantischen Exped., *Meteor*, 1925–27, Band 3, Teil 3, Lief. 1, pp. 59, 95, etc., 1925.

[3] Heron-Allen, Edward, and Earland, Arthur, Foraminifera: British Antarctic (*Terra Nova*) Exped., vol. 6, No. 2, p. 187, 1922.

[4] Op. cit., pp. 62, 63, 100.

[5] Brady, H. B., Foraminifera: *Challenger* Rept., Zoology, vol. 9, p. 603, 1884.

[6] Heron-Allen, Edward, and Earland, Arthur, Foraminifera: British Antarctic (*Terra Nova*) Exped., vol. 6, No. 2, p. 26, 1922.

[7] Op. cit., p. 691.

[8] Schott, W., Die jüngste Vergangenheit des aquätorialen Atlantischen Ozeans auf Grund von Untersuchen an Bodenproben der *Meteor* Expedition: Naturf. Gesell. Rostock Sitzungsber. u. Abh., 3d ser., Band 4, pp. 54–57, 1933.

dwelling faunas are composed of a large number of species whose distribution is variously involved with local factors, such as depth, temperature, kind of bottom, intensity of light, and food supply. Although existing bottom faunas have been rather extensively described, the record of their environment is not yet sufficiently definite or comprehensive to be used as the basis of ecological determinations with as much assurance as is possible with the pelagic faunas. Nevertheless, the climatic distribution of several bottom-living species is fairly well-known, a few being characteristic of cold water and others of warm water.

The information on the bathymetric distribution of the bottom-dwelling Foraminifera is less satisfactory than that on climatic distribution. Investigations now under way at the Cushman Laboratory in cooperation with the Woods Hole Oceanographic Institution promise to yield much definitive information, but the studies are not sufficiently advanced to apply the results to the study of these cores.

Among the enigmatic problems encountered in the study of the core faunas is the occurrence in a few unrelated samples of solitary specimens, in part broken or worn, of *Elphidium* or the closely related genus *Elphidiella*. It seems significant that in nearly all samples in which it was found, there was only a single specimen. Those found in samples H–74, H–83, and H–133 are in zones indicated as warm by other Foraminifera, but those found in samples H–5, H–22, H–100, and H–107 are in zones indicated as colder than normal.

Species of *Elphidium* and *Elphidiella* are characteristic of shallow-water, near-shore marine faunas, especially in the northern hemisphere, and they have been an increasingly prolific constituent of such foraminiferal faunas during and since the Miocene. An exception in the North Pacific Ocean has been recorded by Cushman [9] and apparently another in the North Atlantic Ocean by Cushman, Henbest, and Lohman.[10] Specimens have been dredged in deep water near Islands in the Pacific, but the eroded shells and the anomalous location indicate that they had been transported from shallow to deep water. The presence of *Elphidium* and *Elphidiella* in these deep-sea cores can hardly be construed as evidence for shallow water, because the rarity of specimens in our samples, in contrast with their great abundance in their normal habitat, suggests that they are not indigenous. For these reasons we must look for a more satisfactory explanation of their presence.

We have not yet encountered a record of *Elphidium* and *Elphidiella* living as pelagic organisms. The records of deep-water dredgings almost uniformly indicate their absence from the abyssal benthos. Transportation of shells of these organisms for many hundreds of miles by currents on the ocean bottom seems unlikely. Flotation of shells for a few days by gas generated in dead sarcode is not entirely improbable, though not yet observed or described. However, icebergs and seaweed are transporting agents of great capacity and wide distribution and seem to be the most likely factors in these and similar problems of erratic distribution.

Rafting by icebergs seems possible under conditions that would enable the ice to gouge out or incorporate and carry shallow-water or littoral sediments. It is probably a common occurrence for shallow-water or littoral sediments to become incorporated in ground ice, shore ice, or the bottoms of grounded icebergs and later to be carried to sea when the ice breaks up. At least one of the specimens, *Elphidiella groenlandica* (Cushman), known only from the shallow water around Greenland (found in core 5, sample H–5), suggests this mode of transportation, because the indigenous Foraminifera in this sample indicate a cold-water environment such as would be expected in areas occupied by floating ice.

Seaweed is another important rafting agent. The transportation, for example, of near-shore living micro-organisms as well as certain larger organisms by sargasso weed broken loose from the West Indies and carried to sea by currents is widely known. That mode of rafting is by no means restricted to the Sargasso Sea.

A similar problem of erratic specimens was encountered among the macrofossils. See chapter on "Miscellaneous fossils and faunal distribution."

Rupertia stabilis Wallich (plate 10, fig. 15) was found only in cores 8, 12, and 13, the cores from the shallowest water. It is especially common in core 8 and rather common in core 13, but in core 12 it was found in only one sample (H–133). The distribution is about evenly divided between warm, medium, and cold zones, thus indicating that temperature is not a critical factor in its distribution. The absence of this foraminifer from the cores taken in deeper water, between cores 8 and 12, suggests that depth is an important control. This suggested conclusion is modified, however, by the possibility that the texture of the substrate in cores 9, 10, and 11 might be a factor as well as depth. In cores 8 and 13, *R. stabilis* is found in globigerina ooze of rather coarse texture. The ooze in cores 9, 10, and 11 is generally finer in texture and contains more clay. If depth is a principal control of the distribution of *R. stabilis*, the absence of this species from the cores from greater depths in the eastern Atlantic would indicate that the ocean level was probably not low enough during the glacial stages to bring the abyssal bottom of the region within the depth range of this species. This evidence, though indefinite, lends some support to the conclusion, originally reached in a study of the other

[9] Cushman, J. A., A monograph of the Foraminifera of the North Pacific Ocean: U. S. Nat. Mus. Bull. 71, pt. 4, pp. 30–34, 1914.

[10] Cushman, J. A., Henbest, L. G., and Lohman, K. E., Notes on a core sample from the Atlantic Ocean bottom southeast of New York City: Geol. Soc. America Bull., vol. 48, p. 1304, 1937.

invertebrate fossils in the cores, that extreme changes in ocean level have not occurred during the time represented by our core samples.

Globigerina pachyderma Ehrenberg (plate 8, figs. 1a, b, c) is of particular interest. Most of the species of globigerinids and globorotalids in the core samples are exclusively pelagic, except *Globigerina pachyderma* Ehrenberg and possibly *Globorotalia scitula* (H. B. Brady) (plate 8, figs. 5a, b, c). *G. pachyderma* may be pelagic in its early stages, but little is definitely known of this aspect of its habits. It is a cold-water form originally described from the Davis Straits by Ehrenberg. Brady,[11] Heron-Allen and Earland,[12] and others have considered this form as an indicator of cold water. Brady states that *Globigerina pachyderma* is peculiar to the high latitudes. Its southernmost range observed in the North Atlantic is in the "cold area" in the Faeroe Channel at about latitude 60° north. Brady writes [13] "Within the Arctic Circle it is the most common representative of the genus, occurring sometimes alone and sometimes in company with small specimens of *Globigerina bulloides*. I have never succeeded in finding it in tow net gatherings, although small examples of the tropical *Globigerina bulloides* are not uncommon amongst the surface organisms of the same areas."

In dredgings from the North Atlantic Ocean, *Globigerina pachyderma* constantly appears in inverse ratio to such pelagic species as *Globigerinoides rubra, G. conglobata,* and *Globorotalia menardii,* which are known to be characteristic of tropical and warm-temperate surface water like that of the Gulf Stream.

The presence of *Globigerina pachyderma* or a homeomorph thereof in the Antarctic Ocean was definitely established by Heron-Allen and Earland.[14] They proposed the idea that this species is a precise homeomorph of the true *G. pachyderma* from the Arctic Ocean and that in the Antarctic Ocean the supposed *G. pachyderma* is a variant of the Arctic species *G. dutertrei*. If this is true, *G. pachyderma* is not an example of bipolarity, as sometimes supposed. These authors agree with Brady's conclusions that the species is probably not, as reported by Murray,[15] a pelagic form.

BATHYMETRIC DISTRIBUTION

In general, the bottom-dwelling Foraminifera are most prolific and varied in the cores from the shallowest water and least so in those from the deepest water. In this respect they exhibit, in common with the metazoan fossils, a bathymetric distribution that is parallel with that of marine bottom-living animals of the present day. Although the distribution of fossils in the cores is treated at greater length in the chapter on "Miscellaneous fossils and significance of funal distribution," it is appropriate here to direct attention to a few general features of the distribution of the Foraminifera.

Cores, 3, 4, and 9 represent rather well the character of the foraminiferal population in the cores from the deepest water. In these cores the bottom-dwelling Foraminifera occupy a very subordinate position in number of individuals and include generally a small number of species.

Core 3 contains pelagic foraminifers in all of the 18 samples that were extracted but bottom-living forms are comparatively rare throughout.

In core 4, 13 samples contain a great abundance of pelagic forms; the remaining 6 samples also contain them but they are less abundant. In all 19 samples the bottom forms are comparatively rare.

In core 9, 4 samples out of 16 contain an abundance of pelagic foraminifers; the remainder, with one exception, contain a moderate number. The bottom forms are generally subordinate, in some samples very rare or absent. In 7 samples, diatoms (mainly *Coscinodiscus*) compose a large part of the sediment. In one sample of diatom ooze (H–86), bottom-dwelling foraminifers, excepting *Globigerina pachyderma*, are absent, and metazoans are represented only by echinoid spines and silica sponge spicules. Shards of alkalic volcanic glass are present in large numbers. The pelagic foraminifers indicate cold water.

The core from the shallowest water, No. 8, contains not only a large amount of globigerina ooze but also a varied and prolific to moderately prolific bottom fauna of foraminifers. Throughout this core, the pelagic fauna is generally very prolific. Large diatoms (*Coscinodiscus*) and radiolarians were not seen in the samples studied for Foraminifera. The bottom fauna, both protozoan and metazoan, is more varied and profuse than in the other cores. The core from the next shallowest water, No. 13, and the third shallowest, No. 12, contain bottom faunas decreasing in variety and numbers. The cores from water of intermediate depth are intermediate in these aspects of faunal character.

Though relatively pure globigerina oozes are common in the cores, as well as those that are more argillaceous and arenaceous, shells of bottom-dwelling foraminifers are hardly numerous enough in any core to characterize the sediment, unless *Globigerina pachyderma* is included among the bottom-living species.

In passing from west to east, core 7 is the first to include species of Foraminifera that are European in character. In cores 8 to 13 the character becomes increasingly European.

TEMPERATURE INDICATIONS

In attempting to determine the temperature changes of the past, the top sample of each core was taken as normal, because the top sample represents the present-

[11] Brady, H. B., Foraminifera: *Challenger* Rept., vol. 9, p. 600, 1884.
[12] Heron-Allen, Edward, and Earland, Arthur, Foraminifera: British Antarctic *Terra Nova* Exped., Protozoa, vol. 6, No. 2, pp. 33-36, 1922.
[13] Brady, H. B., Foraminifera: *Challenger* Rept., vol. 9, p. 600, 1884.
[14] Heron-Allen, Edward, and Earland, Arthur, op. cit., pp. 33-36.
[15] Murray, John, The ocean, p. 165, New York, Holt & Co., 1913.

day conditions at each collecting locality, except core station 10. In core 10 the top sample cannot be taken to represent present-day conditions, because the core bit penetrated farther than its length into the bottom sediment, as indicated by the presence of sediment in the water-exit port.

The pelagic and bottom-living Foraminifera were studied separately for indications of temperature, and the results were plotted separately in figures 11 to 21. No attempt was made to express the appraisals in terms of degrees, but a relative scale was established for each core. The top sample of each core, representing the present-day temperature at the collecting locality, was taken as the normal. Departures from this norm are plotted as warmer or colder, and the apparent extent of the departure is indicated on the chart by the distance from the norm. Both positive and negative evidence was used in the temperature determinations, the absence of known cold-water forms being given a certain amount of weight, particularly if such negative evidence was supported by absence of cold-water species in the samples next above and below.

The temperature changes indicated by the individual samples within each core are generally greater than the temperature differences similarly indicated as existing between the top samples of the different cores. However, a standard or norm of temperature for the whole set rather than for individual cores could not be attempted at the present time, because factors of depth and geographic distribution [16] affect the composition of the existing bottom faunas more than temperature alone and to a degree probably greater than the difference in temperature existing in the area represented by these cores. These three major factors are variously concomitant and are only partly separable in faunal analyses. Of course, it must be admitted that the temperature norms could not be maintained for each individual core entirely separate from the others, because the background of previous information on ecology naturally tended to introduce a common denominator for the entire series.

Though the trends of change are generally similar, the pelagic and bottom-dwelling foraminifers do not always indicate temperature changes that are exactly parallel nor equally divergent from the arbitrary norm. This lack of parallelism is to be expected, because extensive chemical and thermal stratification of ocean water makes the connection between local climate and the bottom layers in abyssal areas more indirect than such a connection with the surface layers that are inhabited by the pelagic Foraminifera. Extensive climatic changes are probably always accompanied by more or less local irregularity. Inasmuch as the temperature of the surface water of the North Atlantic Ocean is controlled at the present time principally by the climate of the tropical Atlantic Ocean and Caribbean Sea and as the temperature of the bottom layer of water is controlled by the climate of the Arctic region, it would seem likely that a lack of parallelism in the climatic changes of the tropical and Arctic regions would result in a corresponding lack of parallelism in the temperature changes of the surface and bottom layers of water of the North Atlantic. It therefore seems more likely that the lack of precise parallelism in the temperature changes indicated by the Foraminifera were rather a result of temporary climatic changes than of broad, large-scale geoclimatic changes. The depositional record of the Foraminifera does not show annual or short-period oscillations.

At the present time, temperature, as well as many other ecological factors, usually cannot be interpreted on the basis of shell anatomy alone. Some exceptions or partial exceptions are known, but no consistently workable principles have been discovered. The most reliable source of information on the ecology of foraminiferal faunas is still the known distribution of the species composing the fauna.

AGE AND CORRELATION

The Foraminifera in the cores are species or varieties that have been recorded in existing oceans or in Recent and Pleistocene sediments. No Foraminifera known to be exclusively characteristic of Pliocene or earlier epochs were found. These circumstances set a limit to the time span with which we have to deal, but a number of difficulties, that are for the present insurmountable, stand in the way of determining precisely the age and correlation of the faunas by strictly paleontologic methods. One of the principal obstacles is that the historical range of the pelagic species remains as indefinite, within certain limits, as their taxonomy is generalized. Another is that good stratigraphic sequences of beds bearing late Cenozoic to Recent Foraminifera are rare and few of these have been completely described. This is true not only for the Foraminifera enclosed in sediments of epeiric seas, from which most marine faunas heretofore available to paleontologists are derived, but it is particularly true for deep-sea faunas. All the bottom faunas in the cores are of a deep-sea facies and therefore belong to the group whose history is least known.

The evolutionary and faunal changes in the Foraminifera as a whole during and since the Miocene have been so gradual that the historical aspect of faunal differences cannot be clearly distinguished from the complex of existing geographic differences. For example, the shallow-water Foraminifera now living off the coast of eastern Florida and those living in the abyss at the location of core 12 differ from each other more than the Pleistocene Foraminifera at Cornfield

[16] Factors of geographic distribution include the areal pattern of such ecologic controls as submarine topography, chemical composition of the water, bottom conditions, turbidity, and food supply that set limits to migration.

Harbor, near Point Lookout, Md.,[17] differ from those now living off the coast of Maryland.

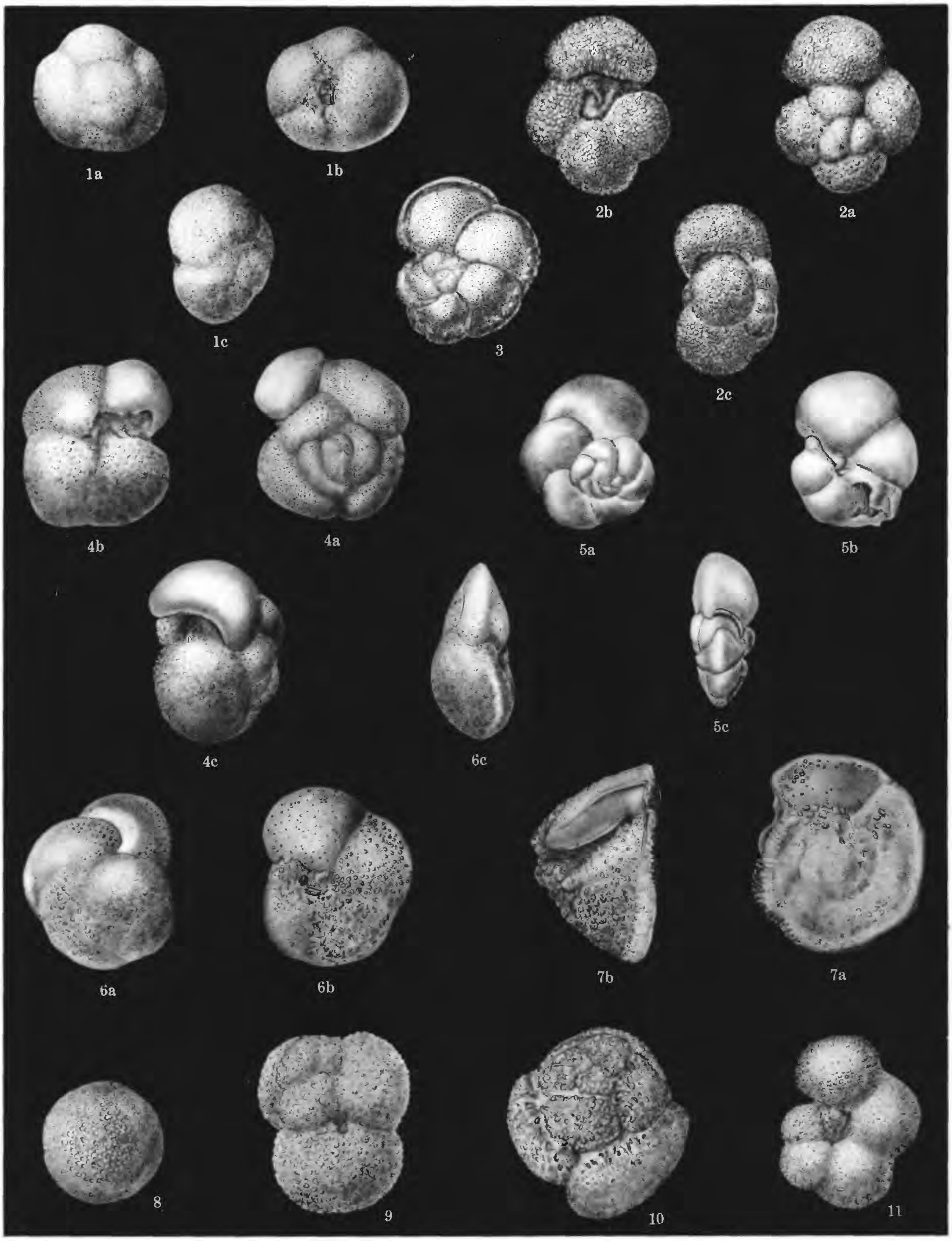
Because of these obstacles, our method of determining the age of the faunas and the associated sediments was the indirect one of comparing the temperatures indicated by the Foraminifera with the physical history of the Recent and Pleistocene epochs. The faunal differences related to ecology and geographic distribution were also obstacles to the direct use of the Foraminifera as agents for the detailed correlation of horizons from core to core; however, by indicating warm and cold periods that were presumably of broad geographic extent, the Foraminifera did furnish criteria that could be used along with zones of volcanic ash and peculiarities of lithology for suggested correlations, which have been worked out by Bramlette and Bradley. (See pp. 5–7.)

[17] Cushman, J. A., and Cole, W. S., Pleistocene Foraminifera from Maryland: Cushman Lab. Foram. Research Contr., vol. 6, pt. 4, pp. 94–100, pl. 13, 1930.

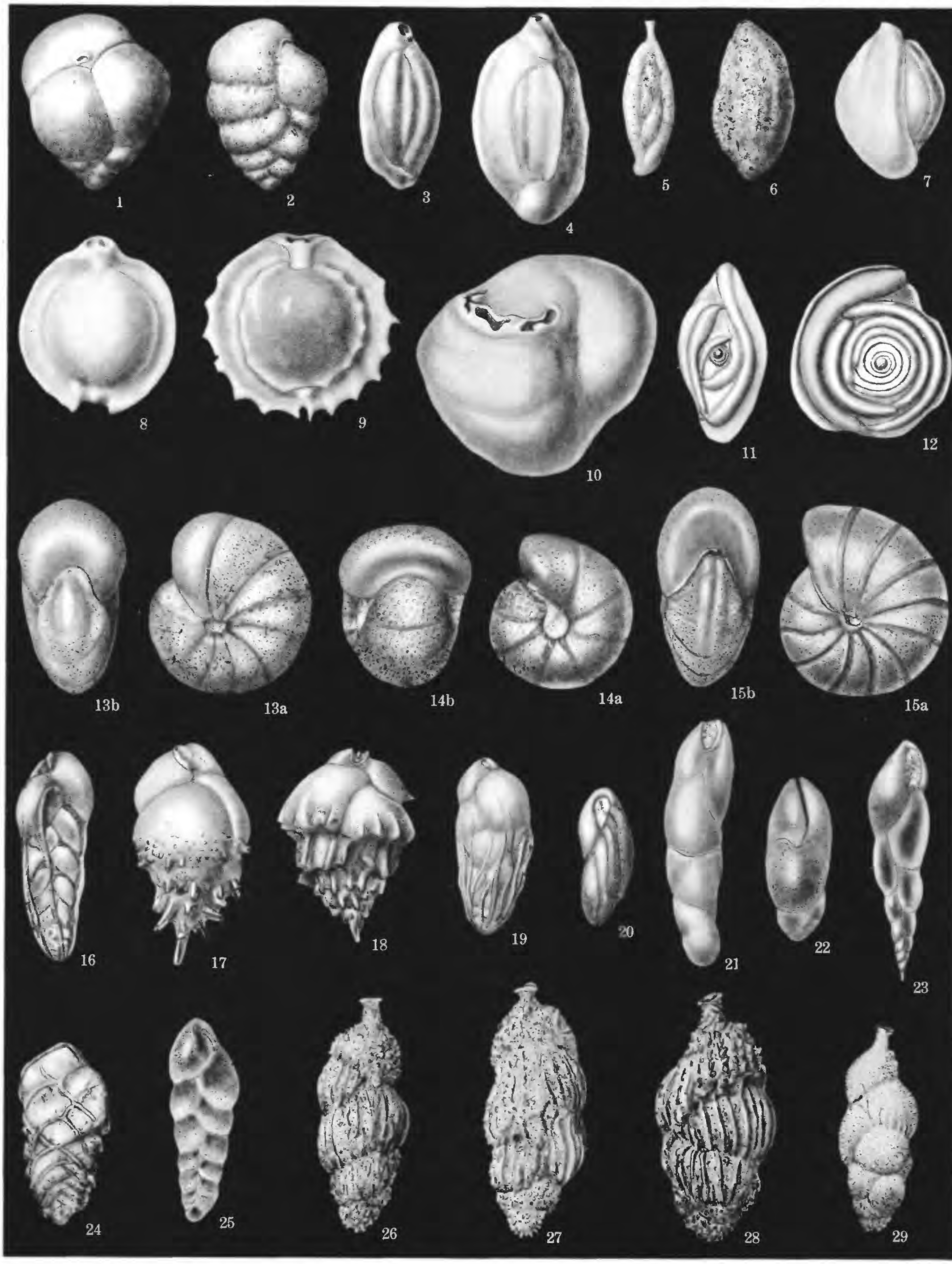
PLATES 8–10

PLATE 8

FIGURE 1. *Globigerina pachyderma* Ehrenberg. × 90. *a*, Dorsal view; *b*, ventral view; *c*, peripheral view. Core 3, H–158.
2. *Globigerina bulloides* D'Orbigny. × 60. *a*, Dorsal view; *b*, ventral view; *c*, peripheral view. Core 4, H–15.
3. *Globorotalia menardii* (D'Orbigny). × 40. Dorsal view. Core 3, H–166.
4. *Globigerina inflata* D'Orbigny. × 60. *a*, Dorsal view; *b*, ventral view; *c*, peripheral view. Core 4, H–15.
5. *Globorotalia scitula* (H. B. Brady). × 70. *a*, Dorsal view; *b*, ventral view; *c*, peripheral view. Core 4, H–15.
6. *Globorotalia hirsuta* (D'Orbigny). × 50. *a*, Dorsal view; *b*, ventral view; *c*, peripheral view. Core 3, H–158.
7. *Globorotalia truncatulinoides* (D'Orbigny). × 50. *a*, Dorsal view; *b*, peripheral view. Core 4, H–15.
8. *Orbulina universa* D'Orbigny. × 33. Core 3, H–158.
9. *Globigerinoides rubra* (D'Orbigny). × 70. Core 3, H–160.
10. *Globigerinoides conglobata* (H. B. Brady). × 40. Core 12, H–132.
11. *Globigerinella aequilateralis* (H. B. Brady). × 50. Core 8, H–78.



PELAGIC FORAMINIFERA FROM THE NORTH ATLANTIC DEEP-SEA CORES.



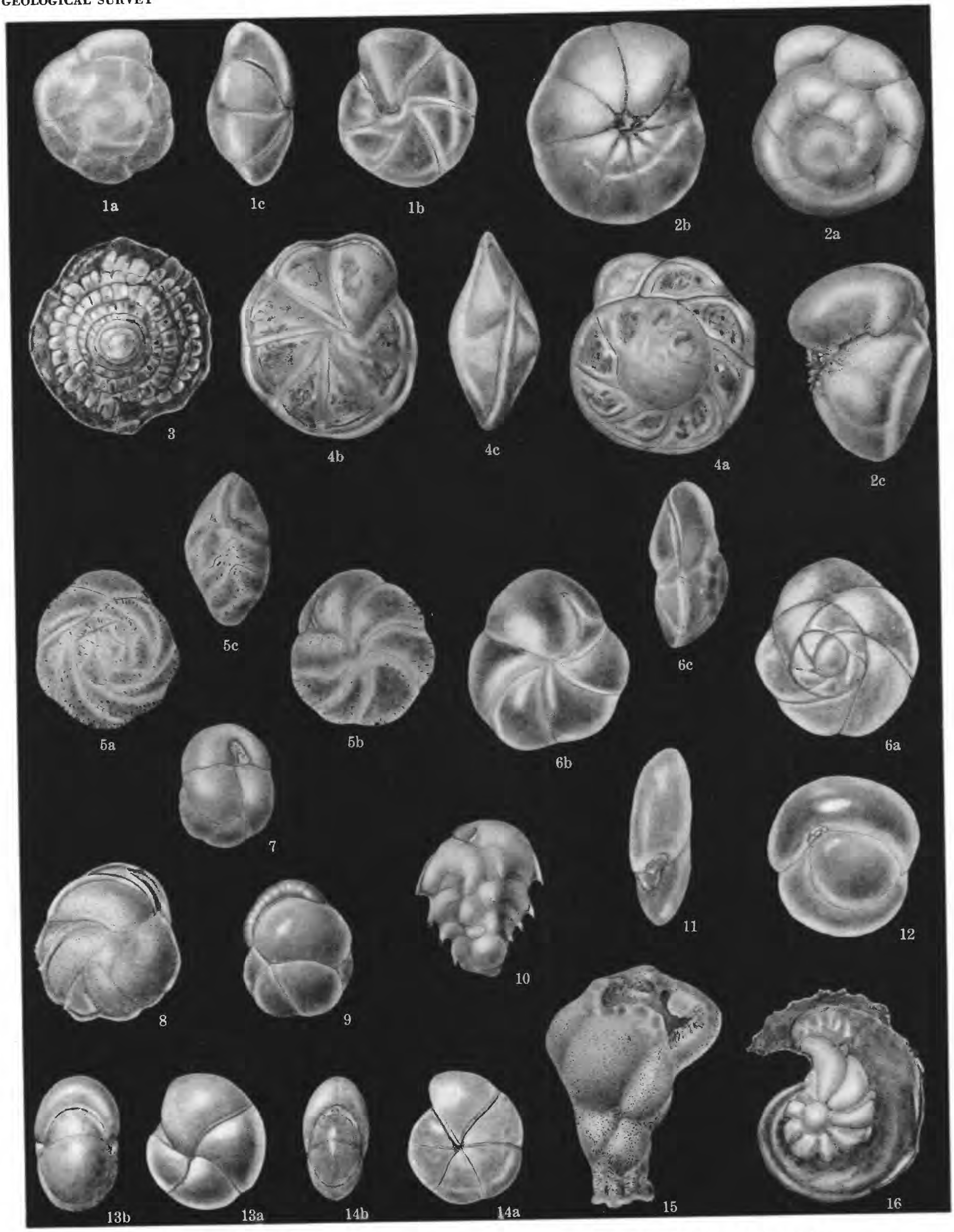
BOTTOM-LIVING FORAMINIFERA FROM THE NORTH ATLANTIC DEEP-SEA CORES.

PLATE 9

FIGURES 1, 2. *Karreriella bradyi* (Cushman). 1, Young stage, ×90; 2, adult stage, × 50. Core 7, H–48.
3. *Quinqueloculina oblonga* (Montagu). × 70. Core 6, H–33.
4. *Quinqueloculina venusta* Karrer. × 33. Core 5, H–13.
5. *Massilina tenuis* (Czjzek). × 50. Core 5, H–14.
6. *Sigmoilina schlumbergeri* A. Silvestri. × 35. Core 7, H–48.
7. *Triloculina tricarinata* D'Orbigny. × 50. Core 5, H–6.
8. *Pyrgo murrhina* (Schwager). × 50. Core 4, H–15.
9. *Pyrgo serrata* (L. W. Bailey). × 33. Core 13, H–142.
10. *Pyrgo irregularis* (D'Orbigny). × 25. Core 8, H–69.
11. *Opthalmidium acutimargo* (H. B. Brady). × 65. Core 3, H–158.
12. *Opthalmidium inconstans* (H. B. Brady). × 50. Core 8, H–71.
13. *Nonion barleeanum* (Williamson). × 65. *a*, Side view; *b*, apertural view. Core 7, H–48.
14. *Nonion pompilioides* (Fichtel and Moll). × 65. *a*, Side view; *b*, apertural view. Core 7, H–48.
15. *Nonion* sp. (?). × 65. *a*, Side view; *b*, apertural view. Core 12, H–133.
16. *Bolivinita* (?) sp. (?). × 40. Core 12, H–133a.
17. *Bulimina aculeata* D'Orbigny. × 40. Core 12, H–133a.
18. *Bulimina inflata* Seguenza. × 50. Core 13, H–140.
19. *Bulimina rostrata* H. B. Brady. × 90. Core 4, H–15.
20. *Buliminella elegantissima* (D'Orbigny). × 145. Core 3, H–171.
21. *Virgulina subdepressa* H. B. Brady. × 50. Core 4, H–30.
22. *Virgulina advena* Cushman. × 50. Core 9, H–89.
23. *Virgulina campanulata* Egger. × 80. Core 4, H–15.
24. *Bolivina* sp. (?). × 90. Core 13, H–145.
25. *Bolivina subspinescens* Cushman. × 70. Core 5, H–11.
26. *Uvigerina* sp. *A*. × 50. Core 5, H–1.
27. *Uvigerina* sp. *B*. × 65. Core 5, H–1.
28. *Uvigerina* sp. *C*. × 50. Core 13, H–156.
29. *Uvigerina* sp. *D*. × 50. Core 12, H–131.

PLATE 10

FIGURE 1. *Eponides umbonata* (Reuss). × 80. *a*, Dorsal view; *b*, ventral view; *c*, peripheral view. Core 3, H–159.
2. *Gyroidina soldanii* D'Orbigny. × 50. *a*, Dorsal view; *b*, ventral view; *c*, peripheral view. Core 4, H–15.
3. *Patellina corrugata* Williamson. × 120. Core 8, H–78.
4. *Epistomina elegans* (D'Orbigny). × 50. *a*, Dorsal view; *b*, ventral view; *c*, peripheral view. Core 7, H–48.
5. *Pulvinulinella* sp. *A*. × 90. *a*, Dorsal view; *b*, ventral view; *c*, peripheral view. Core 3, H–158.
6. *Pulvinulinella* sp. *B*. × 130. *a*, Dorsal view; *b*, ventral view; *c*, peripheral view. Core 3, H–158.
7. *Cassidulina subglobosa* H. B. Brady. × 90. Core 5, H–1.
8. *Cassidulina laevigata* D'Orbigny. × 65. Core 13, H–156.
9. *Cassidulina crassa* D'Orbigny. × 120. Core 12, H–130.
10. *Ehrenbergina serrata* Reuss. × 60. Core 5, H–6.
11. *Chilostomella ovoidea* Reuss. × 70. Core 9, H–79.
12. *Sphaeroidina bulloides* D'Orbigny. × 130. Core 5, H–1.
13. *Pullenia sphaeroides* D'Orbigny. × 65. *a*, Side view; *b*, apertural view. Core 7, H–48.
14. *Pullenia quinqueloba* (Reuss). × 70. *a*, Side view; *b*, apertural view. Core 13, H–135.
15. *Rupertia stabilis* Wallich. × 25. Core 8, H–69.
16. *Laticarinina pauperata* (Parker and Jones). × 50. Core 7, H–48.



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