29 May 1970, Volume 168, Number 3935 SCIENCE

Deep Sea Drilling in the South Atlantic

Cores from the deep sea floor in the South Atlantic strongly support the hypothesis of sea-floor spreading.

Arthur E. Maxwell, Richard P. Von Herzen, K. Jinghwa Hsü, James E. Andrews, Tsunemasa Saito, Stephen F. Percival, Jr., E. Dean Milow, Robert E. Boyce

For many years ocean scientists have dreamed of recovering complete sedimentary sections of the ocean floor in order to understand more thoroughly the earth's history. The epic 18-month cruise of the *Glomar Challenger* under the aegis of the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) has made the dream a reality. Results from the early legs indicate that the sediments so far recovered constitute scientific pay dirt. Leg 3, which covered the South Atlantic between Dakar, Senegal, and Rio de Janeiro, Brazil, has been particularly rewarding because it has provided evidence to support two current global geological hypotheses: sea-floor spreading and continental drift.

A prime obejctive of leg 3 was to investigate sea-floor spreading with a series of long cores transecting the axis of the Mid-Atlantic Ridge. Figure 1 shows the locations of the seven sites on the Mid-Atlantic Ridge flanks and two sites on the Rio Grande Rise. Discussion of site 13 on the Sierra Leone Rise is not included in this paper but has been described in detail elsewhere (*1*).

Each site in this series of seven holes was located within the relatively well-defined magnetic anomaly pattern near 30°S (*2*). Since the age of basement rock in this area had been predicted from the lineal sequence of magnetic anomalies on the assumption of a constant rate of sea-floor spreading (*3*), the ages of the sediment or rock samples obtained from these sites, as determined by paleontological studies or potassium-argon dating techniques, would provide a test both of the concept of magnetic stratigraphy and of the hypothesis of sea-floor spreading.

From the *Glomar Challenger*, a specialized, deep sea drilling vessel, sediment samples were recovered with standard oil well drilling and coring techniques. The vessel is capable of drilling through sediment thicknesses of about 1 kilometer in water depths greater than 5 kilometers. Operation of the ship was handled by Global Marine, Inc., under subcontract to the Scripps Institution of Oceanography, which is managing the Deep Sea Drilling Project as the operating institution for JOIDES.

Drs. Maxwell and Von Herzen are affiliated with the Woods Hole Oceanographic Institution; Dr. Hsü, with the Swiss Federal Institute of Technology; Dr. Andrews, with the University of Hawaii; Dr. Saito, with the Lamont-Doherty Geological Observatory, Columbia University; Dr. Percival, with Princeton University; and Drs. Milow and Boyce, with Scripps Institution of Oceanography, University of California.

Physical Description of Sites

Of the nine sites drilled in the South Atlantic, more than one hole was drilled and cored at four sites (two each at sites 13 and 21, three at site 17, and four at site 20). Table 1 summarizes the physical parameters at each site that are relevant to this discussion. Most of the sites have been correlated with a previously established numbering system for magnetic anomalies in the sea-floor spreading hypothesis (*3*, *4*). Several of the sites were surveyed before drilling by the Lamont-Doherty Geological Observatory vessel *Vema*.

Paleontology

Most of the sediments cored contained an abundance of calcareous microfossils—the calcareous nannoplankton and the planktonic Foraminifera. Siliceous microfossils, such as Radiolaria and diatoms, were also found sporadically at sites 17, 18, and 22. Ages assigned to the sediments in the cores are based mostly on the calcareous microfossils.

An almost continuous composite stratigraphic section has been recovered; it ranges in age from Campanian to Late Pleistocene. The stratigraphic interval recovered from each site is shown in Fig. 2. Within this geological time interval, there has been continuous coring of numerous stage and series boundaries, including the Pliocene/Pleistocene boundary, the Miocene/Pliocene boundary, the Oligocene/Miocene boundary, the Eocene/Oligocene boundary, and the Paleocene/Eocene boundary. Many Cretaceous stage boundaries have also been cored, some repeatedly at the various sites, and the Cretaceous/Tertiary boundary has been cored in holes 20C and 21A.

Cretaceous and Early to Middle Cenozoic floras and planktonic Foraminifera faunas are diverse and bear a close resemblance to those reported from tropical regions of the world. However, temperate planktonic Foraminifera faunas dominate the Upper Miocene through Upper Pleistocene

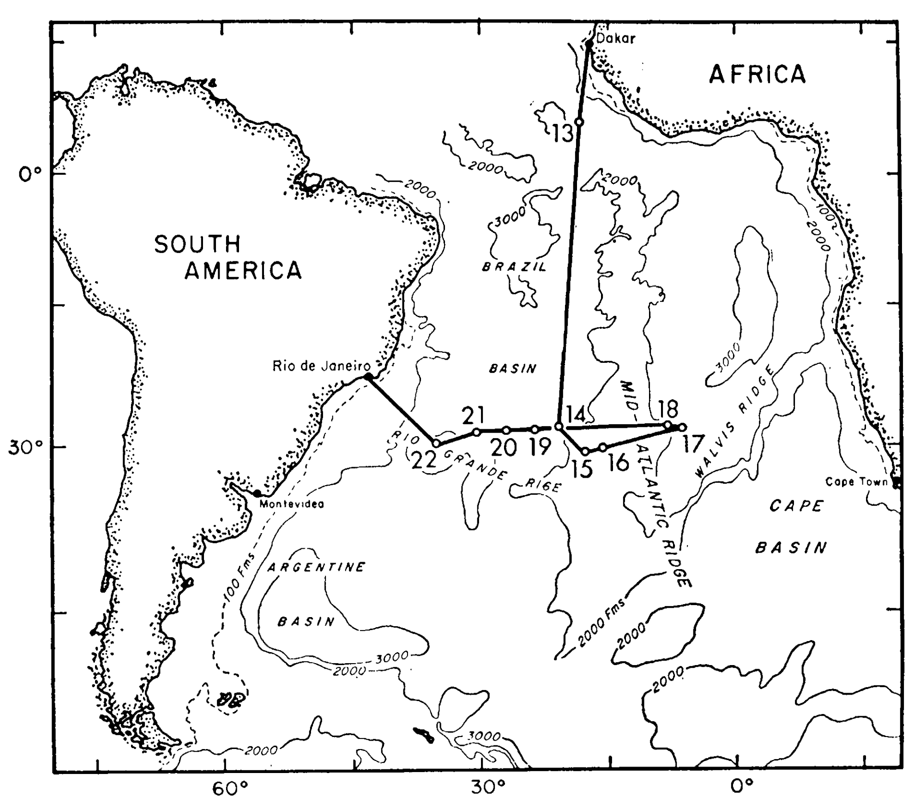


Fig. 1. Geographic location of drilling sites on leg 3 and general topography of the South Atlantic. The site numbers relate to the sequence in which the holes were drilled.

sections in the southernmost sites (sites 15 and 16). These assemblages are markedly different from the highly diverse tropical ones in that they are represented by few species. Because many of the diagnostic tropical species currently used for age determinations are absent, determining the age of these assemblages was difficult. However, the calcareous nannoplankton in this same interval is apparently more eurytopic and very similar to that reported from tropical areas.

One of the more important findings is the presence of several layers of *Braarudosphaera* chalk which occur most frequently in the Late Upper Oligocene but which sometimes occur in the Lower Oligocene. The chalk consists almost exclusively of *Braarudosphaera rosa* Levin and Joeger, as complete specimens and floods of isolated fragments, with a few other species of calcareous nannoplankton. In the Late Oligocene, these chalks usually occur near the boundary of the *Globorotalia opima opima* and *Globigerina ampliapertura* planktonic foraminiferal Zones of Bolli (*5*); in the Early Oligocene, in the interval equivalent to the *Globigerina sellii*/*Pseudoahstigerina barbadiensis* planktonic foraminiferal Zone of Blow (*6*). Although studies of modern *Braarudosphaera bigelowi* suggest that it is abundant in sediments originating at very shallow (approximately 10-meter) depths, all the floral and faunal evidence associated with the Oligocene *Braarudosphaera* indicates bathyal depths. This type of chalk is found widely distributed in the South Atlantic; it occurs at sites 14, 17, 19, 20, and 22. There are two hypotheses that may explain its origin. Either unusual oceanographic conditions must have prevailed in this region for short intervals of geologic time to cause the "bloom" of *Braarudosphaera rosa*, or currents carried these shallow water deposits into deep water. A modern analogy of such a bloom would be the so-called "red tide" bloom of certain dinoflagellates. Whereas the "red tide" bloom is of short duration (several weeks), these Oligocene nannoplankton blooms might have lasted for several hundred or several thousand years to produce the chalk.

With minor exceptions, the paleontologic studies showed that at each site the sediment increased in age with increasing depth, implying relatively undisturbed sedimentation conditions. One of the most useful results of these paleontologic studies is the comparison of the paleontologic ages of the sediments immediately overlying the basalt basement at the sites on the Mid-Atlantic Ridge (sites 14 to 20) with the sea-floor spreading hypothesis (*7*) and with the magnetic stratigraphy concept (*3*). By using the stratigraphic correlation chart of Berggren (*8*), radiometric age dates were determined for the sediments immediately overlying the basalt basement. The planktonic zone correlation and equivalent radiometric ages of the recovered basal sediments are presented in Table 2. The implications of these results for the sea-floor spreading concept are discussed more fully in a later section.

Stratigraphic Nomenclature and Practices

In order to communicate lengthy and repetitive core descriptions in an effective manner, submarine lithologic units that can be traced from one drill site to another have been designated as submarine subsurface formations. A sequence of nine formations, ranging from Upper Cretaceous to Holocene, has been recognized in the Mid-Atlantic Ridge province (*9*). Rather than designating submarine subsurface formations by geographic names, which are relatively rare in the central part of the South Atlantic, we have used the names of historic exploratory vessels. Such a practice employs already familiar names and has an added advantage that the formations at any region could be named in an alphabetical order—for example, from the youngest to the oldest—as a flexible mnemonic device.

Mid-Atlantic Ridge Lithology

The sediments of the Mid-Atlantic Ridge province are almost exclusively pelagic. No turbidity-current deposits or mass slide debris were found, with the exception of a Cretaceous slump block in the Paleocene at site 20. Nonetheless, the lithological changes in time and in space permitted us to identify nine formations. They are, in order of increasing depth, Albatross Ooze, Blake Ooze, Challenger Ooze, Discovery Clay, Endeavor Ooze, Fram Ooze, Gazelle Ooze, Grampus Ooze, and Hirondelle Ooze. The formations have been recognized mainly on the basis of lithological changes with time. Initially, the only criteria selected were (i) variations in Foraminifera content and (ii) differences in noncarbonate content (with corresponding color changes) as determined by visual and smear slide examinations on shipboard, supplemented by shore-based calcium carbonate and grain size analyses. Later, a third criterion—namely, the presence of pink oozes—was chosen to establish the Hirondelle as a formation. The properties of the nine formations are summarized in Table 3 by use of these criteria.

The identification of the lithologic formations appears to be supported by measurements of natural gamma radiation and, to a lesser extent, by the mass physical properties of the sediments, such as wet-bulk density, porosity, sediment sound velocity, and a thermal conductivity. Since the natural gamma radiation is probably the least disturbed physical property that was measured on the cores, it seems reasonable that it would provide the most reliable identification.

In the measurement apparatus on shipboard, natural gamma radiation indicated the presence of clay minerals, zeolites, phosphates, and possibly hematite, dolomite, and some opaque minerals. Some distinct natural gamma radiation signatures of the lithologic formations are shown in Fig. 3 and are listed in Table 3.

A composite stratigraphic section of the Mid-Atlantic Ridge formations has been constructed and is shown with the time range of the formations in Fig. 4. The type section for each of the formations in the composite section (Fig. 4) has been chosen with the following considerations: (i) preferably, the top and bottom contacts of the unit fell within cored intervals; and (ii) lithology of the type section is fairly representative of the formation. In general, the type section is the most completely developed (thickest) section, but not necessarily.

Rio Grande Rise Lithology

Sites 21 and 22 lie on the Rio Grande Rise at a water depth of about 2 kilometers. A composite stratigraphic section of the two sites is as follows: (i) Pleistocene and Pliocene white foraminiferal chalk oozes; (ii) Lower Miocene to Maestrichtian, very pale brown and pink nannofossil chalk oozes, partly recrystallized; (iii) Maestrichtian and Campanian nannofossil chalk oozes, recrystallized, with *Inoceramus* fragments at several horizons; (iv) Campanian or older coquina, cemented by sparry calcite. Noteworthy is the presence of a major unconformity within the Cenozoic. Oligocene and Miocene sediments are missing at site 21, and Pliocene directly overlies Lower Miocene at site 22. The Rio Grande Rise sediments include significant amounts of Foraminifera in calcareous oozes of all ages. Red clays are absent.

Lithological Summary

The distribution of the various Mid-Atlantic Ridge formations in time and in depth is summarized in Fig. 5. The stratigraphic columns of sites 21 and 22 on the Rio Grande Rise are also shown for comparison.

Several obvious conclusions may be deduced from Fig. 5.

1) Basalt basement has been reached at all the seven sites on the Mid-Atlantic Ridge.

2) The age of the sediments above the basalt bears a direct relation to the distance from the ridge axis: older sediments were found farther from the axis.

3) The sediments increase in age with increasing depth below the sea floor at each site.

4) The thickness of the sediments bears no simple relation to the age of the sediments. Paradoxically, the sites with the youngest basement ages (Miocene in sites 16 and 18) have the greatest sediment thickness (176 and 179 meters, respectively), whereas the site with the oldest basement age (Upper Cretaceous at site 20) has the thinnest sedimentary sequence (72 meters). Local variability in sediment thickness and nonrandom site selection probably account for this pattern.

5) The nature of the topmost formation is related to the distance from the

Table 1. Physical characteristics of South Atlantic drilling sites. The numbering of marine magnetic anomalies (column 6) follows the previously established system (*3, 4*). Sites 21 and 22 on the Rio Grande Rise were not correlated within the magnetic anomaly numbering scheme. The acoustic reflection time referred to in columns 7 and 8 is the round-trip travel time below the bottom, measured with a 10-cubic-inch air gun, which is part of the seismic profiling equipment.

Site No.	Latitude (S)	Longitude (W)	Water depth (m)	Maximum sub-bottom penetration (m)	Magnetic anomaly (No.)	Acoustic reflection time (sec)	Remarks
14	28°20′	20°56′	4343	107	Negative 25 km West of 13	0.13	Upper flank of small hill in topography of 40- to 200-m amplitude; acoustic reflection time, 0 to 0.15 sec
15	30°53′	17°59′	3927	142	6	0.15	Lineated N-S topography, sediment thickness, and magnetic anomalies; 40- to 200 m topographic amplitude; acoustic reflection time, 0.10 to 0.15 sec
16	30°20′	15°43′	3527	192	5	0.15	Eastern flank of 1 km high, N-S lineated, 10 km wide topographic rise; acoustic reflection time, 0 to 0.30 sec. Site on small hill 50 m high
17	28°03′	6°36′	4360	127	West of 13	0.18	Lineated N-S topography, sediment thickness, and magnetic anomalies; hills locally 10- to 200-m amplitude. Site at base of hill
18	27°59′	8°01′	4018	178	Between 6 and 13	0.16–0.32	Hills locally 20- to 80-m amplitude; 4800-m deep depression, 50 to 60 km wide in E-W direction, about 100 km east of site
19	28°32′	23°41′	4677	145	21		On east flank of N-S trending ridge, 400-m high; locally irregular topography with diffuse bottom reflections (12 kilohertz)
20	28°31′	26°51′	4506	72	30	0.15(?)	East side of a valley 10 km wide, 4850 m deep. Site on slope extending 600 m above valley floor with uniform sediment thickness
21	28°35′	30°36′	2113	131		0.20–0.25	Northeast slope of Rio Grande Rise. Strong acoustic reflector at 0.1 sec, probably a middle Eocene chalk layer
22	30°01′	35°15′	2134	242		0.52	Small hills (20- to 40-m amplitude); intermediate acoustic reflector at 0.31 and 0.52 sec; higher reflector probably *Braarudosphaera* chalk layer (see Fig. 5)

ridge axis and to the present depth of the drill sites. The Albatross Ooze is present at sites 15, 16, 17, and 18, at distances ranging from 221 to 718 kilometers from the ridge axis at depths ranging from 3527 to 4265 meters. The Endeavor Ooze is present at site 14, at 745 kilometers from the ridge axis and at a depth of 4343 meters. The Discovery Clay (covered by thin veneers of local units of similar lithology) is present at sites 19 and 20, 1010 and 1303 kilometers from the ridge axis, at depths of 4677 and 4506 meters, respectively.

Table 2. Correlation of planktonic foraminiferal zones and calcareous nannoplankton zones from basal Mid-Atlantic Ridge sediments with equivalent radiometric ages (m.y., million years). Reference numbers are given within parentheses.

Site No.	Planktonic foraminiferal zone	Calcareous nannoplankton zone	Equivalent radiometric age (m.y.)
14	*Cribrohantkenina inflata* (6)	*Helicopontosphaera reticulata* (36)	40
15	*Globergerinita dissimilis* (5)	*Triquetrorhabdulus carinatus* (36)	24
16*	*Globorotalia acostaensis* (6) *Globorotalia merotumida* (6)		11
17	*Globigerina ampliapertura* (6)	*Sphenolithus predistentus* (36)	33
18	*Globorotalia kugleri* (5)	*Sphenolithus ciperoensis* (36)	26
19	*Hantkenina aragonensis* (5)	*Chiphragmolithus quadratus* (37)	49
20	*Abathomphalus mayaroensis* (5)		67

* Lowermost sediments recovered were 13.4 m above basalt.

Table 3. Summary of diagnostic characteristics used to identify Mid-Atlantic Ridge sedimentary formations.

Formation	Foraminifera (approx. %)	Terrigenous material (approx. %)	Natural gamma radiation*	Remarks
Albatross	> 10	< 10	0– > 2000	Natural gamma count decreased with depth
Blake	< 10	< 10	100–300	
Challenger	< 10	10–20	200–400	Darker color than Albatross or Blake
Discovery	0	55–100	1100–1700	Red clay
Endeavor	1–8	20–60	250–1600	
Fram	1–3	20–30	250–500	
Gazelle	< 3	40–60	500–1200	
Grampus	10–15	20–30	200–400	Darker color toward base of formation
Hirondelle	< 10	~ 30	400	Pink color component

* Units are counts per 1.25 minutes, scanning a 7.62-cm core segment.

Table 4. Percentage of calcium carbonate measured in the various formations at each site on leg 3. Measurements were made by Anthony C. Pimm, Scripps Institution of Oceanography (*1*). The number of samples analyzed are in parentheses. Where no value is given, the formation was absent at the site. A question mark indicates that the value is unknown, not sampled, or insufficiently sampled.

Formation	Site No. 16	15	18	17	14	19	20	Average of sites
Albatross	90.7 (16)	76.8 (10)	? (1)	86.2 (5)				84.6
Blake	90.7 (25)	91.1 (10)	?	87.6 (6)				89.9
Challenger	89.8 (17)	80.1 (6)	?					85.0
Discovery		46.9 (3)	?			0.0	?	23.5
Endeavor		80.0 (8)	78.9 (5)	76.9 (10)	57.6 (6)	42.8 (6)	37.4 (7)	62.3
Fram			83.8 (9)	84.9 (25)	76.8 (15)	74.5 (8)	72.8 (6)	78.6
Gazelle						67.9 (14)	34.1 (10)	50.1
Grampus		83.8	82.6	? (2)	? (0)	78.6 (23)		81.1
Hirondelle							74.3	74.3

6) The nature of the sediments below the topmost formation bears no simple relation to the present depth of the drill site, which indicates that there were changes in depositional environment at each site with time.

7) The sediments at sites less than 500 kilometers from the ridge axis (sites 15, 16, and 18) are mainly Neogene, whereas the sediments farther out are mainly Paleogene (sites 14, 17, 19, and 20).

8) The formations on the whole are not isochronous. The bases of the formations older than Middle Miocene (Hirondelle, Grampus, Gazelle, Fram, Endeavor, and Discovery) tend to become older at drill sites farther from the ridge axis. On the other hand, the trend is reversed for younger formations (Challenger, Blake, and Albatross), the bases of which are either nearly synchronous or younger at drill sites farther from the ridge axis.

9) The Oligocene *Braarudosphaera* chalk is a remarkable time-stratigraphic marker that has been recognized at drill sites some 2800 kilometers apart (sites 17 to 22). This marker is absent in the sites on the ridge crest (sites 15, 16, and 18) because the age of the basalt basement is not older than Miocene.

10) The stratigraphy has a symmetry about the ridge axis, so that the sedimentary sequence at a drill site is more similar to that at a site nearly equidistant from the axis on the other flank of the ridge than to that of its immediate neighbor (compare sites 14 and 17, sites 15 and 18).

The graphical summary, which shows formations as stratigraphic units, cannot express the lateral variations within each of those units. These variations can be examined through the statistical summaries of shore-based carbon/carbonate analyses. Table 4 lists these summaries as percent $CaCO_3$ by sites that have been arranged in the order of increasing distance from the ridge axis—namely, 16, 15, 18, 17, 14, 19, 20. From this table the variation of the $CaCO_3$ content of each formation is found, in general, to decrease with the distance from the ridge axis; the same formation is least calcareous at the sites farthest away. A similar decrease in the Foraminifera content with the distance from the ridge axis has been measured; therefore, the same formation also contains, in general, less Foraminifera at the sites farther from the ridge axis.

Sedimentation Rates

The sedimentation rates of the different formations vary with lithology. The rates vary from about 1.8 centimeters per thousand years for a foraminiferal chalk ooze unit to 0.02 centimeter per thousand years for a red clay unit—a difference of some two orders of magnitude. To evaluate the changes resulting from production and dissolution of calcareous planktons on net accumulation rate, we have computed both total and noncarbonate depositional rates of each formation. As Table 5 shows, the average values of noncarbonate components still vary from 0.07 to 0.33 centimeter per thousand years (with the exception of Hirondelle). The variation is probably real, reflecting changes in terrigenous influx, although the errors resulting from assigning absolute ages to paleontologically determined stages might have exaggerated the difference. The average rate of noncarbonate deposition is 0.16 centimeter per thousand years, approximately one-tenth that of a chalk ooze that contains some 10 percent noncarbonate impurities (for instance, Albatross Ooze at site 16).

Calcium Carbonate Dissolution

A synthesis of the facts so far presented has led us to adopt a hypothesis that dissolution during deposition played an important role in determining the lithology of the ridge sediments and their net rates of accumulation. It seems reasonable that the red clays represent the insoluble residues of chalk oozes, especially when the depositional rate of a sediment is compared with its calcium carbonate content. On the other hand, whether the rarity or absence of Foraminifera in a nannofossil chalk ooze could be attributed to dissolution is a debatable question.

Bramlette (*10*) emphasized the role of production in determining the composition of calcareous plankton in a pelagic ooze. Production rates do, no doubt, need to be considered. However, several lines of evidence suggest that calcareous Foraminifera are more readily soluble in ocean water than are calcareous nannofossils, so that the paucity of Foraminifera in the nannofossil sediments of the South Atlantic could be attributed largely to differential dissolution. The following indications are noted:

1) The parallel trend in variations of the Foraminifera and $CaCO_3$ content of the ridge formations suggests that dissolution that increases the noncarbonate impurities of a sediment also tends to decrease its Foraminifera content.

2) The calcareous planktons present in siliceous oozes commonly are exclusively nannofossils, with little or no planktonic Foraminifera. This fact suggests that the last calcareous planktons to go into solution are nannofossils, not Foraminifera.

3) The more soluble Foraminifera species are now being readily dissolved at 3000-meter oceanic depth, considerably above the carbonate-compensation depth, so that deeper pelagic oozes include more resistant forms (*11*, *12*). The fact that the only Foraminifera found in some more marly nannofossil oozes of the ridge province are species resistant to dissolution (for instance, *Globorotalia index* and *G. suteri* in Gazelle Ooze, site 19) suggests that all but a trace of the original Foraminifera fauna has been removed by dissolution from such nannofossil sediments.

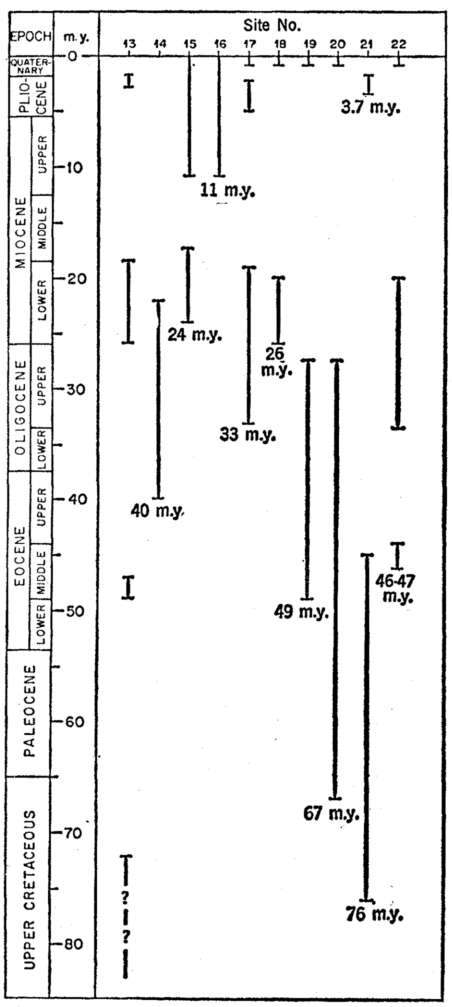


Fig. 2. Stratigraphic interval recovered at each site plotted to illustrate the almost complete coverage of samples dating from Upper Cretaceous to Late Pleistocene. Only Middle Miocene microfossils were not recovered (m.y., million years).

Although these arguments may not be definitive, they seem sufficient to us to justify the adoption of a working hypothesis to the effect that the formations of the Mid-Atlantic Ridge province originally represent primarily calcareous sediments that have undergone different degrees of dissolution during deposition. Accordingly, we have postulated five different dissolution facies and have described their physical properties as exemplified by the South Atlantic sediments:

a) Chalk oozes with no evidence of being dissolved. The Quaternary Foraminifera oozes of the Rio Grande Rise may belong to this facies.

b) Chalk oozes with signs of initial dissolution. The ridge sediments with 10 percent terrigenous matter or less but more than 10 percent Foraminifera may belong to this facies.

c) Chalk oozes with signs of moderate dissolution, particularly the dissolution of Foraminifera. The ridge sediments with 10 to 30 percent terrigenous matter and less than 10 percent Foraminifera may belong to this facies.

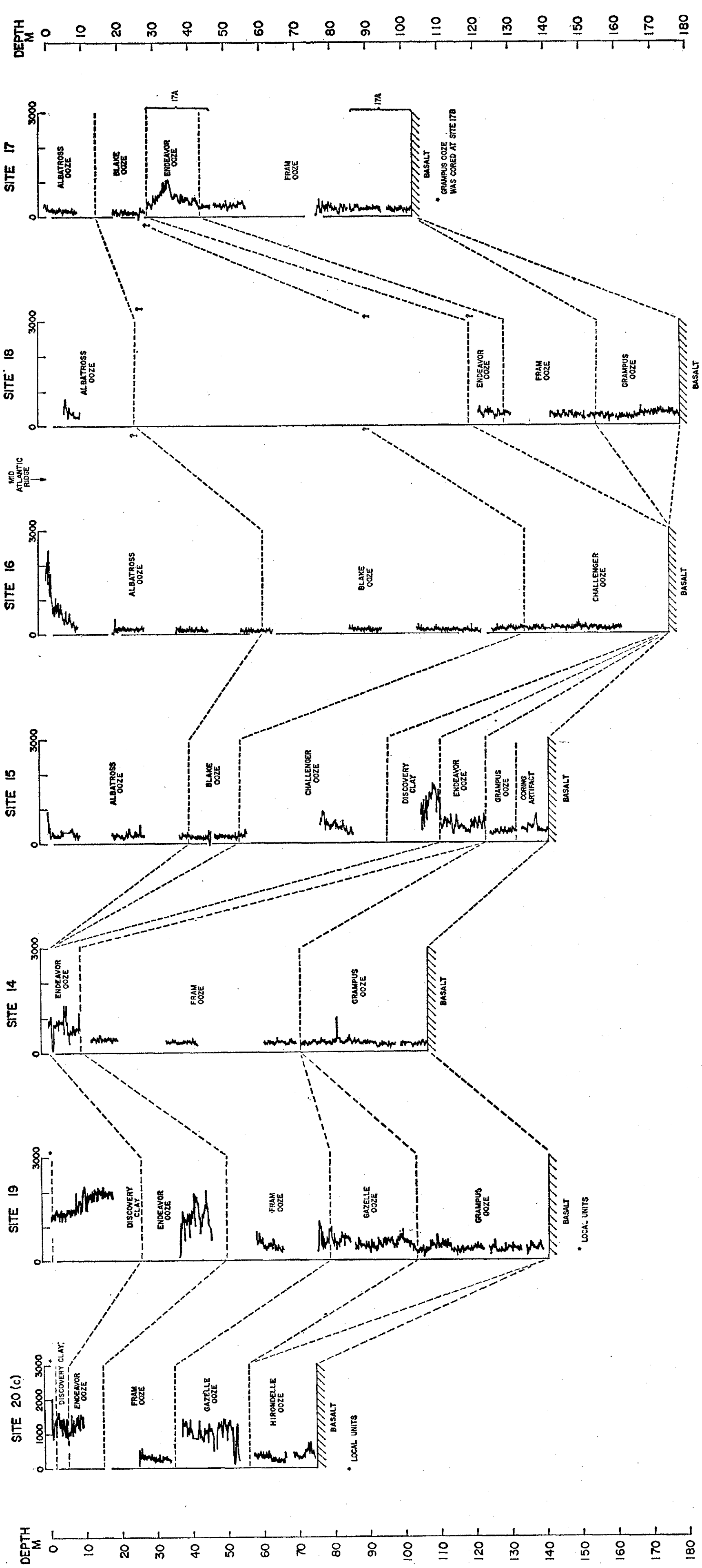
d) Marl oozes with signs of considerable dissolution; only nannofossils and the more resistant Foraminifera species are preserved. The ridge sediments with 30 to 70 percent terrigenous matter and less than 3 percent Foraminifera may belong to this facies.

e) Red clays; all calcareous planktons have been dissolved.

With this outline, we have interpreted the genesis of the formations as follows: Albatross Ooze, (b) slight loss of carbonate; Blake Ooze, (c) moderate loss of carbonate; Challenger Ooze, (c) moderate loss of carbonate but more terrigenous than Blake; Discovery Clay, (d) considerable loss of carbonate at a crestal site (site 15), but otherwise (e) total loss of carbonate; Endeavor Formation, (d) considerable to (c) moderate loss of carbonate; Fram Ooze, (c) moderate loss of carbonate; Gazelle Ooze, (d) considerable loss of carbonate; Grampus Ooze, (c) moderate loss of carbonate, slight loss at more crestal sites; and Hirondelle Ooze, (d) considerable loss of carbonate but only moderate loss (c) at base of hole 20C.

These interpretations permit us to derive two simple generalizations on the sedimentary history of the Mid-Atlantic Ridge province:

1) Each time marker is represented by a more carbonate-rich formation



toward the ridge crest and by a more carbonate-free formation farther out.

2) The Tertiary succession undergoes a cyclic change from carbonate-rich facies to carbonate-free facies, followed by a return to carbonate-rich facies, although the second half of the cycle was developed at the upper flank sites only.

To us, the different dissolution facies appear to be an expression of the varying depths of the accumulation sites as related to the carbonate-compensation depth. The present compensation depth for calcite is approximately 4500 meters in the Pacific (*10*, *13*) and is about the same in the South Atlantic at 30°S, as indicated by the distribution of the modern red clay sediments there. This depth is related to an increase in the rate of calcite dissolution, not to a boundary of equilibrium solubility (*14*, *15*); the boundary of equilibrium solubility may be only several hundred meters deep (*11*, *15*, *16*). The level of compensation depth during the past has been a matter of much speculation. There is evidence that ocean waters were warmer during the Tertiary and Cretaceous than they are at present (*17*). However, whether the compensation level should be deeper or shallower for those warmer oceans is a debatable point.

Hudson (*15*) emphasized the effect of temperature on kinetics and postulated a shallower compensation depth for the warmer Cretaceous Chalk Sea. This unorthodox approach did not take into consideration the effect of the degrees of undersaturation on kinetics. That the calcite was being rapidly dissolved in the cold waters below 4500 meters but not at a more nearly saturated warmer level is an evidence that departure from equilibrium exerts the predominant control on the calcite dissolution by ocean waters.

Various authors (*10*, *18*) have postulated that the calcite-compensation depth may have been considerably greater during the Tertiary. Bramlette (*10*) suggested a 6700-meter compensation depth for a Tertiary bottom-water temperature of 12°C. This figure is probably too high. On the assumption of a nonsubsiding ocean-floor, Heath (*19*) found an apparent maximum com-

Fig. 3. Natural gamma radiation signatures versus depth at Mid-Atlantic Ridge sites. Sites are arranged with respect to location from the Mid-Atlantic Ridge axis. Units in counts per 7.62 centimeters of core per 1.25 minutes.

pensation depth of 5200 meters some 35 million years ago (Oligocene). He recognized, however, that this depth may reflect the postdepositional subsidence of sea floor; there may have been very little change in the actual compensation depth.

A further complicating factor is the effect of cold, CO_2-rich bottom currents. Berger (*11*) suggested the term "lysocline" for the level at which the solution rate increases drastically, a level that is 500 meters or more above the compensation depth. He cited evidence to show that this surface is not horizontal but is inclined in the South Atlantic, because the Antarctic Bottom Water is responsible for the pronounced abyssal $CaCO_3$ dissolution. As this water at 30°S is confined to a path west of the Mid-Atlantic Ridge on its way northward, the lysocline is probably hundreds of meters shallower on the west side than on the east side of the ridge. Also, since depth differences between successive dissolution facies are probably of the order of some hundreds of meters, it would be unwise to make interpretations in terms of absolute depth. Therefore, a relative bathymetric scale for the dissolution facies with reference to the calcite-compensation depth (CCD) is suggested, taking into consideration the distribution of Holocene sediments at 30°S. It is (i) no dissolution: some 1500 meters above CCD; (ii) slight dissolution: 500 to 1500 meters above CCD; (iii) moderate dissolution: 200 to 500 meters above CCD (just below lysocline); (iv) considerable dissolution: 200 meters or less above CCD; and (v) complete dissolution below CCD.

The rapid facies changes near the lysocline surface express the fact that dissolution rate changes rapidly there.

As the Tertiary facies changes of the Mid-Atlantic Ridge sediments at 30°S involve changes in relative depth of 1000 meters or more, it does not appear warranted to attribute such changes to past fluctuations in the absolute depth of calcite compensation. Furthermore, even if Heath's interpretations are accepted, a depression of actual compensation depth during the early Tertiary should result in a succession of increasingly carbonate-rich facies if there had been no crustal subsidence. Instead, a progression from high to low carbonate sediments has been found. Consequently, these facies changes are interpreted in terms of the chronologically changing depth at each depositional site.

Table 5. Summary of total and noncarbonate component sedimentation rates in various formations at each site on leg 3. Rates are in centimeters per thousand years, and the noncarbonate component is given in parentheses. Where no value is given, the formation was absent; a question mark indicates an uncertain rate.

Formation	Site No. 16	15	18	17	14	19	20	Average of sites
Albatross	1.8 (0.17)	1.2 (0.28)	?	0.5 (0.07)				1.2 (0.17)
Blake	1.2 (0.11)	0.6 (0.05)	?	0.45 (0.06)				0.8 (0.07)
Challenger	1.0 (0.10)	0.6 (0.12)	?					0.8 (0.11)
Discovery		0.3 (0.16)	?			?	0.02 (0.02)	0.16 (0.09)
Endeavor		?	?	0.3 (0.07)	?	0.35 (0.20)	0.15 (0.09)	0.27 (0.12)
Fram			2 (0.4)	0.75 (0.18)	1.0 (0.4)	0.6 (0.15)	0.4 (0.11)	0.96 (0.25)
Gazelle						0.3 (0.10)	0.2 (0.13)	0.25 (0.12)
Grampus		?	2 (0.4)	?	0.45 (?)	1.2 (0.26)		1.2 (0.33)
Hirondelle							0.1 (0.03)	0.1 (0.03)
Average								0.64 (0.16)

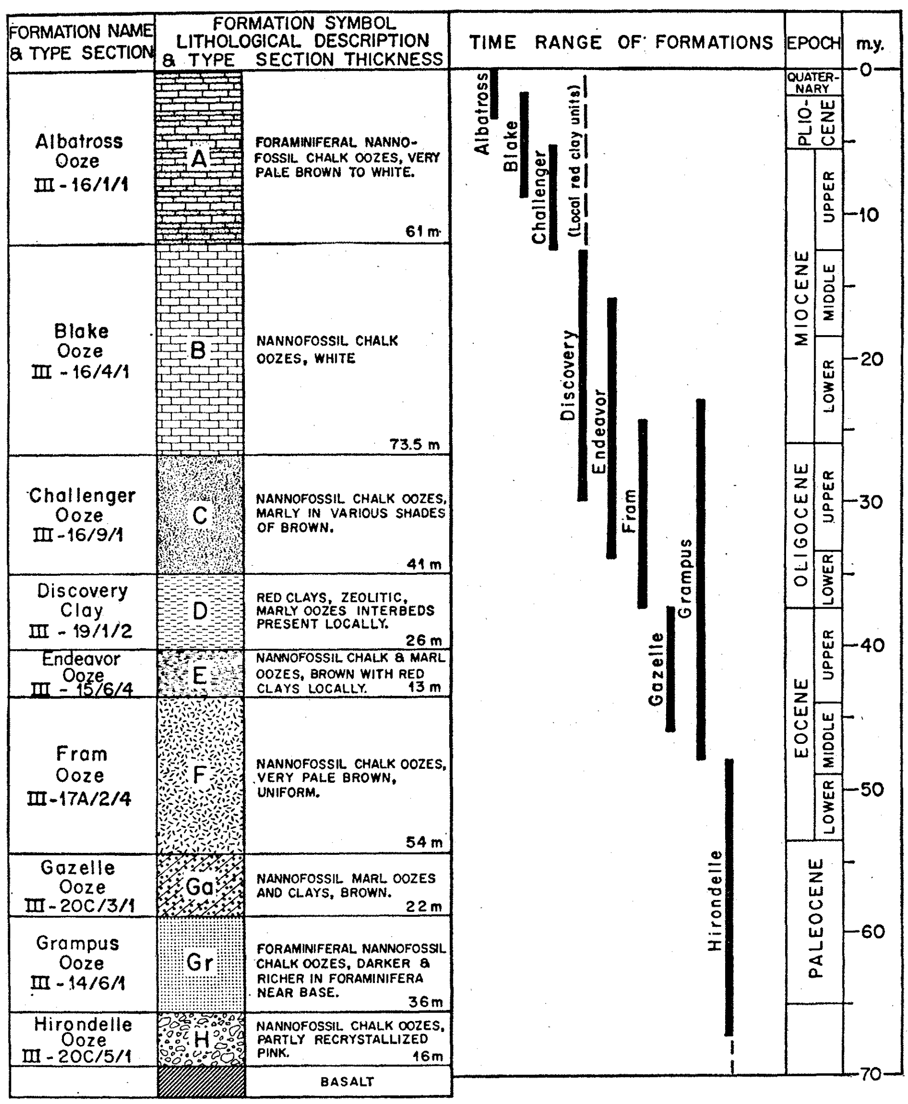


Fig. 4. A composite stratigraphic section of the Mid-Atlantic Ridge formations showing formation type, relative thickness of formation, and range of age of each formation. The numbers identify the core and the location in it at which the lithologic unit was first encountered (m.y., million years).

Sea-Floor Spreading

As has been noted (Fig. 5), the age of the sediments recovered immediately above basalt basement at each Mid-Atlantic Ridge site increases with distance from the ridge axis. To decipher the history of sea-floor spreading from these data, the distance of each site from its point of origin at the ridge axis must be determined. The procedure to obtain this distance is not always straightforward, because the Mid-Atlantic Ridge axis has numerous offsets and changes in strike along its length (*20*).

Near 30°S, the ridge has not been surveyed in detail, although there are a few ship tracks along which geophysical data have been recorded as profiles across the ridge. Location of the ridge axis along these tracks (Fig. 6) has been determined from the prominent magnetic anomaly associated with it, or from the characteristic crestal topography (*21*). Additional data for the trend of the axis are provided from the locations of earthquake epicenters (*22*). From Fig. 6 it is possible to measure the distance from any site to the nearest ridge axis. If only distances from the axis are considered, then the displacement near 29½°S suggests that sites 15 and 16 are associated with ridge segment C, sites 17 and 18 with B, and all others are nearly equidistant from either B or C. Linear distances of sites from the ridge axis are summarized in Table 6, in which the errors in distances represent a subjective estimate of the uncertainty in axis location.

Other values of distances from the ridge axis are obtained from a model of rigid rotation of crustal plates on a sphere. This model requires the trace of the motion of any part of the surface to describe a small circle about its axis of rotation. Thus, the distance traversed by any site on the spreading ocean floor, which is rotating away from the Mid-Atlantic Ridge axis, would be slightly different from that obtained simply by measuring the linear distance to the nearest ridge axis. More importantly, the original location of any site along the axis will be different in the two cases. From a hypothesized fitting of the continents of Africa and South America, it has been shown (*23*) that the present positions of these continents can be explained as a rotation about an axis at 44°N, 30.6°W. Other authors (*24, 25*) have refined the location of rotation axes farther north on the basis of the trends of linear magnetic anomalies and fracture zones and have inferred differential rates of spreading along the ridge axis.

The last column of Table 6 shows the distances of drilling sites from the ridge axis for the rotational spreading hypothesis, obtained by using the rotational axis at 62°N, 36°W proposed by Morgan (*24*). The major difference in distances of sites from the ridge axis is for site 17, which for the case of rotation is associated with segment C (Fig. 6) of the ridge axis. Site 18, however, remains associated with segment B, so that the difference in distances of sites 17 and 18 from the ridge axis is greater than their actual geographic separation.

A fracture zone that displaces the ridge crest, perhaps extending eastward between sites 17 and 18, may support this interpretation. Unusually large depths were recorded between sites 17 and 18; such depths are sometimes characteristic of fracture zones (*20, 26*). If the fracture zones of the South At-

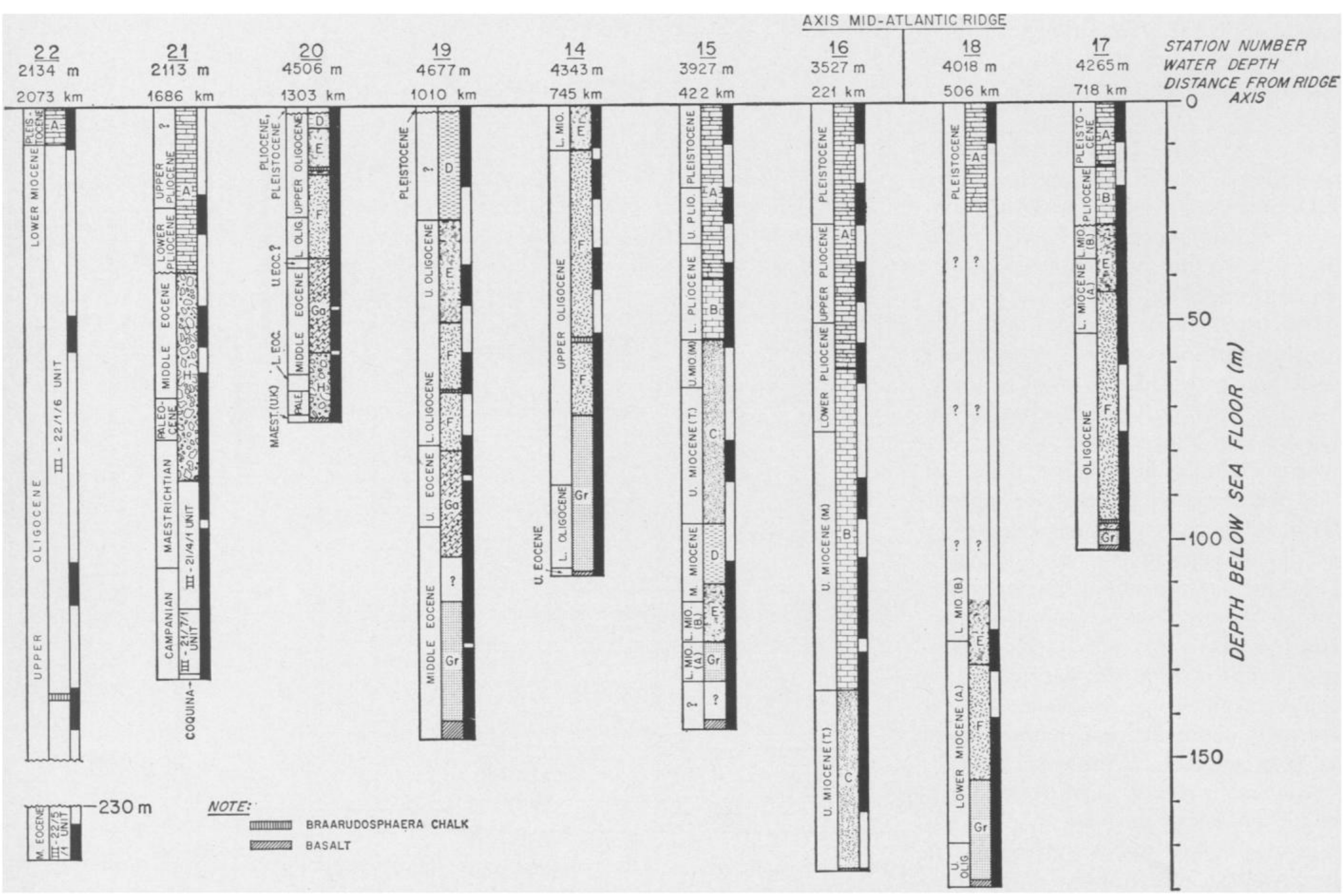


Fig. 5. Summary of formations, ages, and cores recovered from the Mid-Atlantic Ridge and Rio Grande Rise sites. Water depth and distance from the ridge axis have been added, although they are not shown to scale on the plots.

lantic trend somewhat north of due east, a direction consistent with the proposed axes of rotation, then this fracture zone may be the same as that displacing the ridge crest at 29½°S between segments B and C (Fig. 6).

Estimated uncertainties in the paleontologic ages have been determined from the stratigraphic correlation by Berggren (*8*). However, a more recent compilation (*27*), based on radiometric dates within stratigraphic sequences on the continents, gives somewhat different ages for some paleontologic stages, particularly during the mid-Tertiary. Implications of some of these uncertainties will be discussed.

The values in Table 6 show an overall linear relationship of age versus distance from the ridge axis. If the nearest distance to the ridge axis is selected, the average spreading rate back to 66 million years ago for these drilling sites appears slightly less than 2 centimeters per year. For a rotation axis in the North Atlantic, the best-fitting spreading rate appears to be nearly equal to 2 centimeters per year (see Fig. 7). If the more recent paleontologic ages of Berggren (*27*) are accepted, the average rates may be slightly increased in both cases but are still near 2 centimeters per year.

Sites 17 and 18 were selected on the east side of the ridge to test symmetry of the spreading pattern. Whereas the sediment ages at these sites seem to fit well with the pattern for the western flank for linear distances, site 17 appears to be somewhat younger by the rotation axis interpretation (Fig. 7). The lack of fit for site 17 in this case may result from some east-west asymmetry in the spreading pattern, or from fracture zone displacements that may occur between the ridge crest and sites 17 and 18. Unfortunately, the magnetic anomaly pattern on the east flank of the ridge is not well enough determined to be of much help in resolving this minor problem.

The scatter of points in Fig. 7 may be interpreted to indicate past changes in the sea-floor spreading rate (*28*, *29*). For short-term constant spreading, the range of spreading rates corresponding to variations in slope between points of Fig. 7 is from 0.4 to 4 centimeters per year. Similar ranges result if the alternate paleontologic dates of Berggren (*27*) are used. Because of the uncertainty of the data, it does not appear warranted to conclude that sea-floor spreading has actually varied that much over periods of 5 to 10 million years.

Table 6. Magnetic anomaly ages, paleontologic ages, and distances of Mid-Atlantic Ridge sites from the axis. The number of the magnetic anomaly and its age has been taken from Heirtzler *et al.* (*3*). The location of sites 18 and 17 within the characteristic magnetic anomaly pattern is uncertain. Basement rock was not reached at site 21. Magnetic ages (column 2) are based on the magnetic anomaly numbers listed in Table 1; m.y., million years.

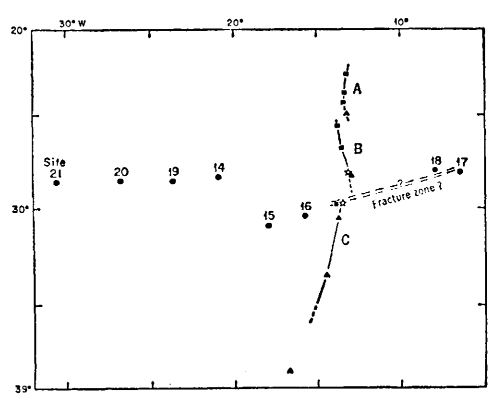
Site No.	Magnetic age of basement (m. y.)	Paleontological age sediment above basement (m. y.)	Distance from ridge axis (km): Linear	Distance from ridge axis (km): Rotation at 62°N, 36°W
16	9	11 ± 1	191 ± 5	221 ± 20
15	21	24 ± 1	380 ± 10	422 ± 20
18		26 ± 1	506 ± 20	506 ± 20
17	34–38	33 ± 2	643 ± 20	718 ± 20
14	38–39	40 ± 1.5	727 ± 10	745 ± 10
19	53	49 ± 1	990 ± 10	1010 ± 10
20	70–72	67 ± 1	1270 ± 20	1303 ± 10
21		> 76	1617 ± 20	1686 ± 10

Further, there seems to be little support in the data for cessation of sea-floor spreading for periods of more than 10 million years, as has been proposed for the Miocene (5.5 to 22.5 million years) and the Paleocene (53 to 65 million years) (*25*). Greater ranges in spreading rates than have been observed would be needed if long periods of low or no spreading are postulated.

Another possible explanation for some of the scatter in the data may be shifts in the axis of injection of new rocks in the sea floor, perhaps resulting in a normal distribution about a geographic axis (*30*). For some clearly defined magnetic profiles across ridges, the standard deviation of the normal distribution appears to be as small as 3 kilometers; on others, it appears to be about 5 kilometers. For the South Atlantic, where the pattern appears relatively regular, the standard deviation is probably not more than 5 kilometers. In this case, 95 percent of the sea floor has an origin within 10 kilometers of its position predicted from ideal sea-floor spreading (±2 standard deviations, or ±10 kilometers, to either side of the ridge axis); or, in other words, there is only a 5 percent probability that any part of the sea floor originated more than 10 kilometers away from its most probable position within the sea-floor spreading scheme, if it is assumed that the process has remained constant throughout the time required to form the sea floor. This additional uncertainty of 10 kilometers might explain some of the data scatter in Fig. 7.

Relative displacements of the ocean floor between drilling sites due to fracture zones may also contribute to the scatter of the data. The relatively small scatter implies that any such displacements have been less than 50 to 100 kilometers.

A South Atlantic spreading rate of 2 centimeters per year has been deduced earlier from studies of the marine magnetic field anomalies (*2*). The magnetic anomaly ages predicted for the drilling



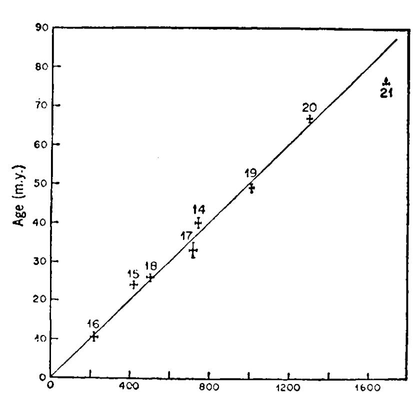


Fig. 6 (left). Trend of the axis of the Mid-Atlantic Range in the South Atlantic as determined from geophysical evidence obtained at the locations indicated, plus earthquake epicenter data. The drilling sites are shown relative to the ridge axis. Sources of data: squares, from (*21*); stars, from (*1*); triangles, from Lamont Geological Observatory data. Fig. 7 (right). The age of the sediment immediately above basalt basement is plotted as a function of distance from the ridge axis (m.y., million years).

sites are listed in Table 6. Reasonably good agreement exists between predicted magnetic ages and ages determined from paleontology, especially when the uncertainty in locating the site in relation to the center of the magnetic anomaly is considered. Perhaps the only significant departures from the predicted ages are at sites 19 and 20. Both sites had ages somewhat younger than predicted, which suggests that the proposed geomagnetic time scale (*3*) may require some minor revision for ages of 50 million years or greater, in the same direction but probably not so large as suggested by Le Pichon (*25*).

It is concluded that the sea floor of the South Atlantic has been spreading at an essentially constant rate for the past 67 million years. Further, the spreading half-rate of 2 centimeters per year (determined from the drilling) is in agreement with and has provided a critical test for both sea-floor spreading and magnetic stratigraphy.

History of the South Atlantic Basin

From the data presented above, an interpretation of the geologic history of the South Atlantic evolves from a model of nearly constant sea-floor spreading with significant vertical movements of the crestal region. Changes in the ridge elevation may be related to small but significant changes in the spreading rate. The idea of a lapse in sea-floor spreading has been suggested earlier by Ewing and Ewing (*29*) on the basis of interpretations of the seismically determined sediment thickness. In addition, the narrowness of the high heat flow at the axial region of the Mid-Atlantic Ridge led Langseth and others (*28*) to suggest an increase in the rate of spreading during the last 10 million years. Schneider and Vogt (*31*) also postulated nonsteady Atlantic spreading, on the basis of additional evidence furnished by discontinuities in ridge topography and in amplitudes of magnetic anomalies. However, the approximately constant spreading rate of 2 centimeters per year since the Cretaceous (determined from the drilling) almost precludes large changes or long interruptions in the spreading rate. Nonetheless, some variations in spreading rate have not been excluded. As we have noted, the data could be interpreted to include short-term changes in spreading rates of nearly one order of magnitude, although we believe it is probable that the spreading has been much more constant.

We have discussed the strong evidence furnished by the sedimentary record of a nonsteady sea-floor depth, which may be correlated with spreading rate variations. For, if there had been steady spreading and flank subsidence only, the geologic column at each site should be a regular succession of gradually deepening sediments. The superposition of moderate to rich carbonate sediments, of Upper Miocene age and younger, over sediments that had been accumulated in much deeper waters (at sites 15 and 17) indicates a Late Cenozoic rejuvenation of the Mid-Atlantic Ridge.

The cause of crestal relief is no doubt related to the abnormally light mantle that now underlies the ridge (*32*). This light mantle density is, in turn, related to the abnormally high heat flows measured on the axial portion of the ridge (*21*, *28*). As a newly created crust was conveyed aside to flank regions underlain by a mantle of normal density, or as the mantle was altered (thermally or chemically) to a more normal structure, subsidence must have occurred. The crestal uplift and the flank subsidence are probably not simply the result of thermal expansion alone. Mantle-density variations caused by phase changes or other processes, as well as isostatic subsidence, must be taken into consideration to explain the relief of ocean bottoms (*31*, *33*).

The drilling results clearly support the evidence that the sea floor of the South Atlantic has been spreading apart since Cretaceous at an average half-rate of 2 centimeters per year, with new basalt crust being continually created at the crestal region. We adopt the premise that the South Atlantic lithostratigraphic formations represent dissolution facies, the depths of which are related to the calcite-compensation depth. In the present discussion, the dissolution facies are attributed primarily to absolute variations in depth of deposition—that is, to variations in ridge elevations—rather than to relative variations of the depth of the lysocline.

As the elevation difference between the crest and flank of the Mid-Atlantic Ridge is some 3000 meters, a crustal segment has probably subsided this amount as it was moved from the crest to the lower flank. The early Tertiary chalk ooze to red clay succession provides evidence for a subsiding conveyor-belt model of sedimentation. Sediments showing slight to moderate dissolution were deposited on a newly created basalt basement in the crestal areas of an ancestral Mid-Atlantic Ridge, which stood hundreds or a thousand meters above the calcite-compensation depth. Sediments of more nearly red clay facies were accumulated as the sea floor was conveyed to the deeper outer flanks by spreading. The sea floor at site 20 reached the compensation depth during Late Oligocene, but the sea floor at site 15 reached it only during Middle Miocene. The carbonate-rich Neogene sediments were deposited in the crestal areas, which remained high above the calcite-compensation depth. This interpretative model best explains the observed facies pattern. The fact that each time marker is represented by a more carbonate-rich formation toward the ridge crest and by a more nearly carbonate-free formation farther out can be considered an expression of the topography of the ancestral Mid-Atlantic Ridge.

A graphic presentation of this interpretation is shown in Fig. 8. In this figure a series of stratigraphic sections has been reconstructed for five reference dates: (a) end of Eocene (37 million years ago), (b) end of Oligocene (26 million years ago), (c) end of Lower Miocene Aquitanian (23 million years ago), (d) end of Miocene (6 million years ago), and (e) present. The following procedures were used:

1) For each reference date the sites were displaced toward the ridge axis a distance corresponding to the amount the sea floor had spread during the period between the preceding reference date and the new one.

2) At the new locations all sediments younger than the reference date were removed from the sections.

3) The bathymetry of each site was then redetermined by examining the newly exposed formation and relating its depositional depth to the calcite-compensation depth, as was discussed earlier.

4) The elevation of the ridge axis at each reference date was extrapolated, primarily on the basis of the interpreted bathymetry of the nearby sites.

5) The lithostratigraphy has been shown by a columnar section for each site, and time lines have been drawn between sections to indicate age of the formations.

Although the average linear spreading rate was 2.0 centimeters per year, in some instances this rate was modified slightly to accommodate stratigraphy. For example, site 15, which is now located 422 kilometers from the axis, includes Aquitanian sediments; therefore, a spreading rate of 1.5 centimeters per year had to be used for the reference date of 23 million years.

Figure 8 shows that the sedimentary regime in the South Atlantic basin has not changed radically during the last 80 millions years. A relatively thin blanket of chalk oozes, with some marl oozes and red clays, has covered the ridge. No turbidity current deposit managed to find its way here, probably because it was trapped in basins near the continents (such as the Brasilian and Angola basins). The formations of the ridge province have been distinguished mainly by their different degrees of dissolution. In contrast, production rate and current erosion may play a more important role in the Rio Grande Rise province. Whereas unconformities between the ridge sediments appear to have resulted largely from dissolution, the hiatus in the rise sediments has almost certainly been the work of mechanical removal. Data from site 21 suggest that the rise remained high, while the ridge widened and, at times, deepened during the Tertiary.

With the assumption of an average spreading rate of 2 centimeters per year, it is possible to estimate that the separation of South America and Africa began some 130 million years ago, or during the Early Cretaceous. This is consistent with a geological comparison of Brazil and Gabon, which has shown a striking similarity of the Aptian and older rocks in these countries, and their separation was thus dated as Middle Cretaceous, or some 120 million years old (*34*). Unfortunately, the results of the leg 3 drilling cannot give a definitive answer on the age of separation, since the oldest dated sediment in the South Atlantic is Campanian (<80 million years). Yet the evidence does indicate that the South Atlantic came into being either during Late Jurassic or during Early Cretaceous, and the ocean was already some 3000 kilometers wide as the Campanian (oldest cored sediment) at site 21 was deposited.

The oldest Cretaceous sediments of the Rio Grande Rise province were deposited in relatively shallow waters, either on a fragment of a foundered continent or on a group of subsiding guyots. The oldest cored sediments of the ridge province is Maestrichtian, or some 70 million years old. By the end of Eocene (Fig. 8a), the ridge was already a distinct topographic feature, although the Atlantic was not yet sufficiently deep for red clays to have been deposited. The very slow rate of deposition of the Maestrichtian, Paleocene,

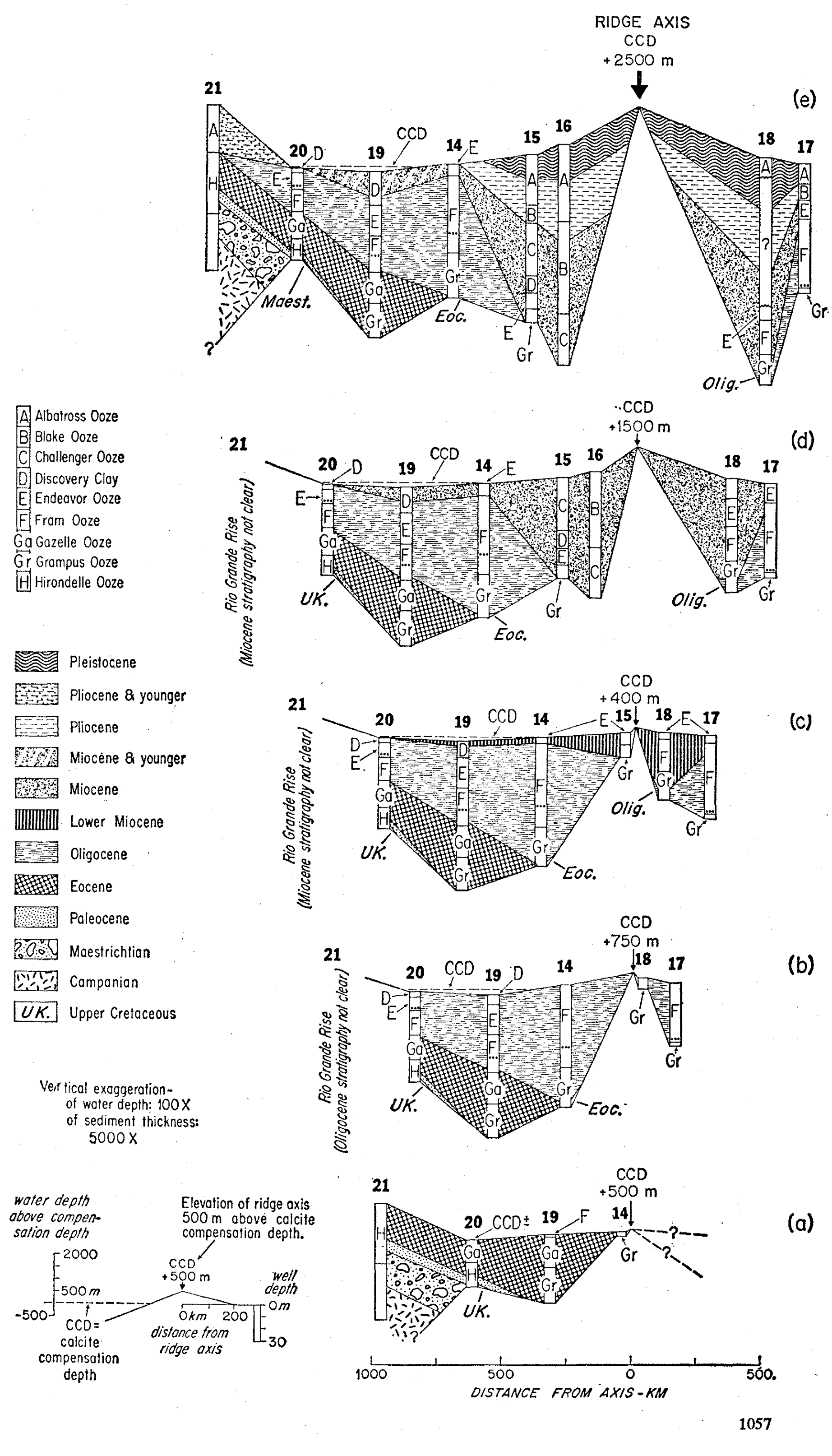


Fig. 8. Reconstruction of the history of the South Atlantic, with sea-floor spreading, paleontologic ages, and lithologic formations taken into consideration. Details of the procedures used are described in the text. The distances between sites, the bathymetry, and the stratigraphical thickness are shown at different scales for effective illustration. The top line connecting each section represents the past topography; the bottom line illustrates the sediment-basalt contact. (a) End of Eocene (37 million years ago); spreading rate, 1.9 centimeters per year. (b) End of Oligocene (26 million years ago); spreading rate, 1.8 centimeters per year. (c) Lower Miocene to end of Aquitanian (23 million years ago); spreading rate, 1.5 centimeters per year. (d) End of Miocene (6 million years ago); spreading rate, 2.0 centimeters per year. (e) Present stratigraphy.

and Lower Eocene sediments in the ridge province and the existence of disconformities indicate, however, considerable dissolution of $CaCO_3$, particularly of planktonic Foraminifera; thus, the Hirondelle Formation at site 20 is considerably thinner and is much poorer in Foraminifera than its counterpart on the Rio Grande Rise.

The Grampus Ooze first appeared during the Middle Eocene at site 19. From then until Early Miocene this unit of moderate and locally high carbonate content invariably includes the first sediments deposited on the newly formed basalt crust (see Fig. 8). The Grampus Ooze can thus be considered the crestal deposit on the ancestral Mid-Atlantic Ridge. The Middle and Upper Eocene flank deposits constitute the low carbonate Gazelle Formation. Site 20 must have deepened to the compensation depth during the Late Eocene time, so that the Upper Eocene deposits are almost entirely missing there, probably having been removed by dissolution.

There may have been a slight uplift of the ocean bottom, or a slight depression of the absolute depth of calcite compensation during the Early Oligocene. In any case, the Fram Ooze of moderate $CaCO_3$ content was superposed on the flank above the low carbonate Gazelle. The rates of the Fram sedimentation are also significantly higher. By the end of the Oligocene, however, the flank sites (sites 19 and 20) dropped below the calcite-compensation depth, whereas the crestal area stood some 1000 meters higher to permit high carbonate sedimentation (Grampus of site 18).

A noteworthy sedimentary event took place during the Middle Oligocene, when the *Braarudosphaera* chalk was deposited. This chalk unit extended across the entire basin at this time and is thickest on the Rio Grande Rise. The reason for this impressive bloom of *Braarudosphaera rosa* and the exclusion of other calcareous planktons is unknown. The condition was apparently recurrent, because more than one such chalk layer was found at site 20.

A general subsidence must have commenced during Early Miocene. The Lower Miocene sediment at site 15, which then lay close to the ridge axis, is the Endeavor Ooze of moderate $CaCO_3$ content, suggestive of a deeper ridge axis. Accordingly, a height for the crest of the calcite-compensation depth plus 400 meters has been postulated as 4100 meters by assuming the present calcite-compensation depth, or as 4600 meters by assuming Heath's (*19*) calcite-compensation depth. The subsidence led also to an encroachment of the compensation depth laterally toward the ridge axis. The subsidence continued during the Middle Miocene, when the Endeavor was superposed by a carbonate-poor Discovery unit at site 15. Solution rates on this deep Mid-Atlantic Ridge must have been rapid. The Middle Miocene is represented either by a red clay barren of calcareous planktons, or by a solution unconformity at the ridge sites farther out than site 15.

The condition of red clay sedimentation in the Middle Miocene was not restricted to the South Atlantic. The Miocene at site 10 on the flank of the northern Mid-Atlantic Ridge showed largely zeolitic red clays (*35*). Mid-Tertiary red clays barren of fossils at site 12 in the Cape Verde Basin (*35*) and at site 13 on the Sierra Leone Rise (*1*) were also deposited during a time span that included the Middle Miocene.

The great depth of the Middle Miocene Atlantic may have coincided with a period of lower crestal heat flow and of denser subcrestal material, which produced a slower rate of sea-floor spreading. This theory is supported for the period from the end of Aquitanian to end of Miocene by the sedimentation pattern, which suggests a rate markedly slower than 2.0 centimeters per year.

A rejuvenation of the Mid-Atlantic Ridge and an increase in spreading rate took place during the Late Miocene. By the end of the Miocene (Fig. 8), the new crestal area stood at about 1500 meters above the calcite-compensation depth (at a depth of 3000 meters, if the present calcite-compensation depth is assumed). At site 16, located near the crest, the Challenger Ooze is high in $CaCO_3$, though poorer at site 15 some 200 kilometers to the west. At sites 14 and 19, the sea floor remained below the compensation depth, where the Upper Miocene is represented by a red clay and by unconformity.

The uplift of the ridge may have continued during the Plio-Pleistocene. The present crestal elevation at a depth of 2 kilometers has probably never been exceeded. The Albatross Ooze with moderate to high $CaCO_3$ content is now being deposited to a distance of some 650 kilometers from the ridge axis (site 17). Farther out, at sites 14, 19, and 20, the ocean floor has remained largely below the compensation depth since Late Oligocene or Early Miocene. Younger calcareous plankton deposits are either absent or are present only as a very thin veneer.

Summary

A series of nine holes drilled in profile across the Mid-Atlantic Ridge in the South Atlantic has provided samples from which a sedimentary history of the South Atlantic can be reconstructed back to Early Cretaceous. Paleontologic studies of the age of the sediment immediately above the basalt basement indicate that the sea floor has, overall, spread uniformly at an average half-rate of 2 centimeters per year during this period. Nine separate sediment formations were identified from their lithologies and physical properties. By assuming a hypothesis of calcium carbonate dissolution during deposition, we have interpreted the distribution of these formations as an indication of major changes in the elevation of the Mid-Atlantic Ridge. The changes in elevation may be associated with short-term changes in the rate of sea-floor spreading. For example, the ridge was depressed in elevation during the Middle Miocene, at a time when the sea floor may have spread more slowly as compared with earlier and more recent periods.

The overall rate of sea-floor spreading determined from the drilling has been found to be nearly identical with the rate determined from the study of magnetic anomalies. This agreement provides strong support for the hypothesis of sea-floor spreading and the concept of magnetic stratigraphy. An extrapolation of the sea-floor spreading rate to the continental shelves in the South Atlantic suggests that the ocean in this area was formed during the Early Cretaceous Period.

References and Notes

1. A. E. Maxwell *et al.*, *Initial Reports of the Deep Sea Drilling Project* (U.S. Government Printing Office, Washington, D.C., 1970), vol. 3.
2. G. O. Dickson, W. C. Pitman III, J. R. Heirtzler, *J. Geophys. Res.* **73**, 2087 (1968).
3. J. R. Heirtzler, G. O. Dickson, E. M. Herron, W. C. Pitman III, X. Le Pichon, *ibid.*, p. 2119.
4. W. C. Pitman III and J. R. Heirtzler, *Science* **154**, 1164 (1966).
5. H. M. Bolli, *U.S. Nat. Mus. Bull.* **215**, 97 (1957).
6. Walter H. Blow, *Proc. Int. Conf. Planktonic Microfossils Leiden 1st* **1**, 199 (1969).
7. H. H. Hess, in *Petrologic Studies*, A. E. J. Engel *et al.*, Eds. (Geological Society of America, New York, 1962), pp. 599–620; R. S. Dietz, *Nature* **190**, 854 (1961).

8. W. A. Berggren, *Micropaleontology* **15**, 351 (1969).
9. J. E. Andrews and K. Jinghwa Hsü, *American Stratigraphic Commission Note 38* (American Association of Petroleum Geologists, Tulsa, in press).
10. M. N. Bramlette, *Geol. Soc. Amer. Bull.* **69**, 121 (1958).
11. W. H. Berger, *Science* **156**, 383 (1967).
12. ———, *Deep-Sea Res.* **15**, 31 (1968).
13. M. N. Bramlette, in *Oceanography*, M. Sears, Ed. (AAAS, Washington, D.C., 1961), pp. 345–366.
14. M. N. A. Peterson, *Science* **154**, 1542 (1966).
15. J. D. Hudson, *Mar. Geol.* **5**, 473 (1966).
16. R. A. Berner, *Geochim. Cosmochim. Acta* **29**, 947 (1965).
17. C. Emiliani and G. Edwards, *Nature* **171**, 887 (1953); H. A. Lowenstam, in *Problems in Palaeoclimatology*, A. E. M. Nairn, Ed. (Interscience, London, 1964), pp. 227–252.
18. G. O. S. Arrhenius, *Rep. Swed. Deep-Sea Exped.* **5** (fascile 1), 1 (1952); W. R. Riedel and B. M. Funnell, *Quart. J. Geol. Soc. London* **120**, 305 (1964).
19. G. R. Heath, *Geol. Soc. Amer. Bull.* **80**, 689 (1969).
20. B. C. Heezen and M. Tharp, *Phil. Trans. Roy. Soc. London Ser. A* **258**, 70 (1965).
21. V. Vacquier and R. P. Von Herzen, *J. Geophys. Res.* **69**, 1093 (1964).
22. C. W. Stover, *ibid.* **73**, 3807 (1968).
23. E. Bullard, J. E. Everett, A. Gilbert Smith, *Phil. Trans. Roy. Soc. London Ser. A* **258**, 41 (1965).
24. W. J. Morgan, *J. Geophys. Res.* **73**, 1959 (1968).
25. X. Le Pichon, *ibid.*, p. 3661.
26. H. W. Menard, *Marine Geology of the Pacific* (McGraw-Hill, New York, 1964), chap. 3.
27. W. A. Berggren, in preparation.
28. M. G. Langseth, Jr., X. Le Pichon, M. Ewing, *J. Geophys. Res.* **71**, 5321 (1966).
29. J. Ewing and M. Ewing, *Science* **156**, 1590 (1967).
30. D. H. Matthews and J. Bath, *Geophys. J. Roy. Astron. Soc.* **13**, 349 (1967); C. G. A. Harrison, *J. Geophys. Res.* **73**, 2137 (1968).
31. E. D. Schneider and P. R. Vogt, *Nature* **217**, 1212 (1968).
32. X. Le Pichon, R. E. Houtz, C. L. Drake, J. E. Nafe, *J. Geophys. Res.* **70**, 319 (1965); M. Talwani, X. Le Pichon, M. Ewing, *ibid.*, p. 341.
33. K. J. Hsü, *Amer. J. Sci.* **263**, 97 (1965); K. J. Hsü and S. O. Schlanger, *Int. Geol. Congr. Rep. Sess. Prague 23rd* **1** (section 1), 91 (1968).
34. G. O. Allard and V. J. Hurst, *Science* **163**, 528 (1969).
35. M. N. A. Peterson *et al.*, *Initial Reports of the Deep Sea Drilling Project* (Government Printing Office, Washington, D.C., 1970), vol. 2.
36. M. N. Bramlette and J. A. Wilcoxon, *Tulane Stud. Geol.* **5**, 93 (1967).
37. W. W. Hay, *Trans. Gulf Coast Assoc. Geol. Soc.* **17**, 438 (1967).
38. The Deep Sea Drilling Project is part of the National Ocean Sediment Coring Program supported by the National Science Foundation. Contribution 2414 from the Woods Hole Oceanographic Institution.

Proteins in Excitable Membranes

Their properties and function in bioelectricity are discussed.

David Nachmansohn

Cell Membranes

During the last decade, the properties and function of cell membranes have been one of the most actively explored fields in biological sciences; much information has been obtained from electron microscopy combined with biochemical and biophysical analyses. The notion of a "unit membrane," which was based on the Danielli-Davson model, proposed a structure about 80 Å thick, formed by a bimolecular leaflet of phospholipids to which proteins are attached on the inside and outside by ionic forces (*1*). These views have been contested (*2*). Membranes appear to be a mosaic of functional units formed by lipoprotein complexes. The proteins apparently form the core of the complexes; phospholipids are attached on the outside, probably by Van der Waals and coulombic forces and by hydrophobic bonds (*3*). This idea has found much support, although it does not exclude the possibility of modifications, for example, lipid layers located between these complexes (*4*). While the precise molecular organization of cell membranes is far from elucidated, the most important change in the last few years has been conceptual. It is now well established that cell membranes are highly organized and dynamic structures, in which many proteins and enzymes are located and form by their activity an essential part of the control mechanisms effected by membranes. An illustration of the character and intensity of the chemical reactions taking place in these structures offers the well-explored mitochondrial (*5*) and other membranes (*6*). The central role of proteins and enzymes in cell membranes accounts for their great diversity of function, their specificity, and their remarkable efficiency more readily than the previous notions based essentially on the physicochemical properties of phospholipids. In view of the crucial role of proteins in membrane function, Sjoestrand and Barajas (*7*) have applied new procedures in preparing specimens for examination by electron microscopy aimed at preserving the conformation of proteins in their native state. Their pictures are quite different from those obtained with the standard procedures and offer evidence for the presence of globular structures.

Nerve impulses are propagated along nerve and muscle fibers by electric currents; bioelectricity is thus linked to one of the vital functions of the body. Since the turn of this century it has been widely accepted that ions are the carriers of these currents; the control of the ion movements was attributed to rapid and reversible permeability changes to ions of the excitable membranes surrounding the fibers. This special ability is a key problem for understanding nerve function. Hodgkin and Huxley proposed that the ion movements are a simple diffusion process and account exclusively for conduction (*8*). This view is difficult to reconcile with a variety of facts and has been repeatedly challenged (*9*). In contrast to conduction, transmission across the junctions from nerve to nerve or from nerve to muscle was proposed to be effected by chemical mediators, in many cases specifically by acetylcholine (AcCh). In view of basic similarities of the electrical properties of the membranes of axons and those at junctions, many neurobiologists questioned the transmitter theory, which was based on experiments in which classical methods of pharmacology were combined with those of electrophysiology (*10*). These methods, essential for the study of many aspects of biology and medicine, are inadequate for an analysis of the molecular events in excitable membranes.

A chemical theory, proposed more than two decades ago, resulted from a new approach based on the notion of

The author is Professor of Biochemistry in the Departments of Neurology and Biochemistry, College of Physicians and Surgeons, Columbia University, New York 10032.