13. SUMMARY AND CONCLUSIONS

The Shipboard Scientific Party[1]

SIERRA LEONE RISE

(K. J. H.)

Sedimentary History

It was not possible to penetrate the earliest sedimentary record of the Sierra Leone Rise; therefore, no cores were collected which would shed light on the pre-Upper Cretaceous history. Unfortunately. it is not possible to answer the simple questions: Were the first sediments deposited on an oceanic crust? Were they shallow- or deep-water sediments? However, whatever the previous history was, the region about Site 13 was already a part of a deep ocean during the early Late Cretaceous time.

The sedimentary history of the section which was penetrated by drill can be divided into four major epochs:

1. Pelagic sedimentation with much terrigenous influx in the Late Cretaceous.
2. Deposition of siliceous planktons in the Eocene.
3. Red clay sedimentation in the Middle Tertiary.
4. Deposition of calcareous planktons in the Pliocene.

The lowest Cretaceous unit (3-13A-7-1) of red shales with chert intercalations represents deposition under bathyal or abyssal conditions below the compensation depth for calcium carbonate. Only rare specimens of deep-water arenaceous foraminifera were preserved. The red color renders this unit superficially similar to the Upper Cretaceous red pelagic formations of the Tethyan Geosyncline in Mediterranean countries (for example, *Capas rojas* of the Betic Cordilleras, *couches rouges* of the Prealps, and *scaglia rossa* of the Apennines). The Tethyan formations are, however, mainly calcareous–including abundant planktonic foraminifera–and were obviously deposited at a somewhat shallower depth.

During Senonian time the bottom depth at this site became more or less equal to the compensation depth for calcium carbonate. Radiolarian and calcareous oozes were laid down alternately to form the main body of Unit 3-13A-6. Red shales are also present as intercalations, suggesting a gradual depth decrease since the earlier time. The oozes have been lithified in part to form cherty limestone and dolomitic chert interbeds. Gradations from pure chert to pure carbonate were represented. These rocks bear a lithological similarity to some of the Cretaceous deep-water cherty limestones of Mexico or of Venezuela. Such similarity may not be entirely coincidental, as a paleogeographical reconstruction on the model of continental drift would place Site 13 fairly close to the Venezuela Coast during the Late Cretaceous.

The deposition of calcareous nannoplankton clays of the Unit 3-13A-2-1 may represent a further decrease in oceanic depth at the drill site during the latest Cretaceous times. The calcium carbonate content increase, from about 6 per cent in lower Senonian clays (3-13A-5) to about 40 per cent in Maestrichtian marl oozes, reflects progressively more conducive conditions for the preservation of calcareous nannofossils. Radiolarians are present, but calcareous planktonic foraminifera are absent or very rare in these clays. The absence of the latter has been a puzzle. The problem will be discussed more thoroughly in a later section of the report by expounding the idea that selective solution, combined with other factors, may explain the preferential preservation of calcareous nannofossils to the exclusion of calcareous foraminifera.

The Late Cretaceous sediments at Site 13, compared to all other cores of Leg 3, are characterized by a high terrigenous content. The average rate for Unit 3-13A-2-1, computed on the basis of 200 to 230 meters (656 to 754 feet) in 15 to 20 million years, is about 1.2 ± 0.2 cm/t.y. Since the sediments include, on the whole, about 20 to 30 per cent calcium carbonate, the rate of terrigenous deposition was approximately 1. This represents a high influx of terrigenous sediments into this area during the Late Cretaceous as insoluble terrigenous residues. Red clay sediments were commonly accumulated at an order of magnitude slower rate.

There was a reduction in the terrigenous influx when the uppermost Maestrichtian foraminiferal chalk ooze

[1]A. E. Maxwell and R. P. von Herzen, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts; J. E. Andrews, University of Hawaii, Honolulu, Hawaii; R. E. Boyce and E. D. Milow, Scripps Institution of Oceanography, La Jolla, California; K. J. Hsu, Geologisches Institut, Zurich, Switzerland; S. F. Percival, Princeton University, Princeton, New Jersey; and, T. Saito, Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York.

was deposited. A major change occurred in the Eocene when the sediments laid down consisted almost exclusively of siliceous planktons, radiolarians and diatoms (Unit 3-13-3-1). The rarity of calcareous planktons (commonly 1 per cent or less) suggests accumulation at, or beneath the compensation depth for calcium carbonate; those that remain are calcareous nannofossils, with no planktonic foraminifera being preserved. Intercalated in the oozes are several thin, but hard chert layers of uncertain origin. At least 40 meters (131 feet) of the siliceous oozes were deposited during the 4-million year Middle Eocene interval, representing a 1 cm/t.y. rate. On the other hand, the whole early Tertiary section was probably not more than 100 meters (328 feet) thick (for some 40 million years), giving an average sedimentation rate of 0.25 cm/t.y. Apparently, there were times (during the Paleocene and, probably, also the Oligocene) when little or no sediments were deposited. The occurrence of siliceous oozes at Site 13 supports the hypothesis of the JOIDES Atlantic Advisory Panel that a strong equatorial current system flowed between the Atlantic and the Pacific during the Eocene. Also noteworthy is the fact that such an Eocene siliceous ooze formation is absent at the sites along the 30°S traverse outside of the equatorial current system.

Deposition of brown zeolitic clay sedimentation took place at the Sierra Leone Rise area during the middle Tertiary. This condition apparently persisted from the Oligocene to the Pliocene here, as well as at several sites in the North Atlantic drilled by the Leg 2 cruise. In contrast, regional red clay sedimentation at 30°S (represented by the Discovery Formation) was restricted to a shorter time span, for example, to the Middle Miocene at Site 15. The average rate of brown clay sedimentation was 0.3 cm/t.y.; the actual rate might be somewhat higher (0.5 cm/t.y.) if the Oligocene epoch was represented by a hiatus here, as may be implied by the study of drill bit samples.

Geological Problems

Site 13 was selected to study the Cretaceous and Tertiary equatorial floras and faunas of the Atlantic, and their relationship to the ancient current system, and to identify the reflector similar to Horizon A of the western North Atlantic Basin. Several problems of general interest arose during the course of shipboard investigation:

1) *Oceanic sedimentation.* Leg 3 findings confirm the results by previous drilling that disconformities resulting from submarine erosion or non-deposition are not uncommon in deep marine sediments. The agents which prevented deposition, or caused erosion may be mechanical (e.g., strong bottom currents), or chemical (e.g., dissolution of calcareous and siliceous planktons). Interesting, too, is the fact that the planktonic organisms in a pelagic sediment may consist almost exclusively of one type of organism: for example, siliceous oozes, calcareous nannofossil clays. There seems to have been an effective sorting mechanism which reflects the production and/or dissolution rates of pelagic organisms. Furthermore, the conditions must have remained sufficiently constant so that sediments of uniform lithology could have accumulated to tens or hundreds of meters in thickness.

2) *Oceanic diagenesis.* The occurrences of multiple layers of hard sedimentary rocks bear testimony to lithification under oceanic conditions. Cherts are present as thin layers in units containing abundant Radiolaria. Calcareous nannofossil claystones (Unit 3-13A-2-1) are silicified in part, also. Some cherts are definitely dolomitic (Unit 3-13A-6). There was no association of cherts with turbidites, since there were no turbidites identified at Site 13. Because there appears to be no firm evidence of a transition between the cryptocrystallized chert and the well-preserved radiolarian, it is possible that chert might have been formed from the lithification of chemical precipitated silica gels.

The occurrence of red shale indicates that pelitic sediments can also be lithified under submarine conditions with moderate overburden (some 450 meters). The change from red shale to green gray nannofossil claystone during the Late Cretaceous might be related to a decrease in bottom depth and corresponding change in p_{O_2} of bottom waters.

3) *Nature of reflectors.* Drilling at Site 13 confirms discoveries by earlier Deep-Sea Project drilling that the Horizon "A" reflector consists of one or more Eocene chert layers at some locations. However, what had been interpreted as a "rough basement reflector" may actually be an Upper Cretaceous chert layer, at 432 meters (1417 feet). It is possible that the "basement" lies at no greater depth beneath this chert, for there is some evidence from the CSP record (Chapter 3, Figures 1 and 2) that the last reflector consists of two reflections only slightly separated in reflection time. Alternatively, the basement may actually be considerably deeper and not detected on the acoustic record. In any case, the results introduce a caution to keep an open mind on the nature of the "Second Layer" in the oceans, and leave the possibility open that the oceanic sediments in this part of the Atlantic may be thicker than previously supposed.

RIO GRANDE RISE

(K. J. H. & J. E. A.)

Sedimentary History

The earliest cored sediment here is a coquina of uncertain age. This megafossil debris was probably deposited on a relatively shallow bank and sorted by winnowing currents. The water depth was not likely to have exceeded a few hundred meters, so as to permit the growth of red algae by photosynthesis.

The bank must have subsided to a depth which rendered the growth of benthonic fauna and flora unfavorable during the Campanian, the time when pelagic sedimentation began—and has continued intermittently till today.

The pelagic sediments of the Rio Grande Rise include abundant foraminifera, and those of the Cretaceous contain *Inoceramus* and other megafossils. Commonly, less than 50 per cent of the constituents are clay-sized particles (mainly nannofossils). This relatively coarse composition may have resulted from (1) the common preservation of the calcareous planktonic foraminifera at depths above the carbonate compensation depth, or (2) the winnowing of the fines from the Rio Grande Rise by bottom currents, or from a combination of these factors. Foraminifera are the dominant constituent of the Quaternary sediments, in contrast to the dominance of nannofossils in the Tertiary. This change may reflect an increase in the rate of production of the pelagic foraminifera during the late Cenozoic as Bramlette (1958) has suggested.

The sedimentary history of the Rio Grande Rise was interrupted by a major unconformity, which covered a span over much of the Tertiary. In contrast to sites on the flanks of the Mid-Atlantic Ridge, where solution unconformities are not uncommon, there is no indication that the Rio Grande Rise ever subsided below the carbonate compensation depth during the Tertiary. Therefore, it is thought that the stratigraphic hiatus on the Rio Grande Rise may have been related to submarine bottom current actions.

The unconformity at Site 21 represents a hiatus which probably spanned from the Middle Eocene to Middle Pleistocene, some 45 million years. Instead of assuming that currents were always strong enough to prevent deposition during this interval, the alternative of submarine erosion seems more probable. When the stratigraphy at the two Rio Grande Rise sites is compared, it is noted that the well-developed Upper Oligocene and Lower Miocene section at Site 22, more than 130 meters (426 feet) thick, and deposited at a 1.3 cm/t.y. rate or faster, is absent at Site 21. The possibility, however, of an incomplete equivalent being within the 17-meter (56-foot) uncored interval cannot be excluded. As Site 21 is located on the side of a deep submarine valley (Chapter 11, Figure 1), it is probable that an Oligocene-Miocene section had also been deposited there before it was removed by bottom current erosion.

Bottom currents are probably active today on the Rio Grande Rise. Less than 10 meters (33 feet) of Quaternary foraminiferal chalk oozes are present at Site 22; and, this thin veneer may represent a transient deposit which could be removed in the future by erosion.

Geological Problems

The original aims of drilling on the Rio Grande Rise were to sample the Cenozoic sediments at Site 22 and the Mesozoic sediments at Site 21, in order to obtain information on the distribution of planktonic organisms in the Southern Hemisphere. Except for the coquina, sediments older than Campanian were not penetrated by drill, and the Cenozoic section sampled is incomplete because of a major depositional hiatus. Nevertheless, valuable information concerning sedimentary processes on an oceanic rise has been obtained, and the cores provide the materials for research to further our understanding of oceanic sedimentation and diagenesis.

At Site 21, it was not possible to penetrate the lithified coquina to reach basement. If the Late Cretaceous is considered the continuation of an earlier trend, it seems probable that the earliest sediments on the Rise could have been an even shallower water deposit. However, as in the Sierra Leone Rise region, the attempt to reach the crystalline basement was frustrated. Therefore, several questions must remain unanswered: Is the Rise a fragment of a continental crust left behind as South America drifted westwards? Or is it an oceanic basalt rising above the surrounding region as a group of seamounts or guyots?

The high porosity of the coquina and its lithification present a puzzle. Equally puzzling is the deposition of the Oligocene Chalk Marker, consisting almost exclusively of one species of the nannoplankton *Braarudosphaera*. This chalk is absent at Site 21, probably because of post-depositional removal. It is 80 centimeters thick at Site 22, some 3000 kilometers west of its easternmost occurrence at Site 17.

Partial lithification of the Rio Grande Rise sediments is not uncommon. All the reflectors penetrated by drill turn out to be sedimentary rocks. The *Braarudosphaera* Chalk is sufficiently lithified to be a weak acoustical reflector. Silicification may have enhanced the hardening of the Eocene chalk oozes, so that these more or less friable cherty carbonate rocks constitute a strong reflector on the Rio Grande Rise, which could be considered a correlative of the Eocene Horizon A in the North and Equatorial Atlantic. The Cretaceous pelagic oozes show signs of progressive lithification with burial. The deeper cores contain relatively fewer identifiable nannofossils and more crypto-crystalline calcite, which apparently formed as a recrystallization product at the expense of nannofossils. The deepest

Campanian oozes have been consolidated into friable rocks (3-21-8, Sections 4-6), and the coquina below may be hard enough to serve as the basement reflector.

The occurrence of *Inoceramus* in Rio Grande Rise sediments is not surprising. *Inoceramus* typically occurs in Cretaceous pelagic deposits of ancient geosynclines, and the *Inoceramus*-bearing pelagic ooze at Site 22 is lithologically very similar to the Seewen Limestone of the Alps (R. Trümpy, personal communication). The question whether *Inoceramus* was a deep-water benthonic genus or acquired a pelagic habitat while attached to floating sea plants could be resolved after a stable isotope analysis of the recovered materials.

MID-ATLANTIC RIDGE SEQUENCE

Paleontology (T. S. & S. P.)

An almost continuous composite stratigraphic section, ranging in age from Maestrichtian (late Cretaceous) to late Pleistocene was recovered in seven core holes (Sites 14 through 20) drilled on the Mid-Atlantic Ridge, along an east-west traverse at about 30°S Latitude. The stratigraphic correlation of all sites is based on the calcareous microfossil zonation shown in Chapter 2, Figure 1 and the stratigraphic interval recovered from each site is shown in Figure 1.

All the sites yielded calcareous sediments characterized by an abundance of calcareous nannoplankton and planktonic foraminifera. Only minor amounts of siliceous microfossils, radiolarian and diatoms were encountered in the late Tertiary and Quaternary on the eastern flank of the Mid-Atlantic Ridge (Sites 17 and 18), in association with a large diatom species, *Ethmodiscus rex* (Ratt.) Hendy. This paucity or complete lack of siliceous microfossil element in planktonic fossil assemblages is the most remarkable feature which makes the Mid-Atlantic Ridge sequences distinct from other sequences recovered from the sites (Sites 13 and 22) relatively close to the continents of Africa and South America. At these two sites, near the marginal part of the oceans, siliceous sediments consisting predominantly of Radiolaria characterize the pre-Oligocene sequence, and these sediments were associated with chert layers. The fact that the pre-Oligocene sediments were repeatedly penetrated at two sites on the Mid-Atlantic Ridge without encountering any chert layers seems to indicate that the occurrence of chert layers in the South Atlantic is closely associated with the abundance of siliceous microfossils in sediments.

The calcareous floral and faunal assemblages from the Mid-Atlantic Ridge holes include those which thrived in various climatic conditions, ranging from tropical to cold-temperate. Most of the floras and faunas prior to the mid-Tertiary are diverse and bear a close resemblance to those from the tropical regions of the world. However, the planktonic foraminifera encountered in the Upper Miocene to Upper Pleistocene sections at

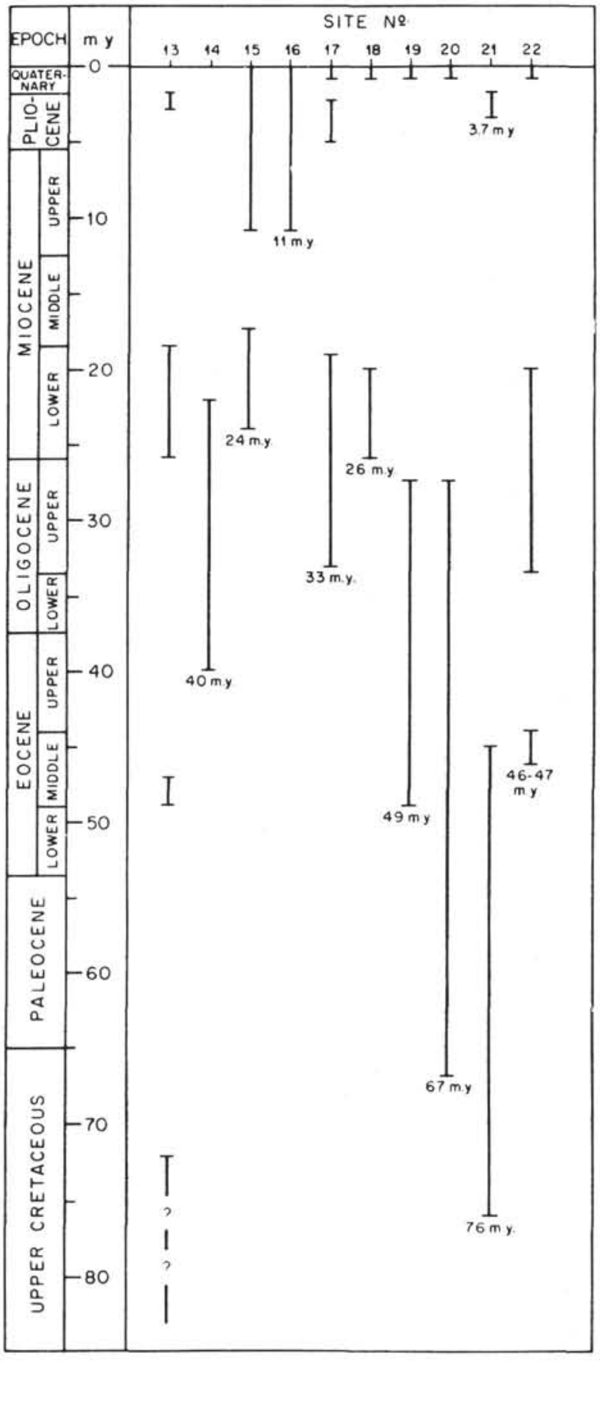

Figure 1. *Stratigraphic interval recovered from each site.*

two southernmost sites (Sites 15 and 16) are temperate ones. These faunas are characterized by relatively few species and differ markedly from the diverse tropical counterpart of the same age. Age determinations of these temperate assemblages were difficult at times because of the absence of the diagnostic species of the late Tertiary planktonic microfossil zones currently in use for stratigraphic correlation. The calcareous nannoplankton from the upper Miocene to upper Pleistocene sediments at this latitude are apparently more ubiquitous, and they include many species which have been reported from tropical areas.

The abundance of well-preserved calcareous nannoplankton and planktonic foraminifera in sediments from the Mid-Atlantic Ridge sections makes these sites ideal for use in establishing standard reference sections for parts of the Quaternary, Tertiary and Upper Cretaceous. Tentative zonal assignments have been made for the time interval from the Maestrichtian to the Middle Miocene for the planktonic foraminifera and from the Danian to Middle Miocene for the calcareous nannoplankton.

One of the more important findings is the presence of several layers of *Braarudosphaera rosa* chalk in the Oligocene section of this region. They occur most frequently in upper Oligocene, but are also present in lower Oligocene. The chalk consists almost exclusively of calcite shields of a golden-brown algae, *Braarudosphaera rosa*, both as complete specimens and isolated fragments, with an admixture of a few other species of calcareous nannoplankton. In the Upper Oligocene section, these chalk layers usually occur near the boundary of the *Globorotalia opima opima* and *Globorotalia ampliapertura* planktonic foraminiferal Zones. In the Lower Oligocene, they are present in the *Globigerina sellii*/*Pseudohastingerina barbadiensis* Zone. Although a modern representative of the pentalith (golden-brown algae), *Braarudosphaera bigelowi*, is known to be abundant in sediments of very shallow water origin—approximately 20 fathoms—all the other flora and fauna associated with the Oligocene chalk indicate bathyal depths. Since this type of chalk is found widely distributed in the South Atlantic, occurring in holes at Sites 14, 17, 19 and 20 on the Mid-Atlantic Ridge and in Hole 22 on the Rio Grande Rise, its occurrence may indicate that unusual oceanographic conditions prevailed in this region for a short geologic time interval. These conditions might either have caused the "bloom" of *Braarudosphaera rosa*, or induced currents which transported shallow-water sediments to deep water over, geographically, a very wide area. A modern analogy to the bloom hypothesis would be the so-called "Red Tide," which is the bloom of certain dinoflagellates. Whereas the Red Tide bloom is of short duration—several weeks, these Oligocene golden-brown algae blooms might have lasted several hundred or several thousand years to produce these chalks. The most interesting finding from the paleontologic studies is the correlation of paleontologic ages of sediments immediately overlying the basalt basement with ages of the basement predicted by the sea-floor spreading hypothesis. The planktonic foraminifera and calcareous nannoplankton were extremely useful for dating these sediments in all seven sites. By using the chronostratigraphic chart of W. A. Berggren (Chapter 2, Figure 1), which shows the correlation of known radiometric age dates with the planktonic foraminiferal zonations, equivalent radiometric age dates for these sediments were determined. At times, calcareous nannoplankton were found in the baked sediments associated with the basalt, thus giving a closer approximation to the age of the basalt. The result indicates that the ages of sediments overlying the basement exhibit some symmetry around the Ridge axes and flanks of the Mid-Atlantic Ridge, and show striking agreement with the ages of the oceanic crust derived from geomagnetic anomaly patterns.

A comparison of the results of the studies of the calcareous nannoplankton found in the shipboard reports and the reports by the shore laboratories—one by Bukry and Bramlette (Chapter 18) and one by Gartner (Chapter 19)—show basic agreement in the age and zonal determinations. Slight variations are found near the Pliocene-Pleistocene boundary and in the Oligocene, in both cases the age determinations used were based on the planktonic foraminifera. Slight variations in zonal determinations occur near the boundaries of the zones; however, most zonal boundaries are in agreement.

Lithology (K. J. H. & J. E. A.)

The sediments of the Mid-Atlantic Ridge province are almost exclusively pelagic. No turbidity-current deposits or mass-slide debris were found, except for the Cretaceous slump block in the Paleocene at Site 20. Yet, the lithological changes in time and in space permitted the establishment of nine formations. They are in descending order:

Albatross Ooze
Blake Ooze
Challenger Ooze
Discovery Clay
Endeavor Ooze
Fram Ooze
Gazelle Ooze
Grampus Ooze
Hirondelle Ooze.

The differences here are sufficiently obvious that eight of these formations were recognized on-board ship; only the Gazelle Ooze was added as a new formation during the course of synthesizing shipboard data for the Leg 3 Report.

A composite stratigraphic section of the Mid-Atlantic Ridge formations has been constructed and is shown by Figure 2. The formations have been recognized mainly on the basis of lithological changes with time. Initially, only two criteria were selected, namely: (1) variations in foraminifera content, and (2) differences in non-carbonate content (with corresponding color changes). Using these criteria, the topmost foraminifera-rich nannofossil chalk ooze has been designated Albatross Ooze. The Blake Ooze is distinguished from the Albatross by a decrease in foraminifera content. The Challenger Ooze (marly chalk oozes) is darker in color and has a higher average terrigenous content. The Discovery Clay is a red clay formation. The Endeavor Ooze (marl oozes) includes more calcareous planktons. The Fram Ooze is a nannofossil chalk ooze formation almost devoid of foraminifera. The Grampus Ooze lies directly above a basalt basement, and it is characterized by an increased foraminifera-content and a darker color toward the base. The cycle of change is thus complete. The only disharmonious note is the presence of a marly chalk ooze unit beneath the Fram Ooze at Sites 19 and 20, which has led to the establishment of the Gazelle Formation.

The correlation of the Hirondelle Ooze required some subjective judgment. The Unit 3-20C-5-1 at Site 20 shows the same increase of foraminifera toward the base as is characteristic of the Grampus Formation. Yet, its overall lithology is similar to the sediments of about the same age at Site 21, and it is distinctly different from the Grampus Ooze by the presence of intercalated pink dolomitic chalk oozes. At this point a third criterion, namely, the presence of pink oozes, was chosen to establish the Hirondelle as a formation.

The type section for each of the formations was chosen with the following considerations: preferably, the top and bottom contacts of the unit fell within cored intervals, and the lithology of the type section was fairly representative of the formation. In general, the type-section is the most completely developed (thickest) section, but not necessarily so.

The distribution of the various Mid-Atlantic Ridge formations in time and depth is summarized by Figure 3. Shown graphically are: total depth of holes, cored intervals, and the formations and their ages. Also shown for comparison are the stratigraphic columns of Sites 21 and 22 on the Rio Grande Rise. Several obvious conclusions can be deduced from a quick glance:

(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 are found farther away from the axis.

(3) The thickness of the sediments bears no simple relation to the age of the sediments. Paradoxically, the holes with the youngest basement ages (Miocene in Holes 16 and 18) have the greatest sediment thicknesses (176 and 179 meters, respectively); whereas, the hole with the oldest basement age (Upper Cretaceous in Hole 20C) has the thinnest sedimentary sequence (72 meters). More than likely this relationship results from the non-random selection of sites.

(4) The nature of the topmost formation is related to the distance from the Mid-Atlantic 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 meters (11,568 feet) to 4265 meters (13,989 feet). The Endeavor Ooze is present at Site 14, at 745 kilometers from the Ridge axis and 4343 meters (14,245 feet) depth. The Discovery Clay (covered by a thin veneer of local units of similar lithology) is present at Sites 19 and 20, and is found 1010 and 1303 kilometers from the Ridge axis and 4677 meters (15,340 feet) and 4506 meters (14,780 feet) deep, respectively.

(5) The nature of the sediments below the topmost formation bears no simple relation to the present depth of the drill site, indicating changes in the depositional environment at each site with time. Paradoxically, the sedimentary sequence (Eocene to Quaternary) at the drill site where the present oceanic depth is the greatest has the highest average calcium carbonate content (see Chapter 15).

(6) The sediments at sites less than 500 kilometers from the Mid-Atlantic Ridge axis (Sites 15, 16 and 18) are mainly Neogene, whereas the sediments farther out are mainly Paleogene (Sites 14, 17, 19 and 20).

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

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

(9) 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

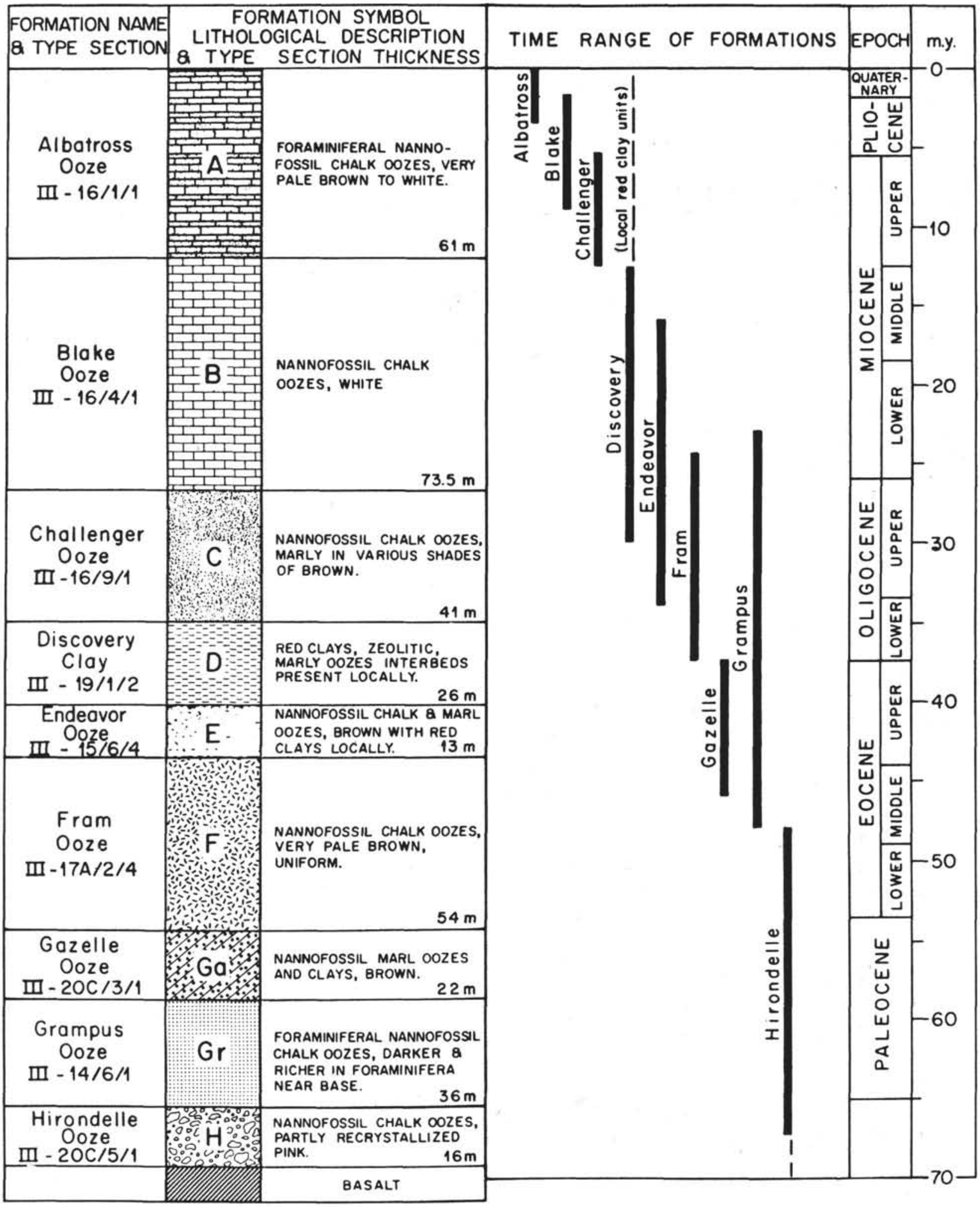

Figure 2. *A composite stratigraphic section of Mid-Atlantic Ridge formations showing formation type and relative thickness. The numbers identify core and location within it where lithologic unit was encountered.*

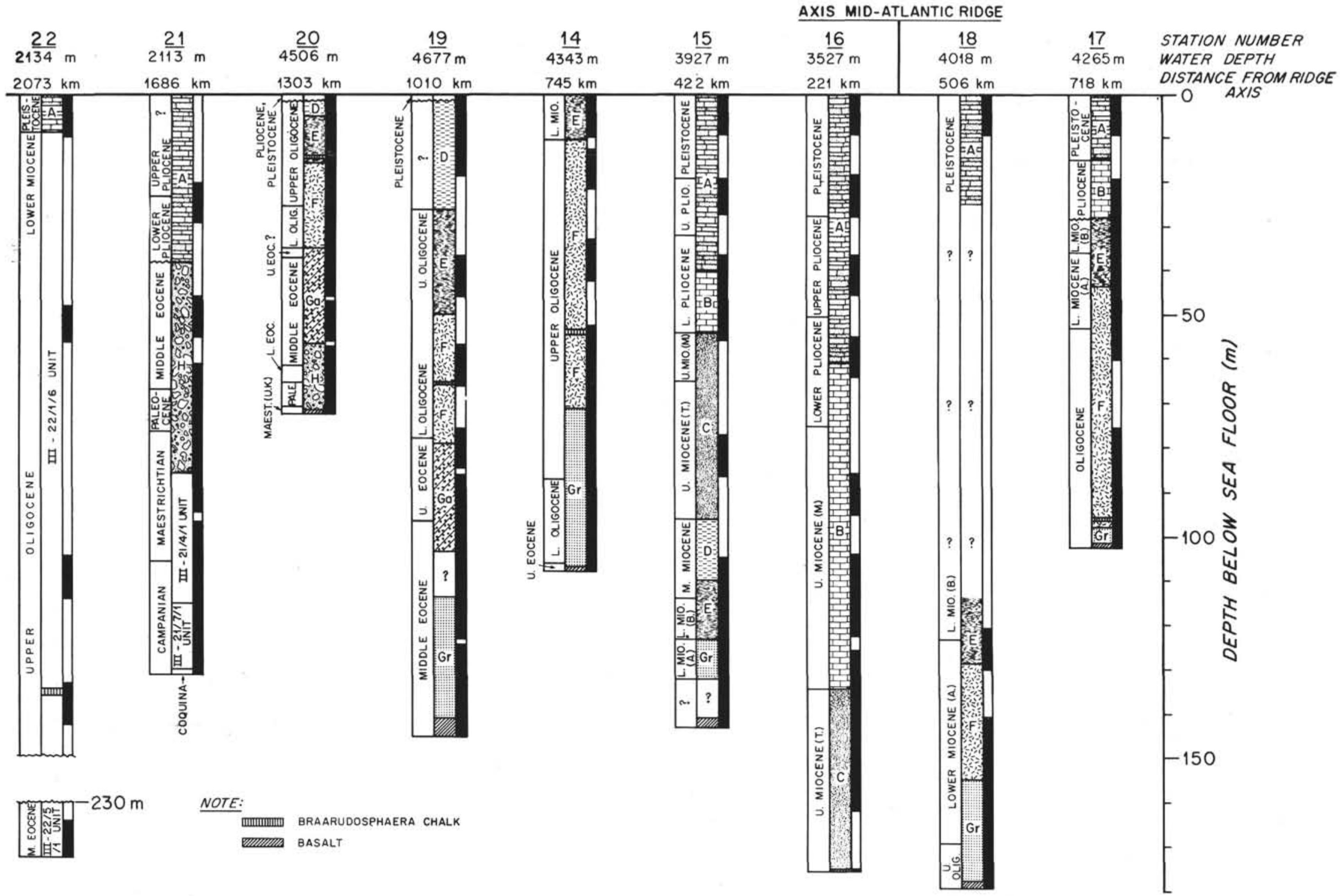

Figure 3. *Summary of formations, ages and cores recovered from Mid-Atlantic Ridge and Rio Grande Rise sites.*

the axis on the other flank of the Ridge than it is to that of its immediate neighbor (comparing Sites 14 and 17, and Sites 15 and 18).

The graphical summary, using formations as stratigraphic units, cannot express the lateral variations within each of those units. These can best be expressed by the statistical summaries of the shore-based analyses of the calcium carbonate- and foraminifera-contents. The sites in Tables 1 and 2 have been arranged in the order of their distance to the Ridge-axis, namely, 16, 15, 18, 17, 14, 19 and 20. The variation trends, with a few exceptions, are as follows:

(1) The calcium carbonate-content of each formation, in general, decreases with the distance from the Ridge-axis; the same formation is least calcareous at the sites farthest away.

(2) The foraminifera-content also decreases with the distance from the Ridge-axis; the same formation contains, in general, less foraminifera at the sites farther away from the Ridge-axis.

These trends are particularly well manifested by the Endeavor Ooze, so that this unit at the lower flank sites (19 and 20) is lithologically similar to the Discovery Clay at the site close to the Ridge crest (15). Likewise, the Fram Ooze at the lower flank sites is similar to the Endeavor Ooze at the upper flank sites; and, the farthest out Grampus Ooze is similar to the Fram Ooze. Such lateral lithological variations explain the fact that the formations had to be defined on the basis of vertical lithological variations at each site, but not on the basis of lithotypes alone.

TABLE 1
Summary of Calcium Carbonate Content [a]

Formation	Site 16	Site 15	Site 18	Site 17	Site 14	Site 19	Site 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

[a]Number of samples analyzed is given in parenthesis.
–Denotes formation absent at site.
?Denotes value unknown, not sampled, or not sufficiently sampled. (See Chapter 15c).

TABLE 2
Summary of Sand Fraction in Sediments [a]

Formation	Site 16	Site 15	Site 18	Site 17	Site 14	Site 19	Site 20	Average of Sites
Albatross	21.4 (21)	11.9 (13)	? (1)	25.0 (5)	–	–	–	19.4
Blake	3.4 (25)	3.4 (8)	?	4.4 (6)	–	–	–	3.7
Challenger	7.3 (17)	3.3 (6)	?	–	–	–	–	5.3
Discovery	–	1.0 (4)	?	–	–	0.3 (11)	? (2)	0.7
Endeavor	–	1.8 (8)	2.2 (5)	1.5 (10)	0.4 (6)	0.2 (6)	0.5 (9)	1.1
Fram	–	–	4.2 (9)	3.5 (25)	2.1 (17)	1.1 (8)	0.4 (6)	2.3
Gazelle	–	–	–	–	–	0.4 (12)	0.4 (10)	0.4
Grampus	–	9.7 (6)	11.7 (11)	? (2)	2.0 (20)	1.5 (23)	–	6.2
Hirondelle	–	–	–	–	–	–	2.1 (11)	2.1

[a]Number of samples analyzed is given in parenthesis.
–Denotes formation absent at site.
?Denotes value unknown, not sampled, or not sufficiently sampled. (See Chapter 14c).

The sedimentation rates of the different formations vary with lithology. The rates range from about 1.8 cm/t.y. for a foraminiferal chalk ooze unit to 0.02 cm/t.y. for a red clay unit—some two orders of magnitude difference. As a whole, the chalk ooze formations have been accumulated at a net rate of about 1 cm/t.y., whereas the red clays accumulated at about 0.1 cm/t.y. Since each formation is more argillaceous toward the outer flank, a trend of a corresponding decreasing rate of sedimentation has been recognized.

In order to eliminate the uncertainties resulting from production and dissolution of calcareous planktons on net accumulation rate, the depositional rate has been computed for the non-carbonate component of each formation. As Table 3 shows, the values still vary from 0.07 to 0.33 cm/t.y. (Hirondelle Ooze excepted). This variation is probably real, reflecting varying terrigenous influx, although the errors resulting from assigning absolute ages to paleontologically determined stages may have exaggerated the difference. The grand average rate of non-carbonate deposition is 0.16 cm/t.y., approximately one-tenth that of a chalk ooze, which contains some 10 per cent non-carbonate impurities (for example, the Albatross Ooze at Site 16).

A synthesis of the facts so far presented here led to the adoption of a hypothesis that dissolution played the most important role in determining the lithology of the Mid-Atlantic Ridge sediments and their net rates of accumulation.

That the red clays represent the insoluble residues of chalk oozes seems obvious, especially when the depositional rate of a sediment is compared to its calcium carbonate content. On the other hand, whether the

TABLE 3
Summary of Sedimentation Rates [a]

Formation	Site 16	Site 15	Site 18	Site 17	Site 14	Site 19	Site 20	Average
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)

[a]All figures are rates in centimeters per thousand years. The figures in parenthesis are rates of sedimentation of non-carbonate component.
–Denotes formation absent.
?Denotes rate uncertain.

rarity or absence of foraminifera in a nannofossil chalk ooze can be attributed to dissolution is a debatable question.

Bramlette (1958) emphasized the role of production in determining the composition of calcareous planktons in a pelagic ooze. Production rates, no doubt, need to be considered. The high foraminiferal content of the Albatross Ooze is probably related, at least in part, to the greater-than-average production rates of foraminifera during the Quaternary. Table 1 indicates that the chalk ooze formations on the east flank sites have a slightly higher foraminifera-content than those at a corresponding distance on the west flank—a second-order variation which may reflect the relatively high production rates east of the Ridge axis (see Berger, 1968). However, several lines of evidence suggest that calcareous foraminifera are more readily soluble in ocean water than calcareous nannofossils, so that the paucity of foraminifera in the nannofossil sediments of the South Atlantic could be attributed largely to differential dissolution. The indications are:

(1) The parallel trend in variations of the foraminifera and the calcium carbonate content of the Mid-Atlantic Ridge formations suggest that dissolution which increases the non-carbonate impurities of a sediment also tends to decrease its foraminifera-content.

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

(3) Organic coating of calcareous plankton skeletons has a protective function (Suess, 1969). Smaller nannofossil particles may tend to be better protected by such a coating than larger, more porous foraminifera tests.

(4) 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 (Berger, 1967). The fact that the only foraminifera found in some more marly nannofossil oozes of the Ridge province are species resistant to dissolution (for example, *Globorotalia index, G. suteri* in the Gazelle Ooze, Site 19) suggests that all but a trace of the original foraminiferal fauna has been removed by dissolution from such nannofossil sediments.

These arguments may not be definitive. Nevertheless, they are sufficient to justify the adoption of a working hypothesis that the formations of the Mid-Atlantic Ridge province represent originally calcareous sediments that have undergone different degrees of dissolution. Accordingly, five different dissolution facies have been postulated, and their physical properties described as exemplified by the South Atlantic sediments:

(1) *Alytic facies* (Gr. 'αλυτος, not dissolved): Chalk oozes with no evidence of dissolution. The Quaternary foraminifera oozes of the Rio Grande Rise may belong to this facies.

(2) *Eolytic facies* (Gr. 'εως, dawn; λυτος, dissolved): Chalk oozes with signs of initial dissolution. The Ridge sediments with 10 per cent, or less, terrigenous matter, but more than 10 per cent foraminifera may belong to this facies.

(3) *Oligolytic facies* (Gr. 'ολιgος, slight; λυτος, dissolved): Chalk oozes with signs of slight dissolution, particularly the dissolution of foraminifera. The Ridge sediments with 10 to 30 per cent terrigeneous matter, and less than 10 per cent foraminifera may belong to this facies.

(4) *Mesolytic facies* (Gr.μΣσος, moderate; λοτος, dissolved): Marl oozes with signs of considerable dissolution, only nannofossils and the more resistant foraminifera species are preserved. The Ridge sediments with 30 to 70 per cent terrigenous matter, and less than 3 per cent foraminifera may belong to this facies.

(5) *Holplytic facies* (Gr. '-ολος, complete; λμτος, dissolved): Red clays belong to this facies; all calcareous planktons, except perhaps some nannofossils, have been dissolved. Using these terms, the genesis of the formations can be interpreted as follows:

Albatross Ooze, eolytic.

Blake Ooze, oligolytic.

Challenger Ooze, oligolytic.

Discovery Clay, mesolytic at a more crestal site (15), otherwise hololytic.

Endeavor Ooze, mesolytic.

Fram Ooze, oligolytic.

Gazelle Ooze, mesolytic.

Grampus Ooze, oligolytic, almost eolytic at more crestal sites.

Hirondelle Ooze, mainly mesolytic, but oligolytic at the base of Hole 20C.

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

(1) Each time marker is represented by a more nearly alytic formation toward the Ridge crest, and by a more nearly hololytic formation farther out.

(2) The Tertiary succession undergoes a cyclic change: first from an almost eolytic facies to a hololytic facies, then a return to the eolytic facies, although the second half of the cycle was developed at the upper flank sites only.

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 (14,760 feet) in the Pacific (Bramlette, 1958; 1961) and is about the same in the South Atlantic at 30°S latitude, as indicated by the distribution of the modern hololytic sediments there. This depth is related to an increase in the rate of calcite dissolution, and not to a boundary of equilibrium solubility (Peterson, 1966; Hudson, 1966); the latter may be several hundred meters deep only (Berner, 1965; Hudson, 1966; Berger, 1967). 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 at present (Emiliani and Edwards, 1953; Lowenstam, 1964). However, whether the compensation level should be deeper or shallower for those warmer oceans is a debatable point.

Hudson (1966) emphasized the effect of temperature on kinetics and postulated a shallower compensation depth for the warmer Cretaceous Chalk Sea. This unorthodox approach did not consider the effect of the degrees of undersaturation on kinetics. That the calcite was being rapidly dissolved in the cold waters below 4500 meters (14,760 feet), 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.

Arrhenius (1952), Bramlette (1958), and Riedel and Funnell (1964) all postulated that the calcite-compensation-depth may have been considerably greater during the Tertiary. Bramlette (1958) suggested a 6700-meter (21,976-foot) compensation-depth for a Tertiary bottom-water temperature of 12°C; this figure is probably too high. Assuming a non-subsiding ocean floor, Heath (1969) found an apparent maximum compensation depth of 5200 meters (17,056 feet) some 35 million years ago (Oligocene). He recognized, however, that this depth may reflect the post-depositional subsidence of sea floor; there may have been very little changes of the actual compensation-depth.

A further complicating factor is the effect of cold, carbon dioxide-rich bottom currents. Berger (1967) suggested the term *lysocline* as the level at which the solution rate increases drastically, which is 500 meters or more above the compensation-depth. He cited evidence to show that this surface is not horizontal but inclined in the South Atlantic, because the Antarctic Bottom Water is responsible for the pronounced abyssal calcium carbonate dissolution. As this water at 30°S latitude 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 difference between successive dissolution facies is probably of the order of some hundreds of meters, it would be foolhardy to make interpretations in terms of absolute depth. A relative bathymetric scale for the dissolution facies with reference to the calcite-compensation-depth is suggested, taking into consideration the distribution of Holocene sediments at 30°S. This scale is:

Alytic facies: some 1500 meters above CCD (calcite-compensation-depth).

Eolytic facies: 500 to 1500 meters above CCD.

Oligolytic facies: 200 to 500 meters above CCD (just below lysocline).

Mesolytic facies: 200 meters or less above CCD.

Hololytic facies: below CCD.

The rapid facies changes hundreds of meters above and below the lysocline surface express the fact that dissolution rate changes rapidly at those depths.

As the Tertiary facies changes of the Mid-Atlantic Ridge sediments at 30°S involve changes in relative depth of 1000 meters (3280 feet) 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 interpretation were accepted, a depression of the actual compensation-depth during the early Tertiary should result in a succession of increasingly more alytic facies, if there had been no crustal subsidence. Instead, a progression from eolytic to hololytic sediments has been found. Consequently, these facies changes are interpreted in terms of the chronically changing depth at each depositional site.

The elevation difference between the crest and flank of the Mid-Atlantic Ridge is 3000 meters (9840 feet). A crustal segment may have subsided some 3000 meters as it was moved from the crest to the lower flank. The early Tertiary eolytic-hololytic succession provides evidence for the subsiding conveyer-belt model of sedimentation. Eolytic or oligolytic sediments were being deposited on a newly-created basalt basement in the crestal areas of an ancestral Mid-Atlantic Ridge, which stood hundreds or thousands of meters above the calcite-compensation-depth. Sediments of more hololytic facies were accumulated as the sea floor was conveyed to 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 the Middle Miocene. The more nearly alytic 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 nearly alytic formation toward the Ridge crest and by a more nearly hololytic formation farther out can be considered an expression of the topography of the ancestral Mid-Atlantic Ridge.

A final argument against the hypothesis of major differences in the calcite-compensation-depth as the cause for the various dissolution facies is the fact that such facies are heterochronous. Changes in dissolution facies resulting from temporal changes in compensation-depths may be related to world-wide temperature changes, and should be more nearly isochronous.

In conclusion, it is stated that the Tertiary sediments of the Mid-Atlantic Ridge province have a complex facies pattern, and that this pattern can be best explained through the assumption of changing bottom-depth at each site during the course of sea-floor spreading.

Interstitial Water Salinity (R. E. B.)

During the Leg 3 of the Deep Sea Drilling cruise, Miocene to Cretaceous interstitial water samples were collected having salinities ranging from 34.4 to 36.0 ppt (see Table 4). In general, salinity variations were small and did not seem to relate systematically to depth, age or formation. Interstitial water salinities at the Sierra Leone Rise ranged from 35.2 to 35.8 ppt; Mid-Atlantic Ridge flank sediments had interstitial salinities of 34.7 to 35.5 ppt; and, the Rio Grande Rise salinities ranged from 34.4 ppt to 36.0 ppt. The largest salinity variation was in samples that were collected from Cretaceous

TABLE 4
Summary of Leg 3 Interstitial Salinities

Hole/Core/Section	Interval (cm)	Depth In Hole (m)	Salinity ppt	Sediment Age	Formation
13-2-4	147-150	27	35.2	Pliocene < Eocene?	
13-2-3	147-150	140	35.8	Eocene	
15-3-5	147-150	44	35.2	Lower Pliocene	Blake Ooze
15-9-5	147-150	139	35.2		Drilling Artifact
19-1-5	147-150	7	35.2	Pleistocene < Upper Oligocene	Discovery Clay
19-5-3	147-150	80	34.9	Upper Eocene	Gazelle Ooze
19-8-4	147-150	110	35.2	Middle Eocene	Grampus Ooze
19-11-3	148-150	137	34.7	Middle Eocene	Grampus Ooze
20C-1-5	147-150	7	35.5	Lower Oligocene	Endeavor Ooze
20C-3-1	147-150	38	34.7	Eocene	Gazelle Ooze
21-3-1	147-150	77	34.4	Upper Cretaceous	Hirondelle Ooze
21-5-2	147-150	97	36.0	Lower Maestrichtian Upper Campanian	Near *Inoceramus* zone
21-8-3	147-150	128	35.5	Campanian	

sediments of the Rio Grande Rise. Parts of the Cretaceous section were lithified, but the samples were from the unlithified material.

In general, the salinity of the ocean water can vary with depth, thermal conditions, currents, etc. Interstitial waters from sediments can be changed by diffusion, filtering through clay-like membranes, diagenetic changes, lateral and vertical migrations, and alteration by organisms. In order to draw any conclusions from the salinity variation in respect to the geologic history of the basins (for instance, low salinity corresponds to shallow depth, etc.), it would be necessary to assume other variables were constant. These variables combined with the very small statistical population make it almost impossible to draw conclusions with any certainty.

Physical Properties of the Sediments (R. E. B.)

The lithologic formations appear to be supported by measurements of natural gamma radiation and, to a lesser extent, the mass physical properties of the sediments, such as: wet-bulk density, porosity, sediment-sound velocity and a thermal conductivity. All of the following measurements are from disturbed sediment samples; thus, they do not accurately represent *in situ* conditions. They probably reflect nominal packings, and porosities of the particular grain size of the sediment. However, they are still of interest as they may be approximations to the corresponding properties in unconsolidated sediments *in situ*. Consistent variations in the physical properties can usually be seen to correlate with certain formational sequences, when these properties are plotted against depth, and the formational boundaries are drawn in.

Natural gamma radiation relates to the lithology, as it generally distinguishes argillaceous formations. In fine-grained sediments, clay and zeolitic minerals have ion-exchange capacities which may hold gamma-ray emitting isotopes; in addition, these minerals have high potassium contents, thus producing relatively higher radiation than the pure siliceous or calcareous oozes. Examples are the argillaceous Discovery Clay, Endeavor and Gazelle Oozes compared with the non-argillaceous Blake and Challenger Oozes.

Natural gamma radiation ranges from zero to 2600 counts per 1.25 minutes scan over a 7.62-centimeter core segment, with an average of about 200 to 400 counts. The higher natural gamma radiation can be related to the presence of clay minerals, zeolites, phosphates and, possibly hematite, dolomite, and some opaque minerals. When two or more of these minerals were combined, high gamma counts were usually recorded. A relatively high natural gamma radiation at Site 16 decreases exponentially from the sediment surface. The time lapse of this strata suggests that this could be caused by gamma-ray emitting Th^{230} or U^{234} isotopes or possibly other radionuclides with similar half lives.

The lithologic formations appear to have distinct natural gamma signatures within the Mid-Atlantic Ridge sedimentary province (Figure 4). The Albatross Ooze emits a slightly higher natural gamma-radiation count at the surface which immediately and exponentially decreases with depth. The remainder of the Albatross and the underlying Blake Oozes have hole averaged counts of 300 to 100 per 7.62-centimeter core segment per 1.25 minutes, respectively. The Challenger Ooze, beneath the Blake, normally has equivalent or slightly higher relative average hole counts of 200 to 400, which is also distinctively less than the Discovery Clay.

The Discovery Clay, Endeavor Ooze, and Fram Ooze sequence emits higher hole averaged gamma counts, which decrease sequentially from 1100 to 1700 (Discovery Clay), down to 350 to 1600 (Endeavor Ooze), and 250 to 500 (Fram Ooze).

Less radiation is emitted from the Fram Ooze, however, than from the underlying Gazelle Ooze, which has average-hole counts of 500 to 1200. Beneath the Gazelle Ooze, the Grampus and Hirondelle Oozes emit relatively less radiation with average hole counts of about 200 to 400, and 400, respectively.

Other mass physical properties, such as, porosity, sound velocity and heat conductivity, show distinct signatures within formations, but their validity is questionable. Their validity depends upon the sediment cores being undisturbed samples; thus they are always suspect of being artifacts resulting from the drilling and coring operations.

Porosity and wet-bulk density appear to be primary properties that correlate to the lithologic formations (Figure 5), with the sediment sound velocity and thermal conductivity relationships being generally related to wet-bulk density and porosity. In general, porosity decreases with increasing depth, and was typically lowest in sediments that were immediately overlying the basalt basement. Porosity consistently varies inversely with wet-bulk density, sound velocity and thermal conductivity. The porosity decrease appears to be a combined function of compaction, sediment and fossil-type and grain-size distribution. The lithologic formations usually have distinct porosity and wet-bulk density differences.

The Albatross, Blake and Challenger Oozes have progressively decreasing moderate average porosities of 72 to 48 per cent (density: 1.52 to 1.88 g/cc), but the sequence lacks distinguishing signatures. The Discovery Clay, being of finer grain-size, has moderate but higher porosities of 57 to 72 per cent, averaging 66 per cent (density: 1.48 to 1.70 g/cc); the Endeavor Ooze also has moderate average hole porosities ranging from 52 to 65 per cent (density: 1.56 to 1.63 g/cc) with a slightly lower overall average of 60 per cent, but still greater than the low average porosities of 50 to 59 per cent (density: 1.65 to 1.85 g/cc) in the underlying Fram Ooze. The *Braarudosphaera* Chalk in the Fram Ooze has densities up to 2.00 g/cc with a corresponding porosity of 43 per cent. The Gazelle and Grampus Oozes have low to moderate average porosities of 48 to 62 per cent (density: 1.62 to 1.82 g/cc) and 57 to 59 per cent (density: 1.71 to 1.84 g/cc), respectively. Water content, obviously, has interrelationships similar to those of porosity.

Uncorrected shipboard sediment sound velocities range from 1.47 to 1.72 km/sec, averaging about 1.54 km/sec. In general, these velocities are lower than had been expected, but they appear to be in reasonable agreement with the velocities determined from a comparison of the depths of cored and observed seismic reflectors. Although these velocities generally increased with increasing depth (below sediment surface), they appear to be primarily a function of the sediment type. For example, the Albatross and Blake Oozes have moderate average-hole sound velocities of 1.50 to 1.53 km/sec, slightly increasing with depth, but without any distinct signatures; but, the Challenger Ooze tends to have slightly higher velocities with hole averages of 1.53 to 1.55 km/sec (Figure 6). While the Discovery Clay has low average hole velocities of 1.49 to 1.51 km/sec, the Endeavor, Fram and Gazelle Oozes have moderate to high average-hole velocities of 1.50 to 1.54, 1.53 to 1.56, and 1.51 to 1.58 km/sec, respectively. The underlying Grampus Ooze has slightly lower average hole velocities of 1.53 to 1.56 km/sec, and the boundary between the Gazelle and Grampus Oozes appears to be characterized by the lowest part of a broad velocity decrease and increase. The Hirondelle Ooze tends to have low to high velocities, averaging 1.55 km/sec.

Penetrometer measurements were too sparse to definitively correlate penetration to other mass physical properties of the sediments or the lithologic formations with any certainty. This is the result of core disturbance and the complete penetration of the penetrometer needle. Yet, in general, penetration appears to irregularly decrease with depth, and the minimum values correlate directly to sound velocity. In a few cases, needle penetration inversely correlates with porosity (directly with wet-bulk density) and natural gamma radiation. This high gamma radiation-low needle penetration relationship may result from the plasticity of the clay- and zeolite-type minerals, and grain-size distribution. The porosity relationship may be secondary, the primary relationship being with the plasticity of clay-type minerals. Clay minerals usually comprise the finer-grained fraction of sediments, which, in respect to unconsolidated fine-grained sediments,

GAMMA RADIATION VERSUS LITHOLOGIC FORMATIONS

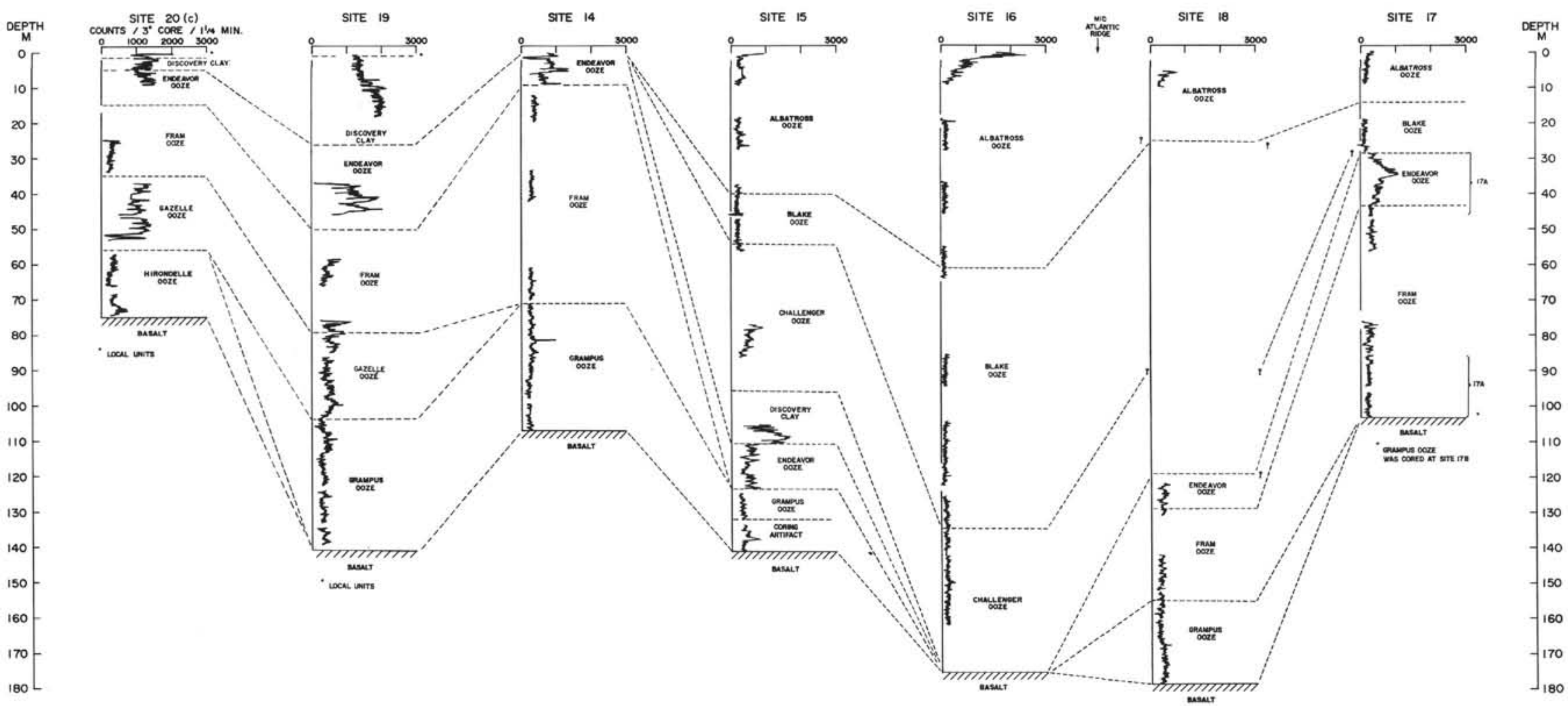

Figure 4. *Summary of Natural Gamma Radiation Measurements.*

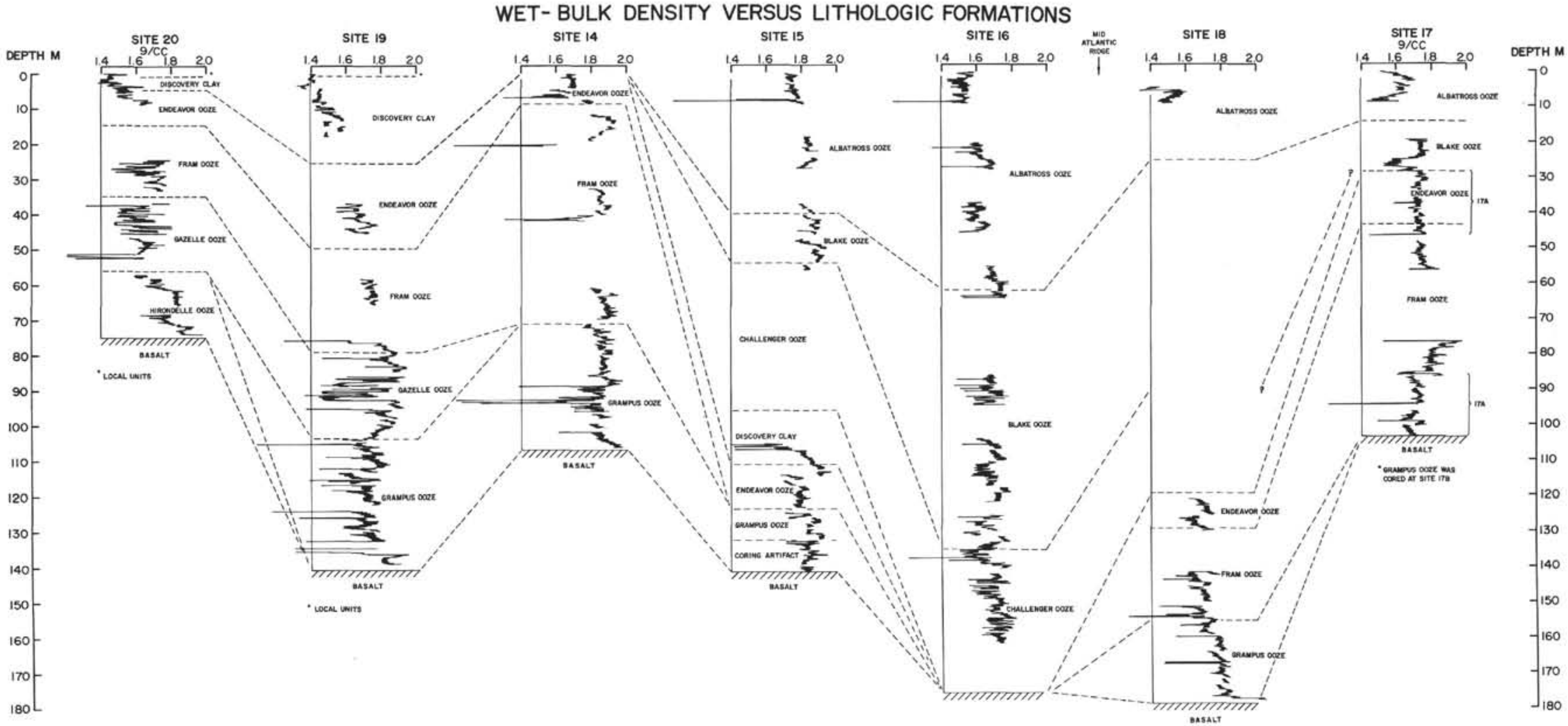

Figure 5. *Summary of Porosity and Wet-Bulk Density Measurements.*

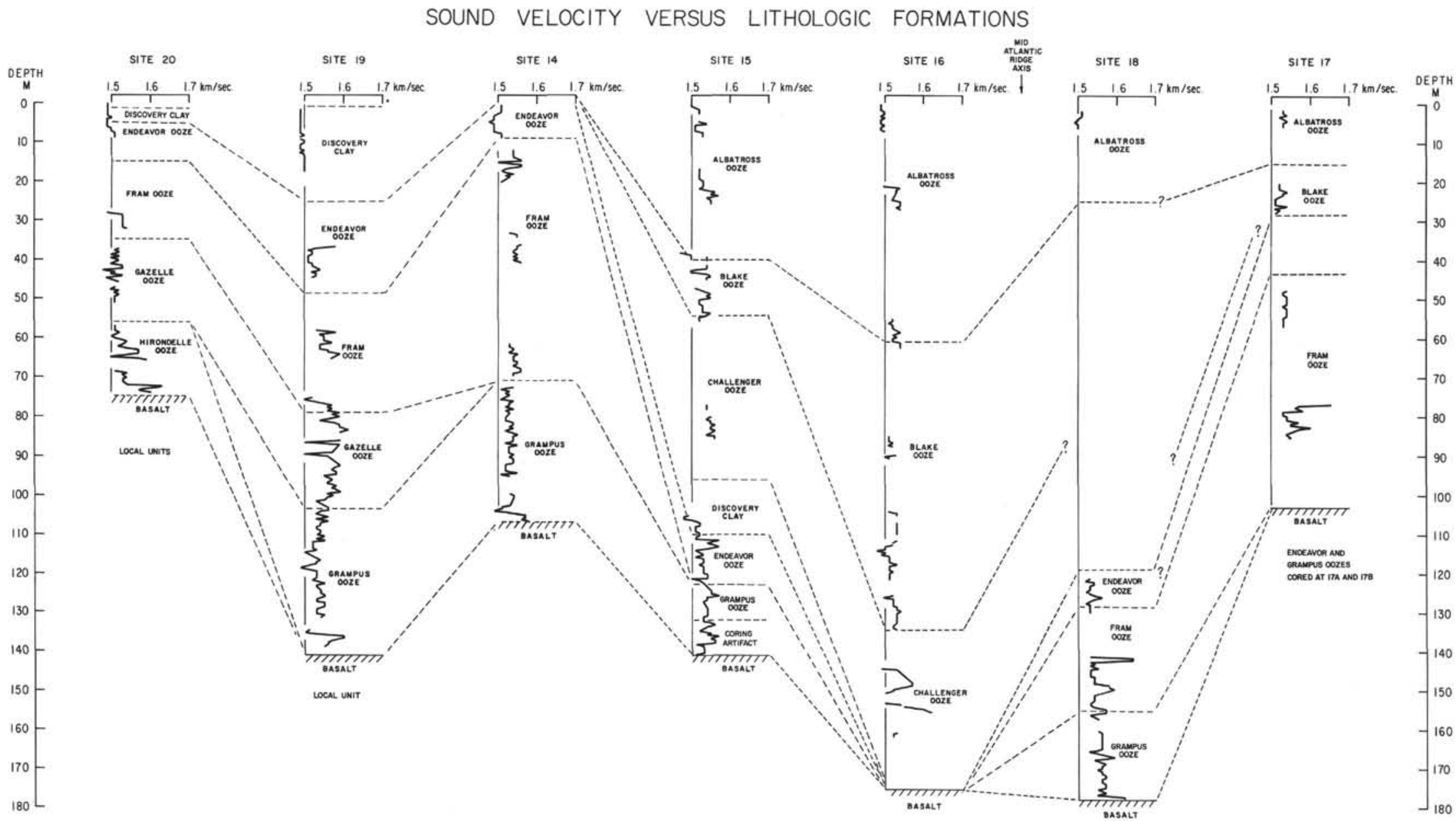

Figure 6. *Summary of Sound Velocity Measurements.*

normally have greater porosities. The pure nannofossil chalk oozes tended to be penetrated easily, as they acted like an aggregate of marble with very little plasticity.

Thermal conductivities range from 2.0 to 3.5 $\times 10^{-3}$ cal $\cdot$ $°C^{-1} \cdot cm^{-1} \cdot sec^{-1}$, and average about 2.9 $\times 10^{-3}$ These data have an apparent inverse correlation with porosity and, to a greater degree, with the water content by weight. In general, thermal conductivity appears to increase with increasing depth, which was, also, a function of porosity, and which is in turn controlled by sediment type and compaction.

In the Mid-Atlantic Ridge sedimentary province, the Albatross Ooze, Blake Ooze and Challenger Ooze have relatively increasing thermal conductivities, respectively, although absolute conductivities vary at each site. These formations have the following range of averages: The Albatross Ooze ranges from 2.5 to 2.9 $\times 10^{-3}$; the Blake Ooze ranges from 2.8 to 3.0 $\times 10^{-3}$; and, the Challenger Ooze averages about 3.0 $\times 10^{-3}$. The underlying Discovery Clay has a markedly lower conductivity than the Challenger Ooze. However, the Discovery Clay, Endeavor Ooze and Fram Ooze also have sequential relative increases. Thermal conductivities in the Discovery Clay range from 2.0 to 2.9 $\times 10^{-3}$; Endeavor Ooze averages range from 2.1 to 3.0 $\times 10^{-3}$; and, Fram Ooze averages range from 2.9 to 3.2 $\times 10^{-3}$. Meanwhile, the underlying Gazelle and Grampus Oozes generally have lower relative conductivities (2.3 to 3.2 $\times 10^{-3}$) than either the Fram Ooze or Hirondelle Ooze (2.9 to 3.1 $\times 10^{-3}$).

Sea Floor Spreading (R. P. V. H. & A. E. M.)

From an examination of the paleontological ages of the fossils contained therein, the age of the sediments recovered from immediately above the basalt basement at each Mid-Atlantic Ridge site has been shown to increase with distance from the Ridge-axis. In order to calculate the rate of sea-floor spreading from these data, it is necessary to know the distance each site has moved from its point of origin on the Ridge-axis. The procedure of calculating this distance is not always straightforward, because the Mid-Atlantic Ridge has numerous offsets and changes in strike along its length (Heezen and Tharp, 1965).

Although the Ridge has not been surveyed in detail near latitude 30°S, there are sufficient ship tracks along which geographical data have been recorded to enable a rough determination of the location of the Ridge-axis. Figure 7 shows the location of the axis based upon geographical information, such as, the characteristic crestal topography (Vacquier and Von Herzen, 1964), magnetic anomalies associated with it and the locations of earthquake epicenters (Stover, 1968). From Figure 7, a simple way to determine the distance a site has moved away from the Ridge-axis is to measure the distance from the site to the nearest point on the Ridge-axis. If this procedure is followed, the displacement near 29.5°S suggests that Sites 15 and 16 are associated with Ridge Segment C, Sites 17 and 18 with Segment B, and all other sites are nearly equidistant from either B or C. Linear distances of the sites from the Ridge-axis are summarized in Table 5, with errors in the distances representing a subjective uncertainty in the axis location. The paleontological ages and their estimated uncertainties have been determined utilizing the chronostratigraphic chart of Berggren (1969a); see Chapter 2, Figure 1. A more recent compilation (Berggren, 1969b), based upon radiometric dates within continental sequences, gives somewhat different ages for some paleontological stages, particularly during mid-Tertiary.

From a hypothesized fitting of the continents of Africa and South America, Bullard *et al.* (1965) showed that the present positions of these continents can be explained as a rotation about an axis at 44°N, 30.6°W. Other authors (Morgan, 1968; LePichon, 1968) have proposed rotation axes farther north, based upon the trends of linear magnetic anomalies and fracture zones, and they have inferred differential rates of spreading along the Ridge-axis. The rotation axes farther north may be representative of recent spreading, whereas that at 44°N may represent the rotation axis for the average motion since the beginning of continental rifting.

For a rigid rotation on a sphere, the trace of the motion of any part of the surface would lie along a small circle with the rotation axis at the center. 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 Ridge-axis will be different in the two cases.

The last two columns of Table 5 show the distances of drilling sites from the ridge axis for both linear and rotational spreading hypotheses, using the rotational axis at 62°N, 36°W proposed by Morgan (1968), for the latter. 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 (Figure 7) 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. Similar results are obtained with the other proposed rotation axes for the South Atlantic.

A fracture zone that displaces the Ridge crest by, perhaps, extending eastward between Sites 17 and 18

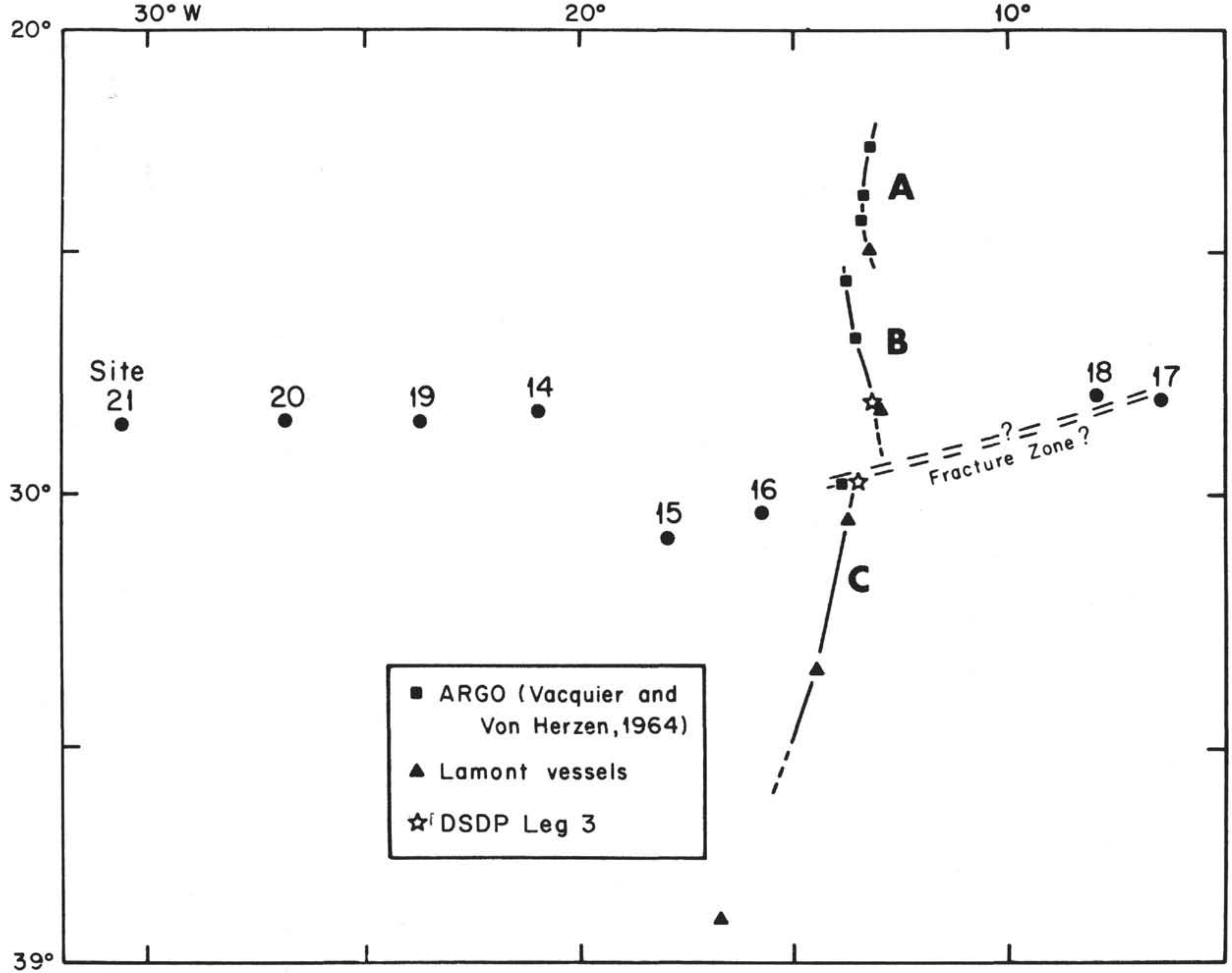

Figure 7. *Location of Leg 3 sites relative to the axis of the Mid-Atlantic Ridge.*

TABLE 5[a]
Magnetic Anomaly Number and Ages, Paleontological Ages, and Distances of Mid-Atlantic Ridge Sites from the Axis

Site No.	Magnetic Anomaly No.	Magnetic Age of Basement (m.y.)	Paleontological Age Sediment Above Basement (m.y.)	Distance from ridge axis (km)	
				Linear	Rotation at 62°N, 36°W
16	5	9	11 ± 1	191 ± 5	221 ± 20
15	6	21	24 ± 1	380 ± 10	422 ± 20
18	---	---[a]	26 ± 1	506 ± 20	506 ± 20
17	---	34-38[a]	33 ± 2	643 ± 20	718 ± 20
14	13-14	38-39	40 ± 1.5	727 ± 10	745 ± 10
19	21	53	49 ± 1	990 ± 10	1010 ± 10
20	30	70-72	67 ± 1	1270 ± 20	1303 ± 10
21[c]	---		>76	1617 ± 20	1686 ± 10

[a]The number of the magnetic anomaly and its age has been taken from Heirtzler, *et al.* (1968).
[b]Location of these sites within the characteristic magnetic anomaly pattern is uncertain.
[c]Basement rock not reached at Site 21.

may explain this apparent uncertainty. Some independent support for this interpretation comes from the recording of unusually large depths between Sites 17 and 18, which are sometimes characteristic of fracture zones (Menard, 1964; Heezen and Tharp, 1965). If the fracture zones of the South Atlantic trend somewhat north of due E, 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 latitude between Segments B and C (Figure 7).

When the values in Table 5 are plotted (see Figures 8 and 9), they show an overall linear fit of ages versus distance from the Ridge-axis. When the nearest Ridge-axis is selected for measurement of distances, the average spreading rate, back to 66 million years B. P., for these drilling sites appears to be slightly less than 2 cm/yr (Figure 8). For a rotation axis in the North Atlantic, the best-fitting spreading rate appears to be nearly equal to 2 cm/yr (Figure 9). The small difference between these two interpretations probably is representative of the uncertainty in such data. Likewise, if the more recent paleontological ages of Berggren (1969b) are accepted, the average rates may be slightly increased in both cases, but will still be near 2 cm/yr.

Sites 17 and 18 were selected on the east side of the Mid-Atlantic Ridge to test symmetry of the spreading pattern. The sediment ages at these sites seem to fit well with the pattern for the western flank Mid-Atlantic Ridge sites in Figure 8, but they may be significantly younger for the rotation axis interpretation (Figure 9). The lack of fit for the eastern flank sites in the latter case may result from some E-W asymmetry in the spreading pattern or from fracture zone displacements, which 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 Figures 8 and 9 may be interpreted to indicate past changes in the sea-floor spreading rate (Langseth, *et al.*, 1966; Ewing and Ewing, 1967). For shorter term linear spreading, the range of spreading rates corresponding to variations in slope between points of Figure 8 is from 1.2 to 6.1 cm/yr. For rotational spreading (Figure 9), the range is 0.4 to 4.2 cm/yr. Similar ranges result if the alternate paleontological dates of Berggren (1969b) 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. 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 (LePichon, 1968). This would necessitate greater ranges in spreading rates than have been observed if periods of low or no spreading are postulated.

Another possible explanation for some of the scatter in the data may be the normal distribution about the Ridge-axis in which new rocks are injected in the sea floor (Matthews and Bath, 1967; Harrison, 1968). 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 per cent 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). In other words, there is only a 5 per cent 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, assuming that the process has remained constant throughout the time required to form the sea floor. This additional 10-kilometer uncertainty might explain some of the data scatter in Figures 8 and 9.

Additional relative displacements of the ocean floor between drilling sites due to fracture zones (Figure 7) may contribute to the scatter of the data in Figures 8 and 9. The relatively small scatter implies that any such displacements have been less than 50 to 100 kilometers. It is most unlikely that displacements between sites could be balanced out by changes in spreading rates. Therefore, such data scatter seems well within the uncertainties of the methods used in this study; and, the simpler interpretation of constant spreading rate back to at least 66 million years B. P. seems as likely from these data.

A South Atlantic spreading half-rate of 2 cm/yr has been deduced earlier from studies of the marine magnetic field anomalies (Dickson, *et al.*, 1968). The magnetic anomaly ages predicted for the drilling sites are listed in Table 5. Reasonably good agreement exists between predicted magnetic ages and those determined from paleontology, especially considering the uncertainty in locating the site in relation to the center of the magnetic anomaly. Perhaps the only significant departures from the predicted ages are at Sites 19 and 20. Both sites had ages somewhat younger than predicted. This suggests that the proposed geomagnetic time scale (Heirtzler, *et al.*, 1968) may require some minor revision for ages of 50 million years, or greater, in the same direction but probably not as large as that suggested by LePichon (1968).

Overall, it is concluded that the sea floor of the South Atlantic has been spreading at an essentially constant

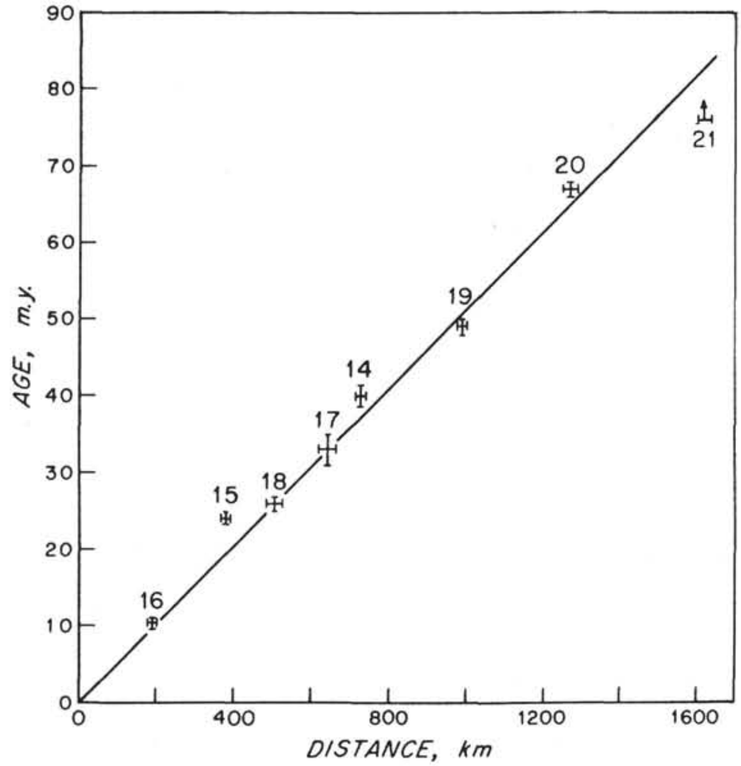

Figure 8. *Plot of age of sediment immediately above basement as a function of nearest distance to Ridge axis.*

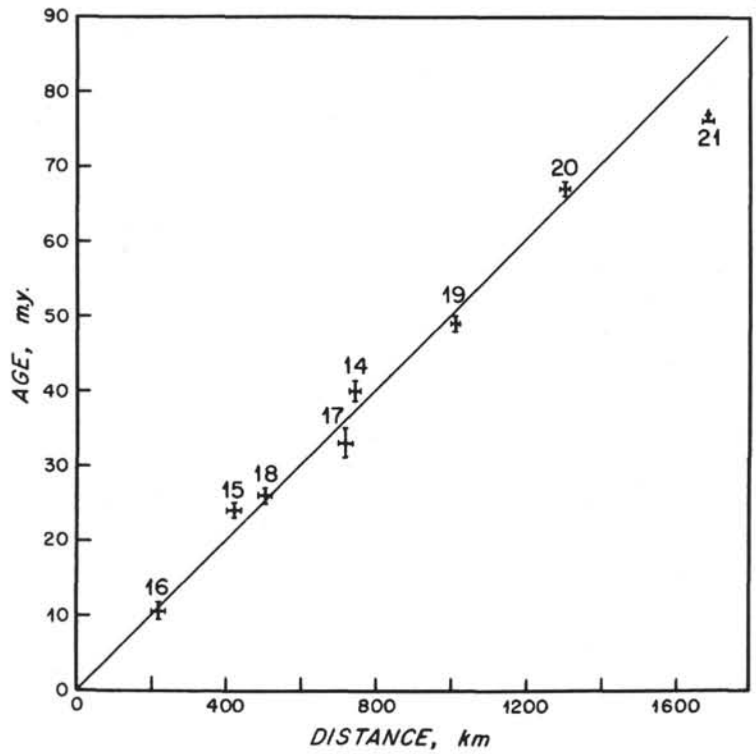

Figure 9. *Plot of age of sediment immediately above basement as a function of distance from Ridge axis as determined from an assumption that the Ridge is spreading about an axis of rotation at 62°N, 36°W.*

rate for the past 67 million years. Accuracy of the data does not permit a valid interpretation of changing spreading rates. Further, the spreading half-rate of 2 cm/yr, as determined from the drilling, is in agreement with and has provided a critical test for both sea-floor spreading and magnetic stratigraphy.

HISTORY OF SOUTH ATLANTIC BASIN

(K. J. H. & J. E. A.)

To interpret the geologic history of the South Atlantic, two major premises have been adopted. Namely:

(1) The sea floor of the South Atlantic has been spreading apart since the Cretaceous at an average half-rate of 2 cm/yr with new basalt crust being continually created at the crestal region; and

(2) The South Atlantic formations represent dissolution facies, the depths of which are related to the calcite-compensation-depth.

The validity of these premises has been discussed previously. A graphic presentation of the interpretation is shown in Figure 10. In this figure a series of stratigraphical sections is reconstructed for five reference dates: (a) end of Eocene (37 million years), (b) end of Oligocene (26 million years), (c) end of Lower Miocene Aquitanian (23 million years), (d) end of Miocene (6 million years), and (e) present. The following procedures were used:

(1) The average spreading rate from the reference date to present is computed. This rate differs somewhat from the average determined from the age of the sediments above basement because stratigraphy must be taken into consideration. For example, Site 15, which is now about 400 kilometers from the axis, includes Aquitanian sediments and, therefore, should appear in the stratigraphic-section for the reference date 23 million years before present (Figure 10c). This is only possible if a spreading rate of 1.5 cm/yr, or less, is assumed. An alternative is, of course, to change the absolute age of the Aquitanian to accommodate the 2.0 cm/yr average rate. However, in order not to prejudice interpretation by changing the time-scale midstream, a slightly variable spreading rate has been assumed for the construction of the interpretative diagrams.

(2) The width of the new crust, created since the reference date, has been computed, and it is appropriately shown in the diagrams. Accordingly, the location of each drill site is moved closer to the Ridge-axis in the section for that date. Those sites which are closer to the Ridge-axis than the half-width of the new crust are eliminated from the section. The spreading-rate has been so computed that no sediments older than the reference date are present at the eliminated sites.

(3) The bathymetry of the drill site during the past is determined by relating the depositional depth of the uppermost sediment at that time to the calcite-compensation-depth, using the quantitative relations postulated in an earlier section on the lithology. The compensation-depth is now about 4500 meters (14,760 feet) deep, and it was either about the same or several hundred meters deeper during the Tertiary.

(4) The elevation of the Ridge-axis at each reference date is extrapolated, based mainly on the interpreted bathymetry of the nearby sites.

(5) The lithostratigraphy is shown by a columnar section for each site. The time lines are drawn between such columns to indicate the age of the formations and the relation between lithostratigraphy and chronology.

The distances between sites, the bathymetry and the stratigraphical thickness have been shown by different scales for effective illustration; the vertical exaggeration of water-depth is 100-fold, and the vertical exaggeration of sediment-thickness is 5000-fold. Thus constructed, the top line of each section illustrates the past topography, and the bottom illustrates the sediment-basalt contact.

Figure 10 shows that the sedimentary regime in the South Atlantic basin has not changed radically during the last 80 million years. A relatively thin blanket of chalk oozes, with some marl oozes and red clays has been covering the Ridge. No turbidity-current deposits were found here; such sediments probably were trapped in basins near the continents (such as, the Brazilian and Angola Basins). The formations of the Ridge province have been distinguished mainly by their different degrees of dissolution. In contrast, however, production rate and current erosion may play a more important role in the Rio Grande Rise province. Whereas unconformities between the Ridge sediments resulted largely from dissolution, the hiatus of the Rise sediments has been almost certainly the work of mechanical removal. Fragmentary data, especially those from Site 22, suggest that the Rise remained high, while the Ridge widened and, at times, deepened during the Tertiary.

Assuming an average spreading rate of 2 cm/yr, it is possible to estimate that the separation of South America and Africa began some 130 million years ago, or during the Early Cretaceous. The discovery of uppermost Jurassic deep-sea sediments in the North Atlantic east of the Bahama Islands (Initial Reports of the Deep Sea Drilling Project, Volume I) is consistent with such a postulate. Geological comparison of Brazil and Gabon show a striking similarity of the Aptian and older rocks in these countries; and, thus, their separation has been dated as middle Cretaceous,

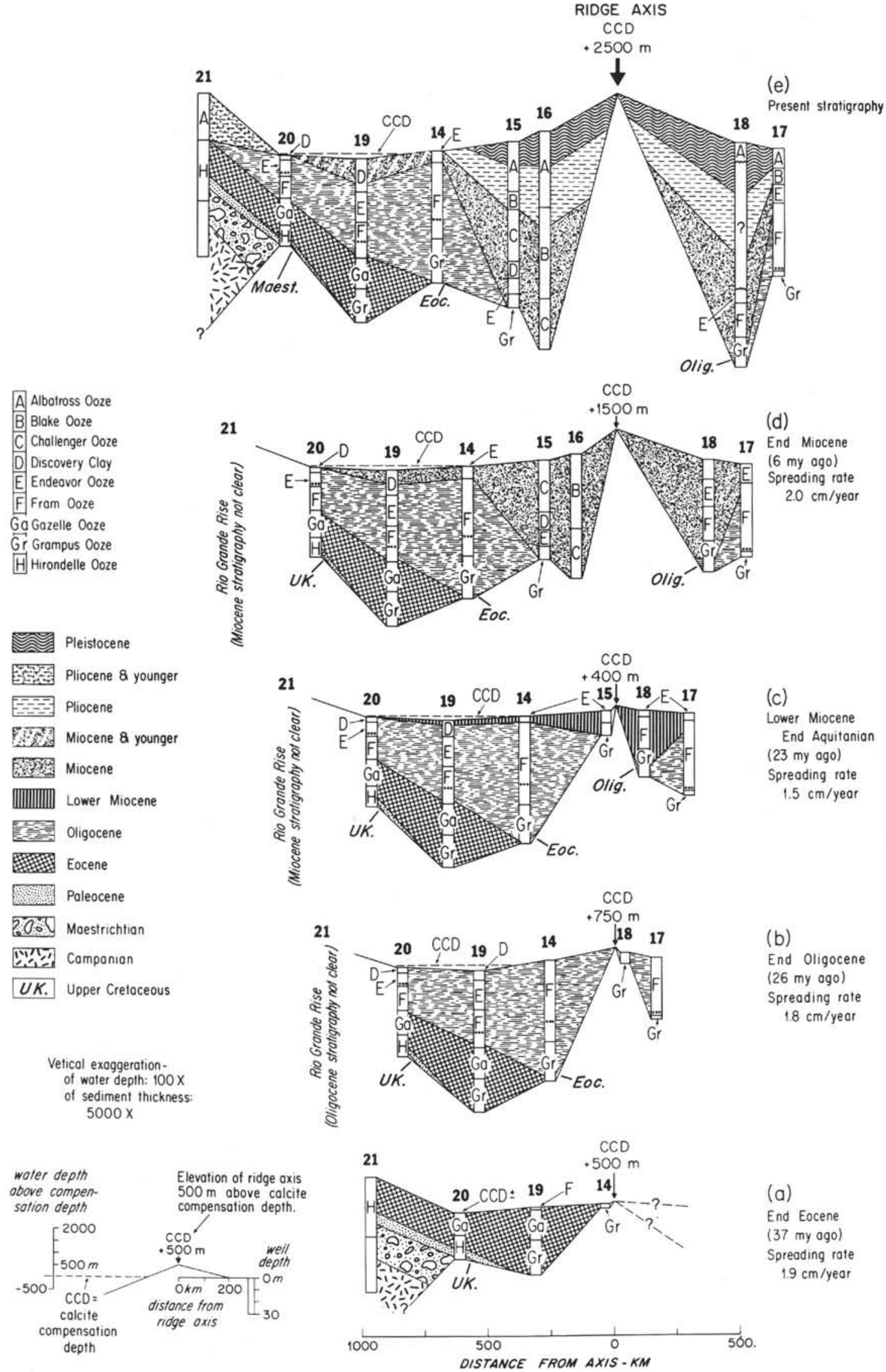

Figure 10. *Reconstruction of history of the South Atlantic Basin, taking into consideration sea floor spreading, paleontological ages and lithological formations.*

or some 120 million years ago (Allard and Hurst, 1969). Unfortunately, the results of the Leg 3 drilling cannot give a definitive answer on the age of separation of the continents since the oldest dated sediments in the Equatorial Atlantic are Senonian ($<$ 90 million years), and in the South Atlantic they are Campanian ($<$ 80 million years). Yet, the evidence does indicate that the South Atlantic came into being either during Late Jurassic or 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 are Maestrichtian, or some 70 million years old. By the end of the Eocene (Figure 10a), the Ridge became a distinct topographic feature. Still, the Atlantic was not sufficiently deep for hololytic red clays to have been deposited. The very slow rate of deposition of the Maestrichtian, Paleocene and Lower Eocene sediments in the Ridge province and the existence of disconformities indicate considerable dissolution of calcium carbonate, particularly of planktonic foraminifera, so that the Hirondelle Formation at Site 20 is considerably thinner and contains much less foraminifera than its counterpart on the Rio Grande Rise.

The Grampus Ooze first appeared during the Middle Eocene at Site 19. From then on until Early Miocene this oligolytic and locally eolytic unit invariably includes the first sediments deposited upon the newly formed basalt crust (see Figure 10a, b & c). The Grampus Ooze can thus be considered the crestal deposits on the ancestral Mid-Atlantic Ridge. The Middle and Upper Eocene flank deposits constitute the mesolytic Gazelle Formation. Site 20 must have deepened to the compensation depth during the Late Eocene time, so that the Upper Eocene deposits are virtually 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, an oligolytic Fram Ooze was superposed on the flank above the mesolytic Gazelle. The rates of the Fram Ooze 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, while the crestal area stood some 1000 meters (3280 feet) higher to permit eolytic sedimentation (the Grampus Ooze of Site 18).

A noteworthy sedimentation 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 it 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 the Early Miocene. The Lower Miocene sediments at Site 15, which then lay close to the Ridge axis, are an oligolytic Endeavor Ooze, suggestive of a deeper Ridge-axis. Accordingly a height for the crest of calcite-compensation depth plus 400 meters has been postulated, namely: 4100 meters (13,448 feet) assuming the present calcite-compensation depth, or 4600 meters (15,088 feet) assuming Heath's (1969, Figure 5) 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 oligolytic Endeavor Ooze was superposed by a mesolytic Discovery Clay unit at Site 15. Solution rates on this deep Mid-Atlantic Ridge of low relief must have been rapid. The Middle Miocene is either represented 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 Middle Miocene hololytic sedimentation was not restricted to the South Atlantic. The Miocene at Site 10 on the flank of the northern Mid-Atlantic Ridge shows largely zeolitic red clays (Initial Reports of the Deep Sea Drilling Project, Volume II). Mid-Tertiary red clays barren of fossils in the Cape Verde Basin (Site 12, Initial Reports of Deep Sea Drilling Project, Volume II), and on the Sierra Leone Rise (Site 13) were also deposited during a time-span including the Middle Miocene. It is possible that the great depth of the Middle Miocene Atlantic may have coincided with a period of slower sea-floor spreading. This is supported for the period from the end of Aquitanian to the end of Miocene where the sedimentation pattern suggests a slower than 2.0 cm/yr rate.

The Mid-Atlantic Ridge was rejuvenated during the Late Miocene. By the end of the Miocene, the new crestal area stood at about 1500 meters (4920 feet) above the calcite-compensation depth (at 300-meter–9840-foot–depth, assuming the present calcite-compensation depth). At Site 16, located near the Ridge crest, the Challenger Ooze is almost eolytic. This unit is definitely oligolytic at Site 15, some 200 kilometers to the west. Farther out at Sites 14 and 17, the sea floor remained below the compensation depth where the Upper Miocene was represented by a red clay and by unconformity, respectively.

The uplift of the Ridge may have continued during the Plio-Pleistocene. The present crestal elevation of 2-kilometer depth is probably as high as ever. The eolytic and oligolytic Albatross Ooze is now being deposited to a distance some 650 kilometers away 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 only present as a very thin veneer.

Throughout the Tertiary the Rio Grande Rise may have stood relatively high, probably not much different from the present 2000-meter (6560-foot) depth. Alytic sediments were deposited, only to be removed locally by active bottom-current erosion.

From this interpretation of the geologic history of the South Atlantic, there evolves a model of nearly constant sea-floor spreading with the ocean floor having significant vertical movements in 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 by Ewing and Ewing (1967) based upon 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 (1966) to suggest an increase in the rate of spreading during the last 10 million years. Schneider and Vogt (1968) also postulated non-steady Atlantic spreading, on the basis of additional evidence furnished by discontinuities in Ridge topography and in amplitudes of magnetic anomalies. The idea that sea-floor spreading virtually stopped for 30 or 40 million years during the Tertiary does not appear tenable in the light of the drilling results, which show an approximately constant spreading rate of 2 cm/yr since the Cretaceous. On the other hand, the possibility of variations in spreading rate has not been excluded. In fact, accepting the time-scale used on board ship, the spreading rate for different Cenozoic Stages may be computed to vary by a factor of 2 or more. Such variations are subject to interpretation and they have been attributed in part to the imperfect knowledge of the absolute ages of paleontologically determined stages and zones. On the other hand, unmistakable evidence of a non-steady sea-floor depth and, perhaps, spreading is furnished by the sedimentary record. If there only had been steady spreading and flank subsidence, the geologic column at each site should be a regular succession of gradually deepening sediments. The superposition of oligolytic and eolytic Upper Miocene and younger sediments 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 related, no doubt, to the unusually light mantle, which now underlies the Ridge (LePichon, *et al.,* 1965; Talwani, *et al.,* 1965). This light mantle density is in turn related to the abnormally high flows measured on the axial portion of the Ridge (Vacquier and Von Herzen, 1964; Langseth, *et al.,* 1966). As a newly created crust was conveyed aside to flank regions, underlain by a mantle of normal density, or the mantle was altered (thermal, chemical) 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 (Hsu, 1965; Hsu and Schlanger, 1968; Schneider and Vogt, 1968).

In conclusion, it is emphasized that deviations from the average linear spreading rate of 2 cm/yr are probably small as shown by Figures 8 and 9). On the other hand, small variations may be related to significant topographical evolutions, which in turn leave a remarkable imprint on the sedimentary record. There are still some uncertainties, about the possible variations of the spreading rate and the Ridge height during the early Tertiary. However, several lines of evidence support the concept that the spreading was relatively slower during the Middle Miocene and has been rejuvenated since Late Miocene (some 15 or 10 million years ago). This rejuvenation may have raised the crestal axis by some 2000 meters (6560 feet) at a rate of about 15 cm/t.y. This rate of vertical movement is about the same order of magnitude as that observed in the Pacific (Hsu and Schlanger, 1968), and it is practically identical to the uplifting rate of the Colorado Plateau (Holmes, 1964, p. 1096).

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