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Leg 4 of the Deep Sea Drilling Project

Coring reveals new information on the geologic history of the western Atlantic and Caribbean basins.

Shipboard Scientific Party

The results of legs 1, 2, and 3 of the Deep Sea Drilling Project (*1–4*) have made major contributions to understanding the geologic history of the North and South Atlantic basins and the Gulf of Mexico. The sites drilled in the earlier legs (particularly legs 2 and 3) were selected to yield a series of data for testing the hypotheses of sea-floor spreading and continental drift.

In contrast to legs 2 and 3, the scientific objectives for most of the sites of leg 4 were not closely interrelated. They were selected to enhance knowledge of several subjects, such as the nature of basins adjacent to continental margins, sea-floor spreading, the nature of transverse fractures of the Mid-Atlantic Ridge, geology of island arcs and trenches, and the geologic history of the Caribbean. It is, therefore, neither practical nor desirable to attempt a regional synthesis for the whole cruise, as more extensive investigations of these areas will be presented in the reports of legs 14 and 15.

Leg 4 of the *Glomar Challenger* Deep Sea Drilling Project in the Atlantic and Caribbean began in Rio de Janeiro on 27 January 1969. During this cruise, 15 holes were drilled at nine sites, the locations of which are shown in Fig. 1. The selection of sites and the drilling and coring objectives for each site were based largely upon the recommendations of the Atlantic Advisory Panel of the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) (*5*). Two sites, 25 and 30, were added to the original plan at the discretion of the scientific party while the cruise was in progress. A summary of the drilling results for leg 4 is given in Table 1. A summary of stratigraphic ages and cores recovered in the western Atlantic and Caribbean on leg 4 is given in Fig. 2.

In the following sections the conclusions resulting from knowledge of the geology of each site will be presented first, followed by general discussion of several topics of interest developed on leg 4, particularly the problems of sedimentation rates, the history of calcium carbonate compensation in the Atlantic, and the nature and relations of subbottom reflecting horizons.

The Brazil Basin

The objectives at sites 23 and 24 were to sample and to determine the nature of the intermediate reflector (possibly analogous to horizon A in the North Atlantic) and basement of the Brazil Basin near the continental margin.

The surficial sediment at these sites is green-gray in color and contains some calcareous plankton fossils, but it rapidly grades downward into barren "red clays," which have a thickness of about 100 meters. The paucity of nannoplankton and planktonic Foraminifera in the surficial layers indicates that this site is at present in the lower reaches of the lysocline for calcium carbonate and was well below the compensation depth during the Middle Miocene.

A core taken at the predicted depth of horizon A (about 112 meters) represents a different kind of sediment—greenish silty clays with interbedded sand layers. In this turbidite zone, which is more than 350 meters thick, the clayey layers are almost devoid of calcareous fossils, an indication that these sediments were also deposited below the compensation depth. The sandy layers contain abundant nannoplankton and planktonic foraminifers. The planktonic foraminiferal assemblages all belong to the basal Miocene *Globorotalia kugleri* Zone. The thicker or the more indurated of these sand beds in the upper part of the zone are probably the source of the so-called horizon A in this area.

The major contact encountered at these sites is that between the red clay and the green turbidites and must be Lower or Middle Miocene. The green turbidites were derived rapidly from a source of primary (not recycled) quartz and must reflect uplift, erosion, and subsequent transportation to this site of deposition. As possible sources, the obvious sites might be (i) the Natal, São Francisco region; (ii) the Amazon region; and (iii) an adjacent oceanic site. In the case of (i) and (iii), cessation of uplift and erosion would produce the change from turbidites to clay.

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In the case of (ii), an opposing deep current would produce the change (note that present Amazon sediments are drifted northward in the surface layer). It would seem possible that the contact might represent the time of origin of the Antarctic Bottom Current.

The deepest sediments cored, of Late Cretaceous age, consist of greenish-gray and brownish-gray compacted mudstone that is locally indurated and contains up to 20 percent terrigenous detritals plus a radiolarian fauna.

In hole 23, at a depth of about 185 meters below the sea floor, 2 meters of basalt were penetrated, but only 0.5 meter was recovered. The rock is heavily altered and much of the texture has been destroyed, but it appears to have been diabasic or porphyritic. The small thickness of the bed—together with the comparatively coarse texture and the lack of glass, which might be the result of alteration—suggests that this rock may be part of a sill rather than a flow. Since softer materials were encountered (but not sampled) below the basalt, it is not considered to represent "basement" rock.

Hole 24 bottomed in basalt. This has been assigned arbitrarily to the bottom 61 centimeters of the hole (557.78 to 558.39 meters). It is a moot question whether this basalt is true "basement" or whether older sediment lies below. This basalt is undoubtedly the source of the "basement reflection," but it is possible that flows at various stratigraphic horizons may be the reason that the basement has such an apparent irregular topography in the area.

North Brazilian Ridge

The continental margin off the northeast coast of Brazil is depicted on hydrographic contour charts (*6*) and physiographic diagrams (*7*) as a region where numerous seamounts mark the base of the continental rise between Cape Calcanhar and the mouth of the Amazon. Topographic and geophysical data accumulated on recent surveys by ships of the Lamont-Doherty Geological Observatory support the view that these features (interpreted in the published charts as isolated seamounts) are, in fact, the result of plotting numerous echo-sounder crossings of a narrow, nearly continuous basement ridge, which extends for a distance of 1300 kilometers parallel to the Brazil coast.

This interesting structure lies about 150 kilometers seaward from the base of the continental slope. Its general features have been described by Hayes and Ewing (*8*), who called it the North Brazilian Ridge. The ridge is located in deep water (approximately 3700 to 4000 meters deep) near the base of a poorly developed continental rise. The crestal relief ranges from 300 to nearly 4000 meters. The ridge is narrow, only about 40 kilometers or less in width at its base, except in the southeast where it has double parallel crests and is about 75 kilometers wide. The cross section of the ridge is roughly symmetric. Sediments are ponded on the continental side of the ridge, with the differential depth due to the ponding ranging from about 250 to 750 meters.

In hole 25, drilled on the top of the ridge, a reasonably complete section was recovered from the sea floor to about 33.5 meters. The deposits consist entirely of light-colored oozes, comprised of large- and medium-sized Foraminifera with varying amounts of nannoplankton and ranging in age from late Pleistocene at the top to Late Middle Miocene at the bottom. Discoasters are especially abundant in the Miocene oozes. Below 33.5 meters recovery was less satisfactory.

At a depth of 45.7 meters the drill penetrated a harder bed. Drilling continued in the harder material down to 59.4 meters, but only a few fragments of core were recovered. They consisted of calcareous material which appears to have been weathered subaerially.

A second hole (25A) was drilled in an attempt to recover more of the sedimentary rocks below the ooze. The first core run was from 49.4 to 58.5 meters, and about 2.4 meters of Miocene ooze was recovered, plus a number of fragments of gray algal limestone coated with manganese oxide and two manganese nodules.

In their discussion of the origin and development of the North Brazilian Ridge, Hayes *et al.* (*9*) found it difficult to reconcile the undisturbed sediments on both sides of the ridge with the evidence of post Middle or Late Miocene subsidence of the ridge indicated by the drilling results. The presence of a prominent flat-lying intermediate reflector at 200 meters below bottom, abutting the oceanic side of the ridge, requires that it and the

Table 1. Summary of holes drilled on leg 4.

Hole	Latitude	Longitude	Dates of drilling (1969)	Water depth (m)	Penetration of sub-bottom (m)	No. of cores	Extent of coring (m)	Core recovered (m)	Core recovered (percent)
23	6°08.75′S	31°02.60′W	1–4 Feb.	5079	208	9	72.5	22.70	31.3
24	6°16.30′S	30°53.53′W	4–6 Feb.	5148	234	4	36.6	5.20	14.2
24A	6°16.58′S	30°53.46′W	6–8 Feb.	5148	558	4	35.1	3.30	9.6
25	0°31.00′S	39°14.40′W	10–11 Feb.	1916	66	9	64.0	25.38	39.9
25A	0°31.00′S	39°14.40′W	11 Feb.	1916	77	3	19.8	2.70	13.8
26	10°53.55′N	44°02.57′W	14–15 Feb.	5169	9	1	9.1	0.00	0.0
26A	10°53.55′N	44°02.57′W	16–20 Feb.	5169	483	5	43.3	13.60	31.3
27	15°51.39′N	56°52.76′W	24–26 Feb.	5251	475	7	55.8	29.20	52.5
27A	15°51.39′N	56°52.76′W	26–27 Feb.	5251	81	5	45.7	31.10	68.3
28	20°35.19′N	65°37.33′W	3–7 Mar.	5521	404	9	64.6	13.90	21.5
29	14°47.11′N	69°19.36′W	9–10 Mar.	4247	230	20	164.6	85.60	52.1
29A	14°47.11′N	69°19.36′W	10–11 Mar.	4247	86	5	45.7	3.40	7.2
29B	14°47.11′N	69°19.36′W	11–12 Mar.	4247	231	10	86.3	52.45	61.0
29C	14°47.11′N	69°19.36′W	12–14 Mar.	4247	248	3	18.3	1.38	7.1
30	12°52.92′N	63°23.00′W	16–17 Mar.	1218	430	16	132.9	61.70	44.6
31	14°56.60′N	72°01.63′W	19–21 Mar.	3369	325	10	91.4	40.90	45.0

undisturbed beds above postdate this supposed subsidence. The extent of this intermediate reflecting horizon is plotted throughout a broad area of the southwestern Guiana Basin (*9*) and is described as a possible counterpart to horizon A of Eocene age in the North Atlantic (*1, 10, 11*).

In order to reconcile the conflicting evidence, an hypothesis related to the ocean-spreading mechanism would appear to fit the observed features of the ridge (Fig. 3). The results of leg 3 (*3*) convincingly demonstrate a spreading rate for the floor of the South Atlantic (at 30°S) of 2 centimeters per year, although Ball and Harrison (*12*) suggest a smaller rate in the latitude of the Antilles. The distance between the Mid-Atlantic Ridge and the North Brazilian Ridge is about 2000 kilometers, if it is assumed that separation and rotation of the continents of Africa and South America have taken place about an axis centered in the North Atlantic (*13*). When the spreading rate of 2 centimeters per year is used, a period of about 100 million years is indicated, since the North Brazilian Ridge (and the South American continental margin) separated from the spreading center. This estimate is in accord with data from site 24 to the southeast, where the oldest sediments were of Upper Cretaceous age. It is also in agreement with the findings of Fox *et al.* (*14*), who report dredging shallow-water sandstone of Late Jurassic age near the base of the Demerara Plateau northwest of the Amazon delta. Paleomagnetic evidence (*15*) suggests that the fragmentation of the South American–African block and the formation of the South Atlantic began in Lower Jurassic time.

If it can be assumed that the basement rock (presently below the seismic velocity layer of 4.8 kilometers per second at the base of the ridge) was at or near the ocean surface at the time of origin (Fig. 3, part a) and that it has subsequently separated from the spreading center at the above rate and subsided to its present depth of nearly 5 kilometers below the ocean surface during that time, a subsidence rate of 0.5 millimeter per year is indicated. If the first part of this 100-million-year movement were accompanied by reef growth that remained at or near the sea surface, it would be possible to build some 2.8 kilometers of reef material on top of the sinking basement foundation. At least the upper part of the reef was then exposed to subaerial weathering (Fig. 3, part b). In Miocene time, either because of increased subsidence rate [suggested by Maxwell *et al.* (*3*)] or some other cause, the reef material ceased to grow and the summit of the ridge began to sink beneath the ocean surface; after a period of minimum deposition, indicated by the manganese layer in hole 25A, deposition of foraminiferal ooze commenced in Late Miocene time and proceeded uninterrupted until the present, as shown in the drilling results, at a rate of 2 millimeters per 1000 years (Fig. 3, part c).

This suggested sequence for the development of the North Brazilian Ridge leaves many outstanding questions. The nature of the sedimentary material of seismic velocity 1.8 km/sec that lies immediately below the drilled section is not explained. The zone of velocity 4.8 km/sec may not be reef material but an igneous or metamorphic rock, as suggested by Hayes and Ewing partly on the basis of bottom photographs of basaltlike rock from the eastern flank of the ridge. If this proves to be the case, then it seems likely that the top of the layer of velocity 4.8 km/sec was initially at the ocean surface and the layer of velocity 3.8 km/sec represents a reef growth that kept pace with subsidence. The subsidence of the North Brazilian Ridge would then be half the above rate for the first 50 to 70 million years and thereafter at the rate given in the first case (0.05 millimeter per year).

Vema Fracture Zone

The Vema Fracture Zone is a deep trench that crosses and offsets the Mid-Atlantic Ridge. It is open at its western end to the Demerara Abyssal Plain, which separates the ridge province from the continental shelf of South America. Reflection profiles across the Vema Fracture Zone show a steep, deep-walled trench, partly filled with sediments. If the irregular bottom reflector is truly basement, this sedimentary fill is 914 to 1066 meters thick. The nature of the sediment in the Vema Fracture Zone has been an enigma to marine geologists for some time. T. H. van Andel *et al.* (*16*) noted that a sedimentary thickness of more than 1 kilometer at such a great distance from the continent must represent a very long interval. However, the hypothesis of sea-floor spreading would suggest a very young age for that part of the fracture zone near the axis of the Mid-Atlantic Ridge. Coring and drilling in holes 26 and 26A show that the top 610 meters of this fill were deposited since the late Middle Pleistocene—that is, during the last 500,000 years. This sedimentation gives an average rate of 12 centimeters per 100 years, a remarkably high rate for any supposedly nonsubsiding area. A second noteworthy feature is that the sediments in the fracture zone seem to have been derived from the South American continent and have been transported across the Demerara Abyssal Plain.

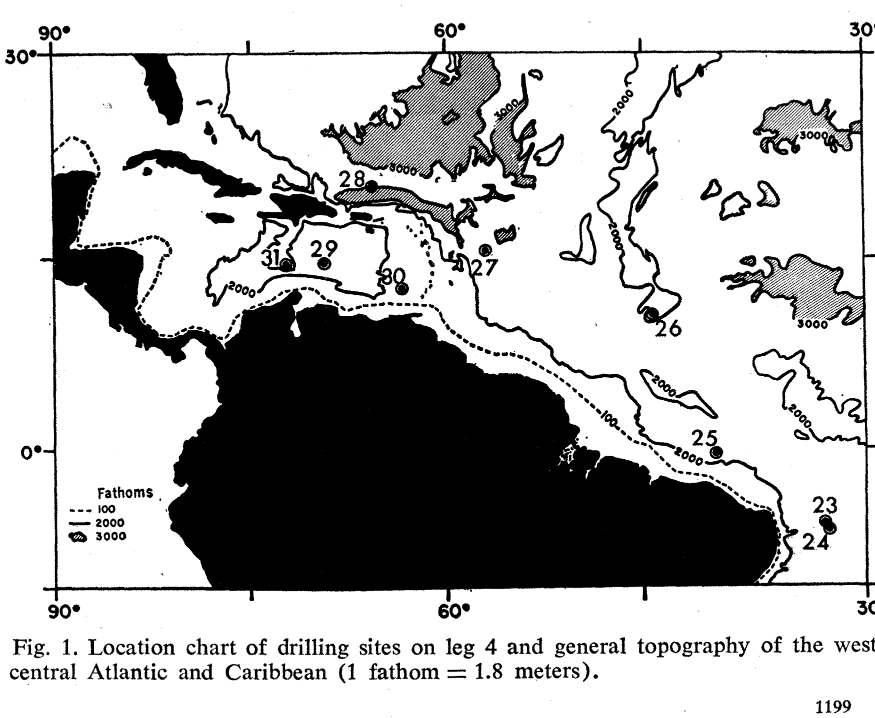

Fig. 1. Location chart of drilling sites on leg 4 and general topography of the western central Atlantic and Caribbean (1 fathom = 1.8 meters).

Two possibilities are suggested: (i) the Vema Fracture Zone is of Tertiary age but did not receive much sedimentation until Pleistocene because the basin under the Demerara Plain is very deep and trapped all the earlier sediments; (ii) the Vema Fracture Zone did not originate until the Pleistocene and has since been filled rapidly by material carried across the Demerara Plain.

Transportation of the large volume of Pleistocene sediments across the Demerara Abyssal Plain poses an interesting geologic problem. The fracture zone deposits closely resemble turbidites and sometimes exhibit graded bedding. If the source of this material is indeed the Amazon cone, we must assume that turbidity currents flowing across the flat floor of the Guiana Basin have deposited vast amounts of material, including sand and heavy minerals, in the Vema Fracture Zone more than 500 kilometers to the northeast.

North Side of Demerara Abyssal Plain

The upper part of the section at site 27 is remarkably uniform; it consists of clays to a depth of at least 400 meters. Strata are almost barren of fossils above 235 meters. Very poor planktonic foraminiferal assemblages from 91 meters and from 143 meters suggest Pleistocene-Pliocene and Pliocene-Miocene ages, respectively. The first beds that have been accurately dated lie at a depth of 244 meters and are basal Miocene; the planktonic Foraminifera are most abundant in turbidite sands that occur at this depth, but nannoplankton occur throughout the clays. Oligocene nannoplankton are an important constituent of greenish clays at 366 meters. At 457 meters, laminated tan to blue-gray clays with interbedded bentonites are strongly reminiscent, both

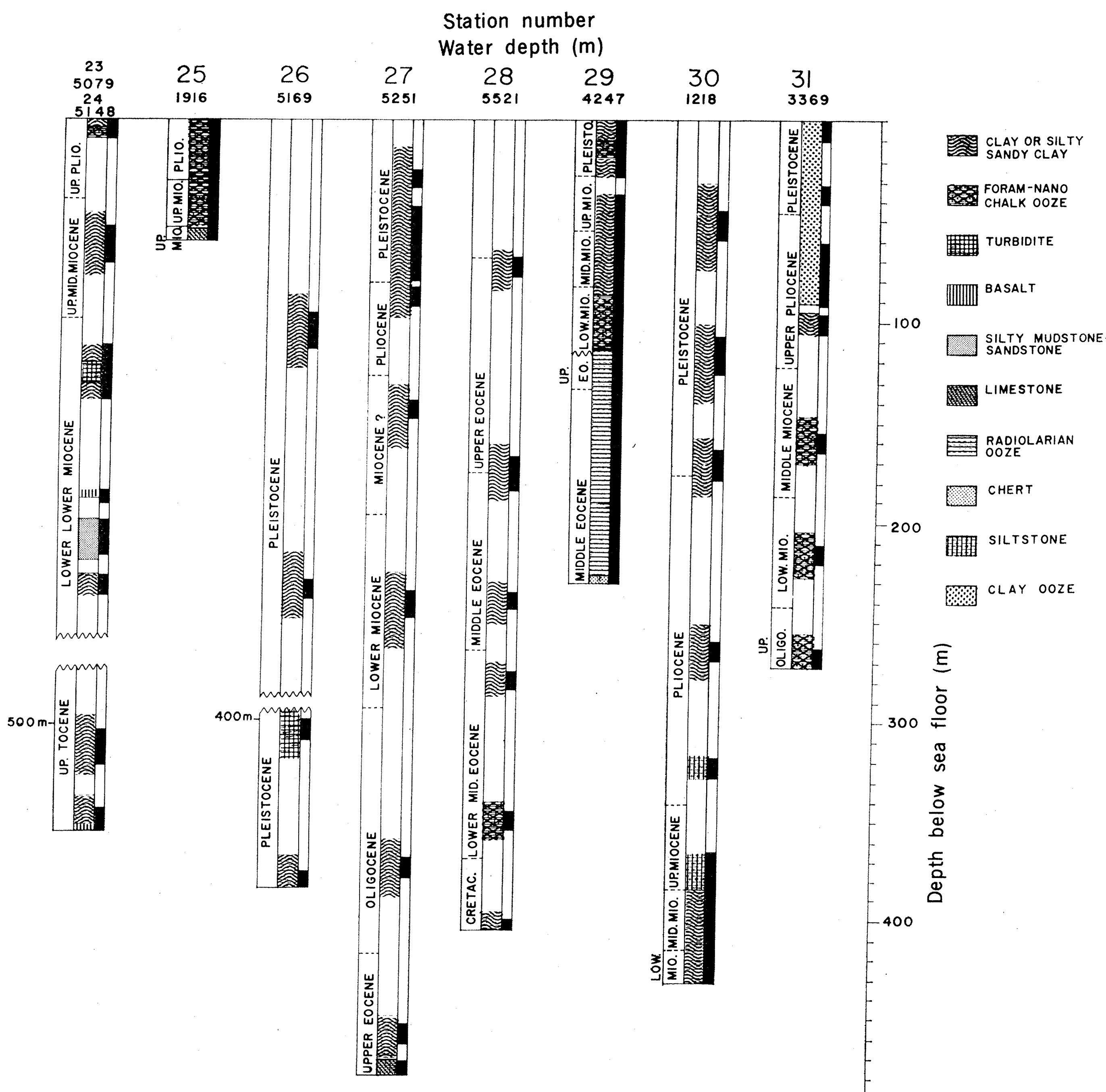

Fig. 2. Summary of stratigraphic ages, lithology, and cores recovered on leg 4.

lithologically and in faunal and floral content, of the Oceanic Formation of Barbados. The hole was terminated in a moderately hard calcareous radiolarian-rich bentonitic clay, similar to the hard beds near the base of the Oceanic Formation, exposed on the east slopes of Mount Hillaby, Barbados.

On Barbados, hard "ashlike" limestones with Radiolaria occur in the basal hundred meters of the Oceanic Formation (*17*), and the Oceanic Formation rests with angular and erosional unconformity on the diverse rocks of the Scotlands Group (*17, 18*), which have been determined to be of Paleocene and Early to Middle Eocene age (*19*). The deepest reflecting horizon recorded at site 27 may have been the hard, calcareous rock recovered by core 7, or it may be an unconformity at a slightly greater depth.

The correlation of the radiolarian-rich calcareous sediments in the deeper part of hole 27 with the Oceanic Formation of Barbados is obvious. This is apparently the first time that a formation that crops out on land has been found and sampled in situ in the upper part of the oceanic crust. It also implies that the Oceanic Formation is a unit of considerable areal extent, which exhibits structural relief in excess of 5000 meters.

Three subbottom reflecting layers were noted in the profiler records taken by the R.V. *Vema* and by the *Glomar Challenger* at site 27. These were calculated to lie at depths of about 70, 235, and 490 meters, respectively. The beds responsible for the upper and intermediate reflections appear to be turbidite layers sampled at depths between 65 and 75 meters and between 235 and 245 meters. The depth of the basement reflector correlates with a hard calcareous formation encountered at 475 meters. The nature of these reflectors in relation to the concept of reflecting horizons in the western Atlantic is discussed later (see "On the Nature of Reflecting Horizons").

The sediments encountered in hole 27 below 370 meters were deposited in the lower part of the zone of calcium carbonate compensation, at a depth below the level of solution of planktonic Foraminifera but above the ultimate depth reached by calcareous nannoplankton fossils; that is, they are truly of deep-water origin. The similarity to the Oceanic Formation of Barbados suggests that it too was deposited in the lower part of the region of calcium carbonate compensation in deep water.

Outer Ridge

The Outer Ridge, which lies between the north wall of the Puerto Rico Trench and the Nares Basin to the north, is covered for the most part with thick, acoustically "transparent" sediments, which diminish in thickness northward where they dip beneath turbidites of the Nares Abyssal Plain.

Along the southern portion of the Outer Ridge, reflection profiles reveal that the basement layer reaches a maximum elevation and that the sediment cover near the north wall of the Puerto Rico Trench diminishes to less than 0.2-second acoustical thickness.

The drilling objectives at site 28 were to sample and to date subbottom reflectors, relating them to presumed comparable features in the North American Basin, and to sample the deepest portion of the sedimentary section, suspected to contain carbonate rocks of Mesozoic age. Only the first of these objectives was partly accomplished.

Another objective for drilling at site 28 was to determine whether subsidence had taken place since the Cretaceous, as Cretaceous calcareous plankton were known from this area, which currently lies below the calcium carbonate compensation level. No new evidence was gained from the borehole, but the problem of calcium carbonate compensation solution levels in the past and subsidence of the bottom had been largely answered by evidence from other sites drilled. As far as is known at present, almost all of the Atlantic sea floor was above the calcium carbonate compensation level and was an area of accumulation of calcareous pelagic oozes during the Late Cretaceous.

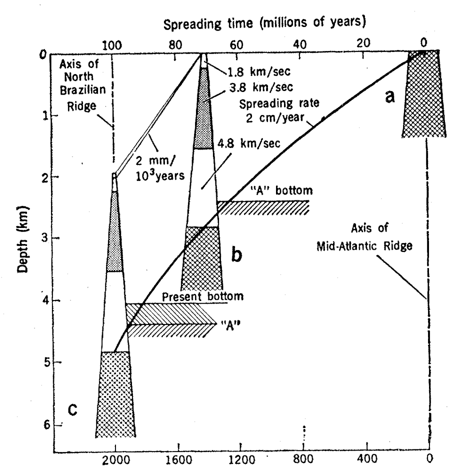

Fig. 3. Schematic drawing of the development of the North Brazilian Ridge: (a) North Brazilian Ridge basement material at the time of origin in Late Mesozoic; (b) position and nature of ridge in Middle Tertiary time, indicating that reef growth has kept summit of ridge near the ocean surface; (c) present ridge situation, showing 50-meter accumulation of pelagic ooze on crest since mid-Tertiary subsidence. Numbers beside ridge component structures are seismic velocities from Hayes *et al.* (*9*).

An upper acoustically transparent zone of 0.15-second reflection time, corresponding to the upper 175 meters, apparently includes beds from Recent to Late or Middle Eocene age. Middle Eocene sediments below 175 meters correlate with a semitransparent zone to which Hershey (*20*) ascribes an acoustical velocity of 4.2 km/sec. Although core recovery was exceedingly poor below a depth of 175 meters, indirect evidence from the drilling operation indicated alternating hard and softer materials. Damage to the diamond bit, believed to have occurred at this depth, suggests that the interbedded hard material was chertlike, thus indicating a tentative correlation with the cherts of Middle Eocene age forming horizon A in the North Atlantic.

Venezuelan Basin

The Caribbean basins, lying between the tectonically active areas of the Antillean Island Arc and Central America, have long been recognized as anomalous oceanic areas. Classical continental geologists, including Schuchert (*21*), Eardley (*22*), and others, have considered the Caribbean to be a subsiding block of continental crust. Marine geologists, such as Ewing *et al.* (*23*) and Officer *et al.* (*24*), have suggested that the Caribbean region may be part of a deep basin in the process of being transformed into a continental area.

The Colombian Basin is known to contain a thick fill of turbidites from the Magdalena region, but the Venezuelan Basin contains a remarkably uniform sedimentary series, and an understanding of its geologic history should lead to an understanding of the nature of the Caribbean region as a whole. Ewing *et al.* (*25*) have described sediment distribution in the Caribbean Sea, with particular emphasis on the nature of the sediments of the Venezuelan Basin as interpreted from profiler records of traverses through the area. Two prominent reflectors have been recognized, termed A″ and B″. Reflector A″ is usually the stronger, and reflector B″ is the lowest reflector but is considered to be far too smooth to

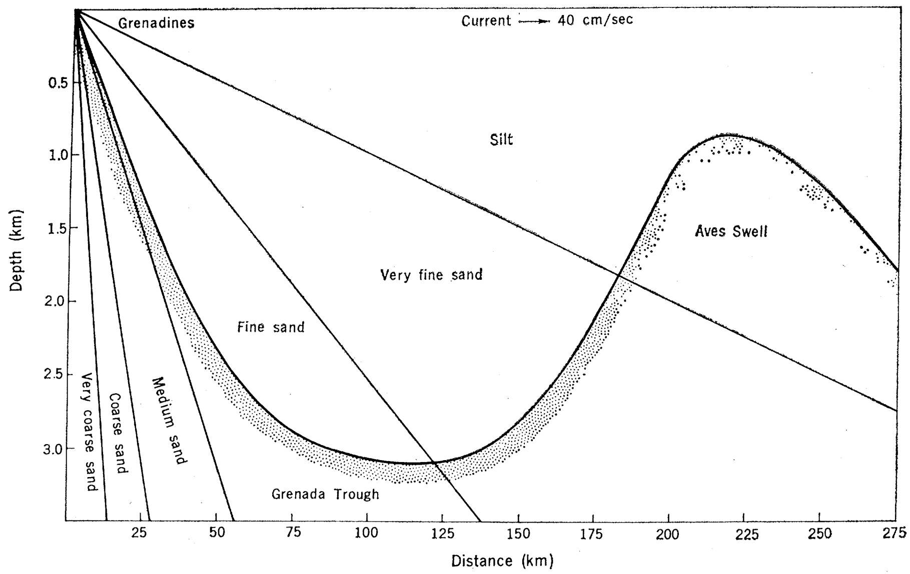

Fig. 4. Schematic cross section from the Grenadines across the Aves Ridge. The settling regions for clastic particles introduced into the water near the Grenadines are shown. A current velocity to the west of 40 centimeters per second is assumed.

be basement. The thicknesses of the strata between B″ and A″, and above A″ in the central part of the basin, are remarkably uniform, each interval having been estimated from profiler records to be about 0.5 kilometer. Reflectors B″ and A″ descend toward the sides of the basin to disappear under turbidites that spread outward from South America and the Antilles. Ewing *et al.* (*25*) have named the acoustically transparent strata above A″ and the somewhat more opaque strata between A″ and B″ the "Carib beds" and have suggested that A″ might coincide with the Mesozoic-Cenozoic boundary. They recognize three phases in the geologic history of the area: phase I, prior to the deposition of the Carib beds; phase II, during deposition of the Carib beds; and phase III, after deposition of the Carib beds.

Site 29 was selected at a location where A″ and B″ are anomalously close to the sea floor and where it was expected that the chance for penetrating to B″ would be good. The reflectors at the chosen site seem typical in character, and they can be traced into adjacent areas with the normal thickness. Multiple holes at this site enabled the entire section down to a depth of almost 250 meters to be sampled. The uppermost section (approximately 120 meters) corresponds to the interval above a minor discontinuous reflector present at this site and consists of tan *Globigerina* nannoplankton ooze grading down into red clays free of carbonate. The discontinuous reflector is interpreted as the contact between the red zeolitic clay and the thick underlying radiolarian ooze, which extends down to 230 meters. This reflector may also represent a major unconformity between the Lower Miocene chalk and the Upper Eocene radiolarian ooze, where the entire Oligocene section is missing. This contact is clearly indicated at 118 meters in both the gamma-ray and electric logs taken at this site. Reflector A″ is thought to correspond to the contact between the unconsolidated radiolarian ooze and the chert that lies below a depth of 230 meters. The upper part of the acoustically defined Carib beds corresponds to the radiolarian ooze (of Middle Eocene age) and possibly some of the overlying red clay. The lower part of the Carib beds consists of chert, at least at the top of the sequence, as was already known from core samples taken from a fault scarp on the southeastern extension of the Beata Ridge into the Venezuelan Basin (*26*, *27*). Work carried out by the *Glomar Challenger* has produced no data that permit a more detailed interpretation of phase I of the history of the Caribbean region, but phase II can be stated to have been a time of massive accumulation of siliceous sediments. Phase II also corresponds to the time of maximum connection of the Atlantic with the Pacific through the Panama–Costa Rica region (*21*, *22*). North and South America were presumably connected during the Cretaceous, disconnected during the Eocene and Early Miocene, and connected again since the Pliocene. During the Oligocene and later Miocene, the Central American region was probably a series of islands, which restricted the mixing of Pacific and Atlantic waters. Phase III, which, according to Ewing *et al.* (*25*), "dates from the deformation that bent the Carib beds into their present configuration and is characterized by gradual burial of the deeper parts of the floor by younger turbidites," may correspond to the Oligocene-Recent. In any case, it now seems that, if future drilling discovers siliceous ooze at other sites in the Caribbean, the Carib beds may be recognized as a formational unit composed of predominantly pelagic siliceous sediment. Although the age of this material is known to be Middle Eocene at site 29 and Early Eocene on the fault scarp of the southeastern extension of the Beata Ridge (*26*), the full extent of this deposit remains to be determined.

Aves Ridge

Site 30, on the Aves Ridge, was chosen to provide a suitable reference section for calcareous plankton biostratigraphy in place of site 29, which had been found to lie mostly below the zone of calcium carbonate compensation during the pre-Pleistocene. The original intention was to core continuously through the Early Pleistocene, Pliocene, Miocene, and (it was hoped) older strata. By analogy with hole 25 on the North Brazilian Ridge, it was expected that the Aves Swell would be mantled by planktonic foraminiferal-calcareous nannoplankton ooze and that the section would have thicknesses typical for oceanic oozes with sedimentation rates of 0.5 to 1 centimeter per 10^3 years.

Drilling revealed that the Pleistocene and Pliocene sediments are chiefly silts, probably derived from volcanic activity in the Grenadines to the east. The Pleistocene sedimentation rate was two orders of magnitude higher than would normally be expected, and the Pliocene sedimentation rate was about half that of the Pleistocene. The Miocene sediments were found to be chalk with an admixture of terrigenous material but with a more normal pelagic sedimentation rate of about 0.25 centimeter per 10^3 years. Large-scale delivery of volcanically derived silts to the Aves Ridge in this region appears to have started during the Early Pliocene and to have steadily increased during the later Pliocene and Pleistocene. Figure 4 is a schematic representation of transport, sorting, and settling conditions for terrigenous sediments derived from volcanic sources in the Grenadines. The sediment is carried westward by the Atlantic Equatorial Currents, and the diagram was prepared on the assumption of an average velocity of 40 centimeters per second. The diagram shows that the Grenada Trough can be expected to have a thick accumulation of fine and very fine sand-sized material in addition to the turbidites that would normally be expected. The Aves Ridge should catch much of the silt, so that only the very fine silts and clays should be carried into the Venezuelan Basin.

The sedimentological peculiarities of the Aves Ridge hole are reflected in grain size analyses. The Pleistocene sediments are mostly silty clays. The very small sand fraction is actually the tests of Foraminifera and other microfossils and is usually a few percent. The sand fraction, chiefly the tests of planktonic Foraminifera, in the Miocene chalks from the deeper part of the hole is several tens of percent, between one and two orders of magnitude greater than in the upper, higher sediments. This coincides generally with the much greater sedimentation rate for the younger sediments.

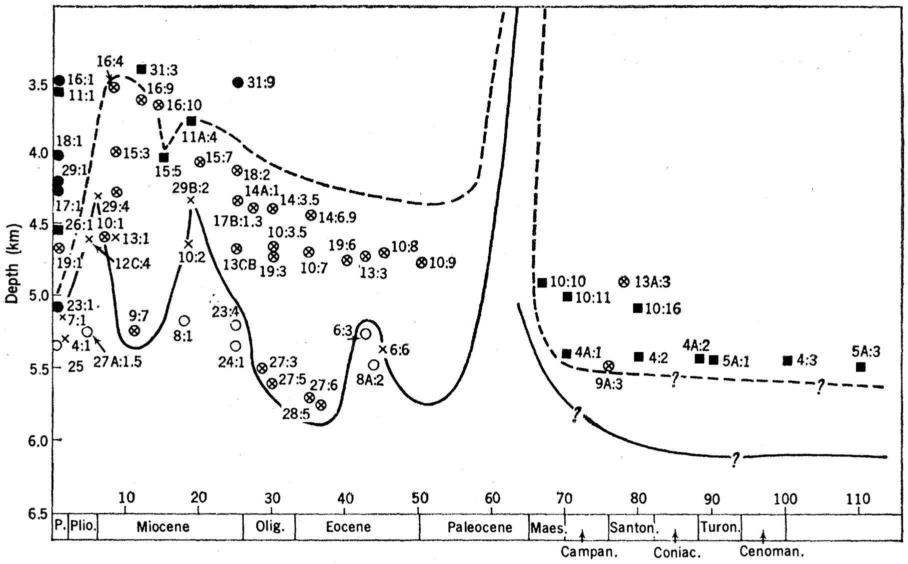

Fig. 5. Schematic diagram of the vertical fluctuations in two important calcium carbonate compensation datum levels plotted against time: the upper (dashed) curve indicates the lower limit of planktonic foraminiferal tests; the lower (solid) curve indicates the lower limit of calcareous nannoplankton fossils. Time scale after W. A. Berggren [see (*3*)]. Solid circles (or squares), planktonic foraminiferal tests and calcareous nannofossils present; circles with X in the center, calcareous nannoplankton fossils present; open circles, no calcareous plankton fossils present. Numbers beside symbols indicate the Deep Sea Drilling Project site number and core number from which data are derived.

Beata Ridge

Site 31 was chosen at a location where it was thought that horizon A″ was absent, so that penetration to levels older than those sampled by hole 29 might be achieved. Technical difficulties prevented sampling of strata older than Late Oligocene, but interesting new data on the later Tertiary history of the Beata Ridge have been revealed.

An excellent summary of the geology of the Beata Ridge has been presented by Fox *et al.* (*14*). They indicate that the ridge was produced by normal faulting during the early Tertiary and that the crest of the Beata Ridge was close to sea level in the Eocene, citing as evidence the recovery of Eocene shallow-water carbonate pebbles dredged from the steep western slope of the ridge. They further indicate that by Late Oligocene time the ridge had subsided into deep water, where it remained a site of pelagic sedimentation.

The deepest unit cored by the *Glomar Challenger* in hole 31, between 207 and 325 meters, is somewhat indurated chalk of basal Miocene to Late Oligocene age. The somewhat corroded condition of the planktonic Foraminifera in the Late Oligocene chalk indicates that deposition occurred in the upper part of the zone of calcium carbonate compensation. The basal Miocene chalk and Middle Miocene ooze show no signs of solution and can be assumed to have been deposited above the zone of calcium carbonate compensation. The Pliocene samples show strongly corroded planktonic Foraminifera and great enrichment of discoasters, which suggests that, during this time, deposition occurred in the lower part of the calcium carbonate compensation zone. A curve showing the fluctuation of the zone of calcium carbonate compensation in the Atlantic through the Late Cretaceous and Cenozoic is given in Fig. 5. This curve, discussed at length in a later section (see "Calcium Carbonate Compensation"), indicates that the compensation level rose during the Pliocene and Pleistocene. The drilling at site 29, to the east in the central part of the Venezuelan Basin, confirms this general scheme. At site 31, however, the sediments least affected by calcium carbonate compensation are the Miocene chalk and ooze. This can only be interpreted as indicating that vertical motions of the Beata Ridge during the later Tertiary exceeded the fluctuations of compensation level. The observations are best explained by assuming that the ridge had subsided to a depth in the lower part of the calcium carbonate compensation zone (probably at about its present depth) by Late Oligocene time. During the Miocene the ridge was uplifted somewhat, probably about 1000 meters or so. Since the Miocene, the Beata Ridge has gradually subsided again to reach its present depth.

On the Nature of Reflecting Horizons

One of the more important geophysical tools developed for exploring the floor of the ocean is the continuous seismic profiler (*28*). By means of a high-energy acoustic source, commonly an electrical "arcer" or a pneumatic "air gun," a signal is sent down, partially reflects off the bottom, but also penetrates below the sea floor and reflects off deeper sediment and rock layers beneath it. The profiler records the vertical cross section of the bottom and subbottom reflecting surfaces (interfaces caused by changes in acoustic impedance) along the ship's track. Seismic profiler records across many ocean basin areas commonly reveal one or more strongly reflective interfaces between the ocean bottom and "basement" (the deepest reflector, below which no other reflectors appear).

Intermediate reflectors: Horizon A. As a result of numerous seismic profiles, Ewing *et al.* (*10, 29*) and Windisch *et al.* (*30*) have shown that, in most parts of the North Atlantic, sediments at some distance from the Mid-Atlantic Ridge have one strong intermediate reflector, and sometimes two. The uppermost of these they called horizon A, and they suggested that it could be used for both stratigraphic correlation and structural interpretation. They did not claim that this was a single continuous bed, but they did suggest that is seemed to be at about the same stratigraphic horizon everywhere. The results of legs 1 through 3 of the Deep Sea Drilling Project confirmed their inferences that the top of the horizon is a generally synchronous zone of Early to Middle Eocene age. In both the eastern and western parts of the North Atlantic, horizon A was shown to consist of hard cherts, and the deeper and less prevalent horizon β was also found to be chert of Cretaceous age. Evidently the Late Cretaceous–Eocene was a time when silica precipitation in the North Atlantic was greater than at any time since.

In the South Atlantic a reflecting horizon believed to be analogous to horizon A has been traced over broad areas from the Rio Grande Rise to the southern Argentine Basin (*31*). In the North Atlantic, horizon A is level regardless of sea-floor topography; in the Argentine Basin, it is generally conformable to the topography.

Seismic reflection measurements (*32*) along a transect from Recife, Brazil, to Freetown, Sierra Leone, show a prominent intermediate reflector similar to horizon A across the northwestern Brazil Basin, which is difficult to trace continuously near the Brazil slope, owing to the presence of numerous seamounts. Unlike its counterpart in the eastern Atlantic Basin, this horizon in the western basin is not a seismic refractor. Hayes *et al.* (*9*) plot a broad area of the Demerara Abyssal Plain, underlain by a prominent intermediate reflector presumed to be comparable to horizon A. However, it cannot be traced continuously to adjacent regions.

Drilling results from the Atlantic sites of leg 4 point out that predictions on the nature of reflecting horizons in unsampled areas, based upon projections from sampled sites, can be misleading. Sites 23 and 24 had a strong reflector at about 137 meters that had been assumed to be horizon A. Cores recovered at this depth show that the reflection is apparently due to a series of uncemented turbidites of Middle Miocene age. Site 24 bottomed in basalt, above which were sediments of Late Cretaceous age; no chert was encountered in the entire section.

Site 27 shows a very strong "A" reflector at about 69 meters and a less strong "β" reflector at about 236 to 244 meters. The upper part of the section was cored continuously with good recovery and consisted of typical deep sea clays except for the interval at 67 to 70 meters, which had two beds of sandy silt turbidites (Pleistocene or Pliocene). Evidently, the contrast in lithology between the clays and the turbidites can create sufficient change in acoustical impedance to show up as a reflector. Similarly, the lower reflector seems to be due to two thin turbidites of Miocene age.

Site 28, drilled on the Outer Ridge only 500 miles southeast of the well-known horizon A and β outcrop area (*10, 30*), was expected to have a substantial intermediate chert reflecting horizon within the upper 200 meters. This was not confirmed in the drilling, which penetrated to 404 meters. A problematic thin, hard layer or layers may have been encountered at and below 175 meters, but the material was not sampled; unlike the typical horizon A chert, the reflecting layer did not stop the drilling operations.

It is apparent from these results that not all prominent intermediate reflecting horizons in the Atlantic are chert and that Eocene cherts are not ubiquitous. The above discussion should not be interpreted as negating the value of horizon A. It means that, unless a strong reflector has been traced from a known area, or until it has been penetrated by the drill, it should not be presumed to be of any particular age or composition.

Basement. In most areas of the ocean the geophysical basement is assumed to be basalt. On leg 4, basement was penetrated at two sites, 24 and 27. At site 24 it proved to be a basalt just below sediment of Campanian age. The shallow penetration of basalt at this site does not positively confirm that it is basement. At nearby site 23 a thin basalt flow was penetrated at about 200 meters, below which unconsolidated sediment of possible Upper Cretaceous age was penetrated. Comparison of the crystalline nature of the basalt samples at these two locations suggests, however, that the sample from site 24 has more the character of true basement basalt. At site 27 the hole bottomed in a hard, clayey limestone, the cores of which show bedding that dips about 24°. The seismic basement at site 27 shows a rough topography with relief of about 0.5-second two-way travel time (about 450 meters). The correspondence of core depth with seismic depth and the sampling of steeply dipping limestone beds give support to the view that basement here consists of steeply folded limestone beds of Late Eocene age.

Calcium Carbonate Compensation

An extensive account of the problems of calcium carbonate compensation in the oceans and its relation to the accumulation of pelagic sediments has been presented by Maxwell *et al.* (*3, 4*).

As was noted on leg 3 and in a number of previous publications, pelagic Foraminifera are more readily dissolved than calcareous nannofossils, but within both groups there is differential solution so that some species are removed at levels considerably higher than those at which the most resistant forms are dissolved.

Figure 5 represents the data available from a survey of leg 4 and the previously published Atlantic legs concerning the fluctuation in the depth of two important calcium carbonate compensation surfaces through time. The upper surface is the lower limit of occurrence of the tests of pelagic Foraminifera; the lower surface is the lower limit of the occurrence of calcareous nannofossils. Symbol X indicates a datum point that lies on the lower compensation curve; that is, the transition from nannofossil-bearing clay to barren red clay occurs within a single core barrel and can be accurately dated.

From these data, it is evident that considerable fluctuations in the two recognized levels have taken place during the Cenozoic and Cretaceous. In the article by Maxwell *et al.* (*3, 4*) the data were interpreted as indicating that the calcium carbonate compensation level remained at a constant depth in the oceans while the ocean floor moved up and down. The fluctuations suggested by Fig. 5 would require a complex motion of the ocean floor over broad areas. These are more easily explained by assuming that the only vertical motion of points on the ocean floor has been downward, as they moved away from the crest of the Mid-Atlantic Ridge, but that the zone of calcium carbonate compensation has fluctuated through considerable distances in the water, owing to paleogeographic factors (changing interconnections among basins) and paleooceanographic factors (changes in chemical composition, circulation, and biological productivity). During the later Tertiary, this fluctuation would be of the order of 1 kilometer. An extreme fluctuation is postulated for the end of the Cretaceous–early Paleocene, at which time the two compensation levels indicated here are thought to have risen well into the photic zone (*33*).

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Regulation of Enzyme Activity

The activity of enzymes can be controlled by a multiplicity of conformational equilibria.

Gordon G. Hammes and Cheng-Wen Wu

The living cell seldom either synthesizes or degrades more material than is necessary for normal metabolism and growth. In fact all major metabolic pathways contain the capacity for self-regulation. The control of cellular metabolism ultimately involves the regulation of enzyme activity. In broad terms, enzymes can be regulated in two ways: genetic control and direct control of catalysis. Some of the regulatory mechanisms are illustrated in Fig. 1.

In many microorganisms, as well as in a few mammals, the addition of a substrate has been found to induce the synthesis of an enzyme which reacts with this particular substrate; conversely some compounds can cause the repression of enzyme synthesis. Both induction and repression of enzyme synthesis act at the genetic level, and the biochemical and genetic hypotheses involved have been extensively reviewed (*1*).

Direct control of enzyme activity can occur either through the catalytic mechanism itself or through a coupling of the catalytic mechanism with other processes. An example of the former case is simply the Michaelis-Menten kinetics characterizing enzymatic reactions: As the substrate concentration increases, the reaction rate increases until a limiting value is reached; moreover, as the product accumulates, the reaction rate decreases. A more subtle case is where one compound serves as a substrate for more than one enzyme: At low concentrations of substrate, reaction occurs with the enzyme for which it has a higher affinity, and at high concentrations it reacts with the second enzyme, enhancing the dissipation of the substrate. For many enzymes, coenzymes are necessary for catalysis. Since small amounts of coenzymes exist in the cell relative to the number of enzymatic reactions in which they are involved, the concentrations of these coenzymes could have a control function. Normally the binding of substrate to enzyme follows a hyperbolic isotherm, but in enzymes with multiple subunits the binding isotherm may become sigmoidal

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