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PELAGIC SEDIMENT, DEEP WATER CHEMISTRY, AND TECTONICS: AN APPLICATION OF THE HISTORY OF BIOLOGICAL SEDIMENT ACCUMULATION ON THE TECTONIC HISTORY OF THE CARIBBEAN

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Key-words: Pelagic sediment, Biogenic silica, Central American isthmus, Tectonic history.

Riassunto. La distribuzione della silice biogenica nei sedimenti pelagici consente di dimostrare che l'istmo dell'America Centrale si è gradualmente sollevato tra 35 e 15 MA, impedendo progressivamente il flusso delle acque profonde ed intermedie ricche in silice dal Pacifico ai Caraibi. L'istmo continuò a sollevarsi tra 15 e 4.2 MA, ma in quest'ultimo periodo il flusso delle acque pacifiche ricche in silice nei Caraibi era già cessato.

A circa 40 MA i Caraibi erano separati dall'Atlantico occidentale da una barriera, situata probabilmente in corrispondenza delle Piccole Antille attuali e della Dorsale di Aves. Questa barriera impediva alle acque ricche in silice dei Caraibi di penetrare nell'Atlantico occidentale nel momento in cui la massa d'acqua profonda nord-atlantica di neoformazione (NADW) veniva a sostituire le acque profonde e intermedie atlantiche, pur esse ricche in silice. La barriera si interruppe a circa 19 MA, permettendo così il flusso delle acque ricche in silice dai Caraibi all'Atlantico, almeno per una distanza di qualche centinaio di chilometri ad est delle Piccole Antille (DSDP Site 543).

La variazione delle profondità di compensazione dei carbonati (CCD) al limite Miocene-Pliocene, testimoniata in tutto l'Atlantico, viene risentita anche nei Caraibi (Site 29). Questo sta ad indicare che la breccia che aveva interrotto la barriera a circa 19 MA era ancora aperta a quel tempo. La chiusura totale della stessa è databile a tempi molto più recenti, probabilmente in conseguenza della collisione delle Piccole Antille con il Sud America.

I tempi di formazione delle barriere, che sono il riflesso dell'attività nelle zone di subduzione, come pure la loro estensione orizzontale, possono essere meglio stabiliti usando lo strumento biostratigrafico piuttosto che le ricerche geologiche tradizionali sul terreno.

Abstract. The distribution of biogenic silica in pelagic sediment enables us to demonstrate that the Central American isthmus shoaled from 35 to 15 MA, gradually stopping the transfer of dissolved silica in intermediate ocean water into the Caribbean. Between 15 and 4.2 MA it continued to shoal, but during this interval the effective transfer of silica had ceased.

A barrier existed at 40 MA between the west Atlantic and the Caribbean, probably on the site of the present Lesser Antilles - Aves Ridge. This barrier prevented the transfer of silica to the western Atlantic at the time of the removal of Atlantic intermediate and deep water silica by the newly formed North Atlantic Deep Water (NADW). The barrier was breached at about 19 MA, enabling silica from the Caribbean to penetrate at least to a few hundred km east of the Lesser Antilles (Site 543 DSDP).

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The Miocene-Pliocene boundary variation of the CCD recorded throughout the Atlantic is also seen at Site 29, within the Caribbean. This indicated that the breach formed at 19 MA was still open at this time. At a more recent time this breach has closed, probably by the collision of the southern Lesser Antilles and South America.

The timing of the formation of barriers, which reflect the activity of subduction zones, as well as the horizontal extent of these barriers, can be established better using the biostratigraphic powers of pelagic sediment analysis than through conventional field geological investigations.

Introduction.

The tectonic history of the Caribbean has been the subject of numerous studies. The forthcoming volume H of the Geological Society of America's series on the Decade of North American Geology (Case and Dengo, in press) is devoted to this subject. Many issues in the tectonic history of this area were and will remain controversial, especially those debating the extent and timing of the eastward movement of the Caribbean Plate, which has been reckoned to have moved eastward during much of the Cretaceous and Cenozoic. It is not the purpose of this paper to debate these issues, which are exhaustively covered elsewhere. Instead, I intend to focus narrowly on questions of the tectonic history which can be approached by the analysis of the history of pelagic sediment accumulation. These questions involve the formation of terrestrial or island-chain connections between the Greater Antilles and South America (The Lesser Antilles or Aves Ridge) and between nuclear Central America and Colombia (isthmian or southern Central America) (Fig. 1). These "terrestrial connections" are edifices erected above active subduction zones. Their horizontal extent and the timing of their formation are fundamental tectonic problems.

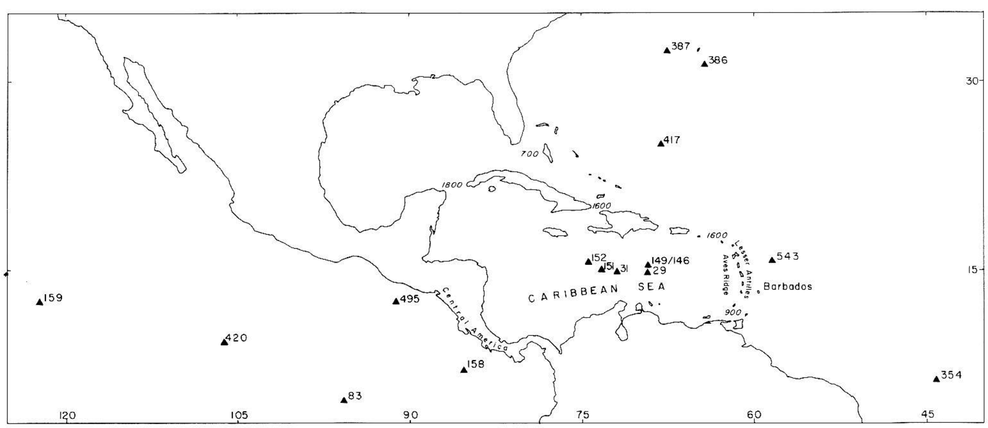

Fig. 1 - Map of the Caribbean and adjacent oceanic areas, showing the location of barriers discussed in the text, of DSDP Sites considered here, and of the sill depths (italics, in meters) surrounding the Caribbean Sea.

The approach that I will pursue here is that the nature of these tectonically significant events can be elucidated by an analysis of the pelagic sediment accumulating on either side of these features. The two ridge/rise areas named above form significant barriers to the circulation of intermediate and deep ocean waters. The erection of a barrier to deep and intermediate water circulation has caused in the Caribbean the termination of a supply from the Pacific of deep and intermediate water silica, causing in turn a cessation of siliceous productivity and sedimentation on the down-current sides of the barriers. Another phenomenon resulting from the erection and breaching of barriers is the position of the CCD (or carbonate compensation depth), which results from the balance between carbonate ion activity and saturation value for calcite. Bodies of water that are connected at appropriately great depths commonly share vertical movements of this surface; such movements are reflected in their sedimentary histories. Commonality in the histories of adjacent basins implies a deep-water connection, in turn demonstrating the absence of a barrier or a major breach in that barrier. In the Caribbean there is ample evidence for both phenomena. Because the pelagic biostratigraphic record for the Cenozoic is capable of establishing ages to about a million years or better, the application of pelagic sediment analysis is an especially valuable tool for tectonic history, for which the timing of tectonic events is commonly very difficult to establish with any degree of precision using traditional field geology approaches.

The examples used here are drawn from the record of the Deep Sea Drilling Project in the Caribbean (Leg 4: Bader, Gerard et al., 1970; Leg 15: Edgar, Saunders et al., 1973), and in the adjacent Atlantic (Leg 78A: Biju-Duval, Moore et al., 1984). In addition, I have used chemical data for other sites taken from Donnelly (1980). Data for Sites 495 and 543, for Barbados, and some new data for Site 149 are unpublished. Chemical data for oceanic water chemistry are from GEOSECS (Bainbridge, 1981; Broecker et al., 1982).

Siliceous Sedimentation and Isolation of Deep Waters.

The present Atlantic and Pacific oceans show a profound difference in the abundance of silica in intermediate and deep waters. This has been convincingly explained (for example, Broecker, 1974) as having resulted from formation of deep waters in the North Atlantic, the passage of this deep water to the Pacific, and the return of shallow water to the Atlantic. Because silica is carried in deep water but not in shallow, it has become highly concentrated in the Pacific (Fig. 2).

The upwelling of this deep water results in siliceous productivity and sedimentation. Although this productivity is much higher in the well-known zones of upwelling (equator, eastern margins of the oceans), there is detectable siliceous productivity almost everywhere in the Pacific. Most of the descending siliceous microorganism debris is dissolved and the silica returned to oceanic circulation; however, a small fraction is preserved within the sediment and becomes a record of silica productivity for later examination.

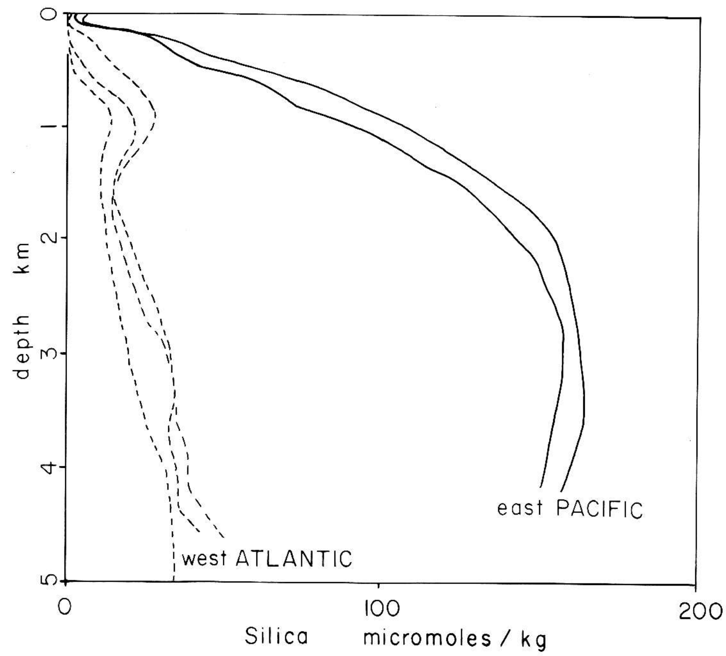

Fig. 2 - Graph showing the distribution of silica in the present ocean with depth, showing three Sites (33, 37, 40) from the low-latitude western North Atlantic and two Sites from the low-latitude eastern Pacific (337, 343), from Bainbridge (1981) and Broecker et al. (1982).

The conventional measure of silica in sediments is a direct measure of the amount of opal, either through an infra-red spectroscopy technique or through a chemical extraction. I believe that these methods are not reliable, because opaline fossils are unstable and tend to react with pore water to produce siliceous authigenic minerals, which characteristically appear at stratigraphically lower levels of siliceous pelagic sequences. Diatoms, which are probably the volumetrically most important silica producers, are especially evanescent and are generally not well preserved in older sediment.

I have been using a chemical technique to estimate the content of biological silica in sediment. The relationship between silica and alumina was first noted by Boström et al. (1972); my method is based on the same relationship. It assumes that silica enters sediment in two forms: alumino-silicate debris of terrestrial origin and biological silica. If the ratio of silica to an immobile element is fairly constant for terrestrial debris from a variety of origins, then the measure of the immobile element is used to estimate the silica of that origin. The most abundant immobile element is alumina and is used here (Titanium would work almost as well except for its lesser abundance and, hence, analytical problems. Iron and potassium are also possible elements but present some additional problems). Leinen (1977) suggests a similar method using aluminum and the square of magnesium as a means of estimating terrigenous sediment. The uptake of Mg by siliceous sediments is well known, but highly variable depending on conditions of accumulation (Donnelly & Merrill, 1977). The estimate of amount of a material added linearly by the use of a non-linear variable is likely to succeed only under special circumstances, which I do not feel have been demonstrated.

The present western North Atlantic Ocean is useful as a reference value for non-siliceous pelagic sediment. There is a minor radiolarian fauna found associated with the upwelling of the eastern side of the temperate ocean, but siliceous productivity is essentially absent west of the mid-Atlantic ridge. There are siliceous fossils deposited in the far north and south associated with conditions that do not obtain in the temperate ocean. Rivers bring major quantities of silica to the sea; much of this is trapped in the eastuaries. The supply of riverine silica to the surface waters of the Atlantic is delivered to depth as siliceous organisms and subsequently transported from the Atlantic to the Pacific in North Atlantic Deep Water (NADW). The western North Atlantic serves as a good sample of the Si/Al ratios of typical pelagic sediment which lacks biological silica. The more northerly samples are richly illitic, and the equatorial samples highly kaolinitic; thus clay minerals of widely varying silica contents are both represented in the suite.

Pacific sediment, on the other hand, is richly siliceous, except in the centers of the gyres and on the western boundary of the ocean. Abundantly preserved opal (Leinen et al., 1986) reflects the zones of notably high productivity, which are the belt of equatorial upwelling, the Antarctic convergence, and the gyre-margin upwelling on the polar and eastern sides of the gyres. In my experiences the Si/Al values of Pacific surface sediment show that original siliceous sedimentation is widespread in this ocean; the occurrence of preserved opal is somewhat more restricted (see also Lisitzin, 1972).

Figure 3 shows histograms of surface sediment samples from the western North Atlantic and from the Pacific. Both sample sets were chosen to represent most closely the surface sediments which might have been found adjacent to the Caribbean throughout the Cenozoic. Interestingly, biological silica is so pervasive in the Pacific that one could very nearly use the Si/Al ratio to discriminate between Pacific and Atlantic sediment. Using a ratio of 2.5 (atomic basis; this is close to the weight ratio of 3 suggested by Boström et al., 1972), 76 per cent of the Atlantic samples fall below this ratio, and 83 per cent of the Pacific samples fall above it.

Thus the preserved silica in pelagic sediment records the presence or absence of silica-enriched deep water. The record can be measured in two ways: the qualitative and quantitative. The qualitative method (Fig. 4-7) utilizes the Si/Al ratio as an indicator of the presence of biological (excess) silica. The quantitative method estimates the accumulation (not sedimentation) rate of biological (or excess) silica in grams per square centimeter per million years. This method requires the availability of a biostratigraphic age determination and some indication that the sample is representative of the entire section. The qualitative method provides the quickest determination of the presence of excess silica. The numerical value of the Si/Al ratio is, however, subject to external influences, which include solution of siliceous debris, sedimentary thinning due to bottom currents, and dilution by terrigenous debris. In a given site a change in Si/Al ratio is

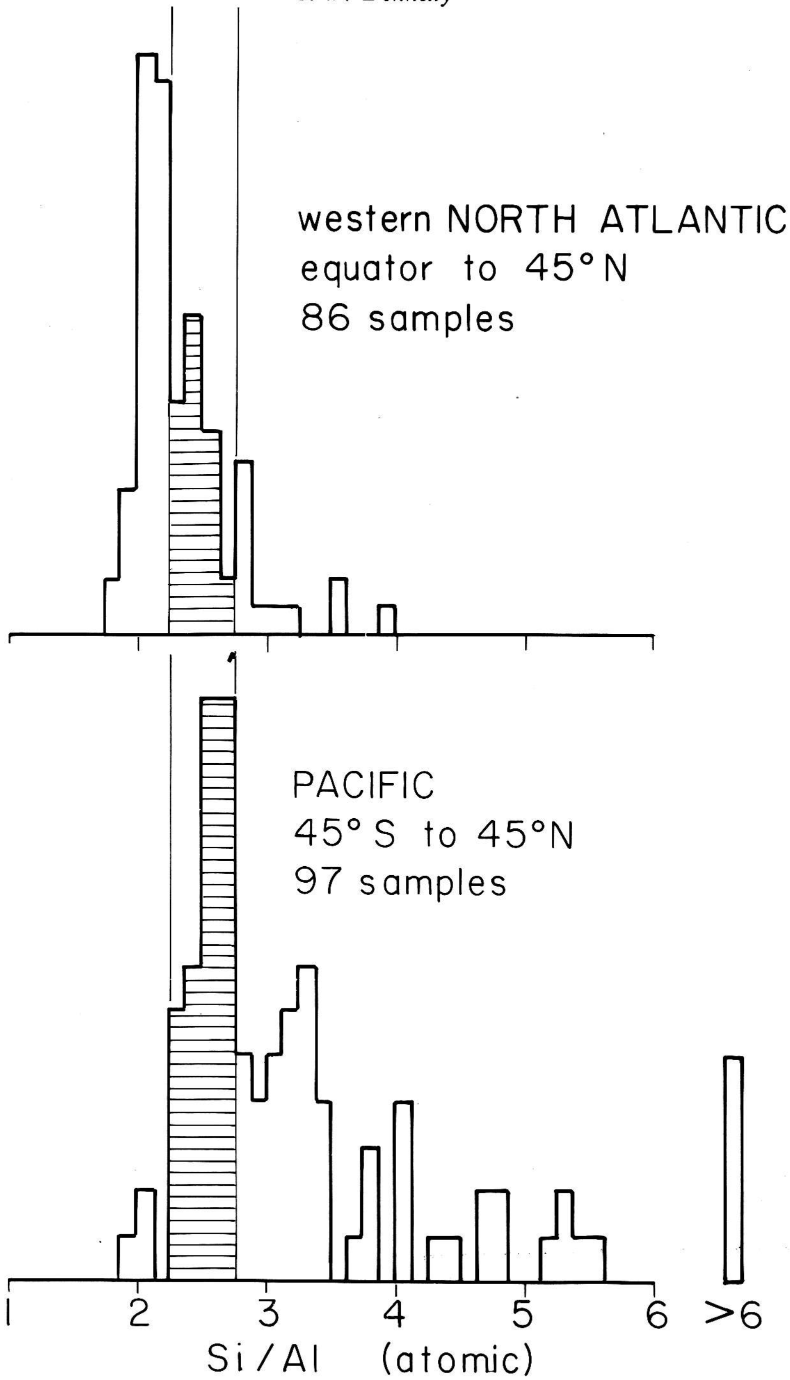

Fig. 3 - Histograms showing the distribution of Si/Al (atomic) ratios for surface sediments, as follows: western North Atlantic (equator to 45°N), 86 samples, and eastern Pacific (45° N to 45°S), 97 samples. The samples between ratios 2.25 and 2.75 (the "range of ambiguity" of Fig. 8 and 9) are indicated by horizontal lines. Date are mainly unpublished piston-core analyses, from Donnelly.

most readily interpreted as a change in silica productivity but is influenced by these other factors. Because of the ambiguities involved, I prefer to draw the conclusion of changing silica productivity mainly in cases in which silica productivity essentially ceases or renews after cessation, and preferably if the effect can be seen at several sites with differing sedimentary regimes. Both the western Atlantic and Caribbean (Fig. 5-7) meet these criteria.

The quantitative method (Fig. 8, 9) can be use if there is an adequately sampled section for the determination of an accumulation rate, and if the porosity (or density) of the sediment is available for calculation of the rate of accumulation of solid materials. The results of a quantitative determination are necessarily somewhat ambiguous because the reference value of Si/Al in the terrigenous debris is not known. In the example calculated here I have designated a range of "ambiguity" (Si/Al 2.25 to 2.75) which includes the mode of the Atlantic histogram shown in Fig. 3. If the terrigenous sediment is less siliceous than 2.25 Si/Al (i.e., higly kaolinitic), then the amount of terrigenous silica will be overestimated and the biological silica underestimated. The reverse is true for a highly illitic terrigenous sediment with a Si/Al ratio greater than 2.75. Inspection of Fig. 8 and 9 show that the former case (terrigenous silica overestimated) is clearly represented in the Neogene portions of many sections, which would imply negative excess silica accumulation. There is no physical meaning to negative accumulations of biological silica, and the terrigenous silica must have been in these cases less siliceous than 2.25.

Clearly the method becomes less ambiguous as the aluminum accumulation rate decreases; with little aluminum in the sample, virtually all of the silica must be biologic (A matter not pursued here is that aeolian sediment, which is conventionally detected by its quartz content, is in fact fairly aluminous). Most siliceous debris is dissolved either in the water column or at the sediment surface. Thus, the accumulation of biological silica is far higher in sediment in which the total accumulation rate is high, though its computation may be more ambiguous. A further problem with all accumulation measurements is that pelagic sediment is now recognized to be highly subjected to thinning and even hiatuses for reasons which are still not completely understood. While the quantitative approach might potentially more valuable than the qualitative, its application is more limited because of the more limited stratigraphic information on complete sequences, and because of problems of thinned sections and solution of siliceous debris in regimes of low total sediment accumulation. Both the qualitative and quantitative methods are shown here and give similar results.

Rise of the Central America Isthmus.

The Central American isthmus has been considered to play a major role in New World biogeography since Darwin's observations (notebooks from the voyage of the BEAGLE) that the special character of fossil South American mammals required a long period of isolation of these mammals from the North American stock. Subsequently, the rise of the Central American isthmus has been the focus of numerous investigations which culminated with the result of Keigwin (1982) that the planktonic foraminifera of Caribbean and Pacific drilling sites showed essentially identical oxygen isotopes until about 4.2 MA. This showed that at that time the rising isthmus had isolated the surface waters of the Caribbean and Pacific. Isolation of oceanic waters is the converse of terrestrial connections, and mammalian paleontology records the appearance on each side of the isthmus of the first waif, island-hopping elements, and at slightly later times, the first dry-land immigrants. Marshall (1985) records the appearance of the first North American waif elements in South America *(Procyonidae)* at 7.0-7.5 MA, 6.4-6.9 MA, and 5.4-5.8 MA at three sites. In North America the first South American elements *(Megalonychidae)* appear at 8.2 MA and 8.0 MA at two sites. He records the first land-bridge immigrants in South America *(Cricetidae)* at about 3 MA. A mustelid and a tayassuid appear at about 2.4-2.5 MA. In North America the first dry-land immigrants are members of the families *Erethizontidae, Hydrochoeridae, Glyptodontidae,* and *Mylodontidae,* and appear at about 2.6 to 2.8 MA. Thus, the data from oceanic planktonic foraminifera and from mammalian paleofaunas record a rising isthmus creating first a chain of island capable of passing a few of the more adventurous and mobile mammals, followed by a dry-land connection permitting a vast exchange of mammals in both directions. The sequence is 1) island chain with extensive shallow water passage (mammal evidence, 8.2-8.0 to 5.8-5.4 MA from several sites; 2) shallow water passage terminated (oxygen isotopes of foraminifera, 4.2 MA), and 3) a dry-land connection (mammal evidence, about 3 to 2.4-2.5 MA).

The earlier state of the isthmus is not clear from these or other investigations. A widely cited view (Wadge & Burke, 1983; Pindell & Dewey, 1982) is that the isthmus is an emergent flap which swings shut as the Caribbean plate moves eastward more or less continuously through the Cenozoic. An alternative view (Donnelly, 1985; in press) is that the isthmus occupied it present position (although not necessarily having its present contorted shape in Panama) and simply rose to emergence. In the first view the volume of sea water exchange is slowly diminished, but there is not necessarily a termination of deep water circulation at an early time. The second view holds that sea water exchange is terminated first at greater depths and later at shallower depths.

History of the Aves Ridge and Lesser Antilles.

The eastern end of the Caribbean has received less attention from both the biogeographers and geologists. At present the Caribbean is closed at the east by the Lesser Antilles, which consist of an inner (Recent volcanic) and outer (Paleogene and Neogene limestone) chain surmounting a ridge with sill depths of about 1 kilometer. The Lesser Antilles arc records about 20 million years of volcanic activity; its history as a continuous barrier during this interval and its earlier history are not known.

The Aves Ridge is a largely submarine barrier a few hundred kilometers west of the Lesser Antilles. Submarine investigations (Bouysse et al., 1985) have shown that the ridge is the site of an older volcanic arc. However, it is clear that this arc ceased to function when the Lesser Antilles became active. In fact, there is a broad overlap of ages of volcanic materials, suggesting that there were two arcs during much of the Late Cretaceous and Paleogene.

Donnelly (1985; in press) has suggested that the Early and Middle Cretaceous island arcs formed a more or less continuous chain between the Americas. Late Cretaceous eastward movement of the Caribbean plate stretched and broke this chain, and at this time there was no island chain closing the eastern end of the Caribbean. The rise of the Aves Ridge and Lesser Antilles closed the eastern end of the chain as relative eastward movement of the Caribbean plate was converted into subduction and accompanying volcanism, but there is no obvious evidence from field geology that this barrier spanned the gap between the Americas.

Siliceous Sedimentation in the Cenozoic of the Caribbean and Adjacent Oceans.

Central America Barrier.

Fig. 4 shows Si/Al ratios vs. age at five sites in the eastern Pacific. Because of the velocity of plate movement, only the Neogene record is available. Virtually all of the samples fall on the excess-silica side of the "region of ambiguity". This region of the ocean is consistently siliceous during this period. Sections from the central Pacific (not shown here) record a similar siliceous sedimentation in the Paleogene (Lisitzin, 1972). This analysis becomes both unnecessary and essentially impossible to apply in much of the older Pacific pelagic sediment, because chert becomes a significant but variable fraction of older Pacific sediment. The process of chert formation leads to irregular secondary distribution of silica (hence, scattered Si/Al ratios), and, also to incompletely recovered sections due to the difficulty of both drilling and recovering soft sediment in these intervals. However, I would maintain that the lithological and drilling record, as well as recorded Si/Al ratios of less cherty younger sediments and sparsely recovered older sediments, shows that the eastern and central Pacific was consistently siliceous during the Cenozoic.

Each of the five sites shown in Fig. 4 shows some decline in Si/Al at younger ages. The explanation for this seems is probably found in the world-wide increase in aluminum sedimentation during this interval (Donnelly, 1982).

The Caribbean (Fig. 5) was highly siliceous in the Paleogene, with the Si/Al values decreasing through the Miocene to reach an essentially excess-silica free condition at about 15 MA. Only Site 149/146 was cored completely through the Cenozoic. However, enough material was recovered from four additional sites to show that the siliceous sedimentation recorded at that site occurs generally throughout a wide region. The later Paleogene and earlier Neogene sections show an high degree of agreement in the Si/Al ratio, even though other aspects of their sedimentation, including their carbonate content and total accumulation rates, vary widely. The earlier Paleogene samples show a wide scatter, reflecting the formation of chert and resultant secondary redis-

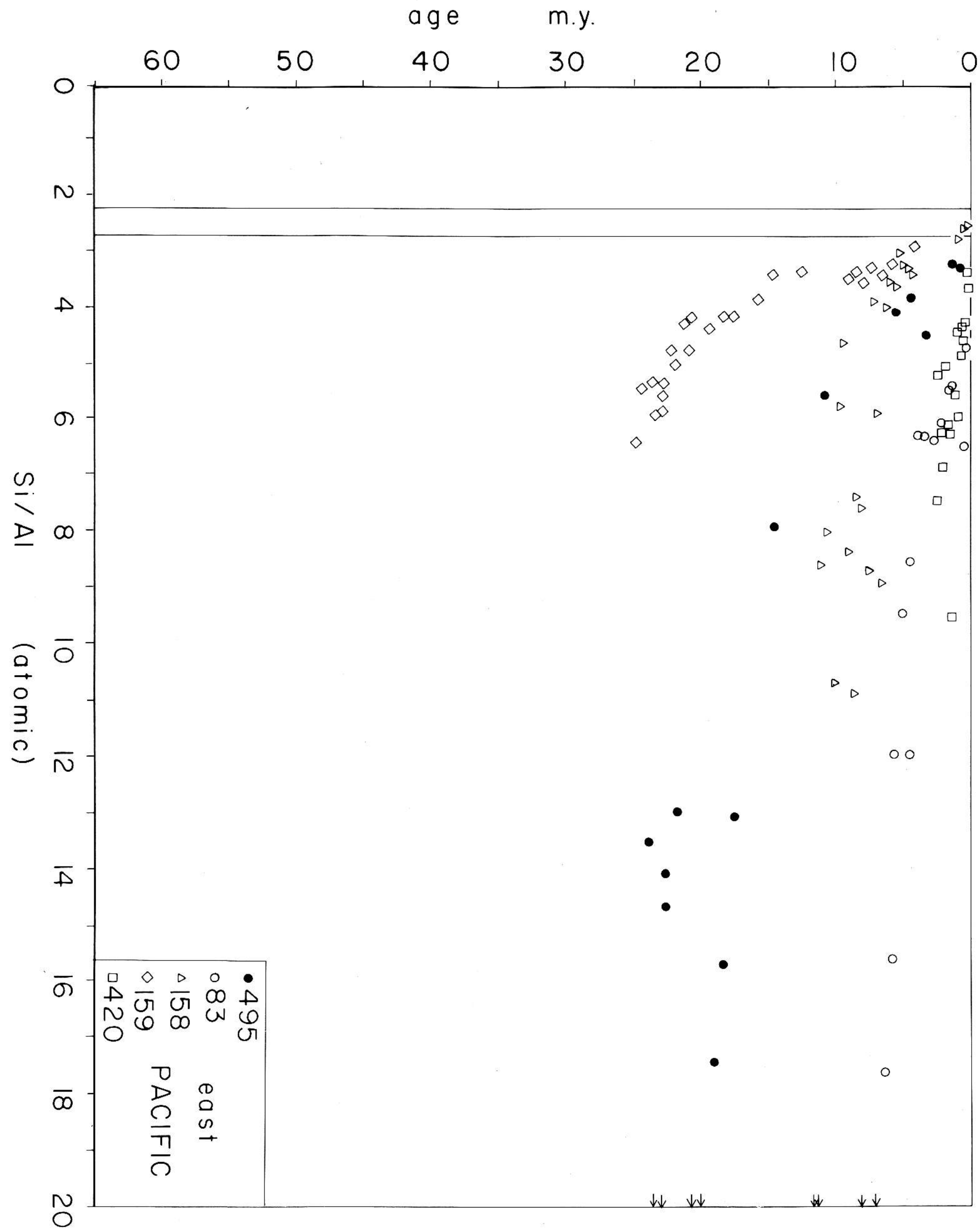

Fig. 4 - Si/Al (atomic) ratios of drilled sediment vs. age, for 5 east Pacific DSDP Sites. The "range of ambiguity" is indicated by two vertical lines at 2.25 and 2.75.

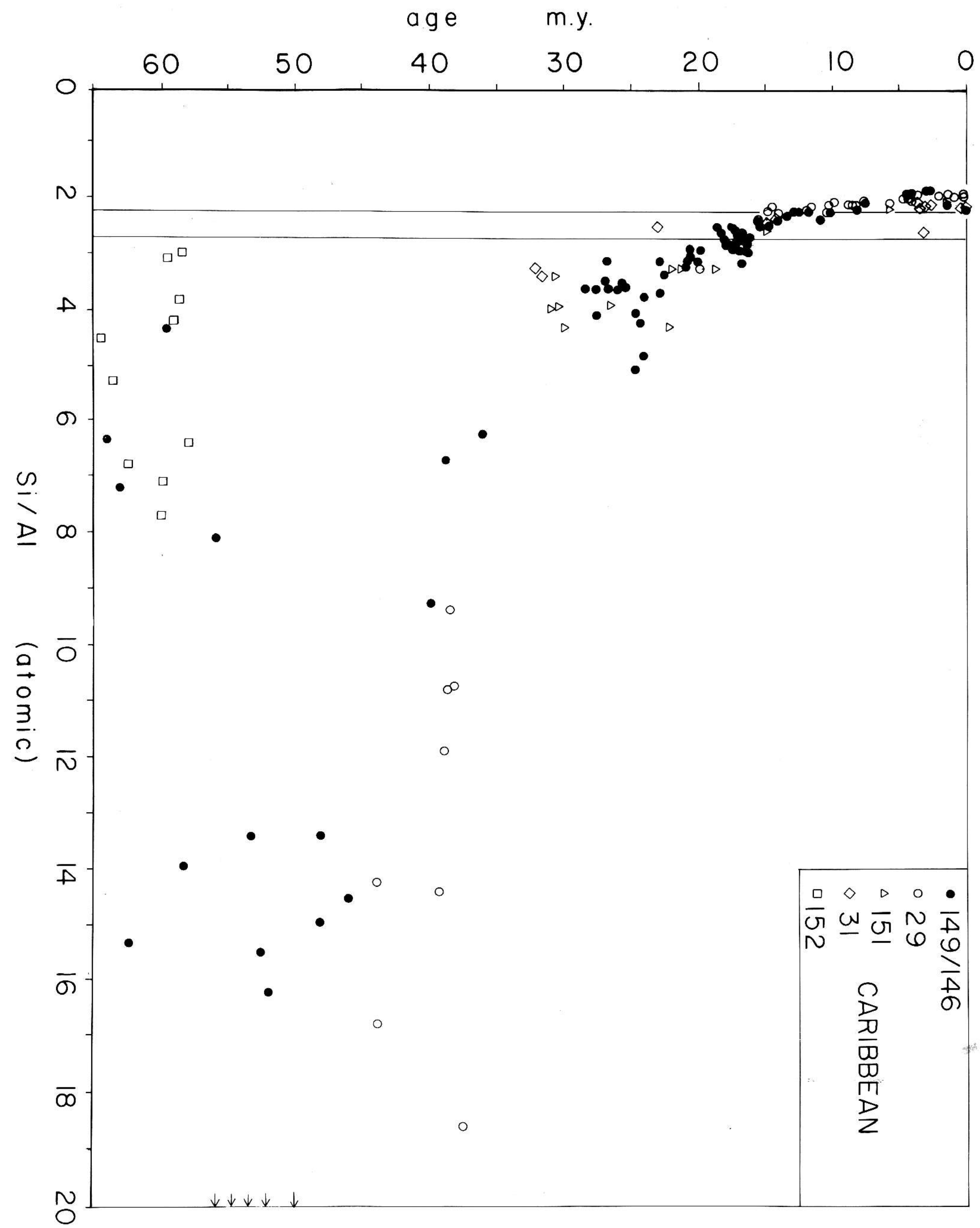

Fig. 5 - Si/Al (atomic) ratios for 5 Caribbean DSDP Sites, with "range of ambiguity"shown as in Fig. 4.

tribution of silica within the sediment. Thus, although the results for a single site are necessarily subject to a variety of interpretations, the parallel decrease in Si/Al ratios at four sites show that a general decrease in excess silica sedimentation has been recorded.

Fig. 8 shows the accumulation rates calculated for those million- year intervals for which samples were available. This calculation is made by converting the recorded sediment densities into densities of solids, and using the biostratigraphically determined ages (converted to the scale of Berggren et al., 1985) to calculate accumulation rate of solids, and, from this, excess silica. As in Fig. 5, the various sites show close parallels, with four sites (Site 152 only recovered older Paleogene) showing a gradually decrease in silica accumulation through the critical interval from 35 to 15 MA.

The interpretation offered here is that the Central American Isthmus rose through the interval from 35 to 15 MA, gradually eliminating the flow of highly siliceous deeper water across the barrier, until its cessation at about 15 MA. Shallow water circulation across this barrier continued for an additional 10 million years (evidence of oxygen isotopes from Keigwin, 1982). This conclusion does not address the problem as to how currents were distributed with depth between the Caribbean and Pacific. It merely notes that the only source of silica in the Caribbean could have been from the Pacific; the origin of NADW at about 40 MA had essentially ended this ocean as a potential supplier of abundant silica. It seems likely that the Miocene Caribbean was rather like the contemporary Mediterranean Sea, with higher salinity than the Pacific and a likelihood of a saline water outflow into the Pacific. However the currents might have been arranged, at about 15 MA siliceous water was no longer able to enter the Caribbean from the Pacific.

Lesser Antilles - Aves Ridge Barrier.

The West Atlantic was sampled at five DSDP sites (Fig. 1) occurring over a wide latitudinal range. Unfortunately, no one site was ideal; several were spot cored, and the two completely drilled sites (417 and 543) were unfossiliferous in much of the younger part of these sections. However, Fig. 6 shows that the sites are broadly consistent in showing high Si/Al ratios older than about 40 MA, with a sharp drop in values younger than this age. The poor biostratigraphic control of much of the Neogene section is ultimately of little consequence; the precise age of silica non-sedimentation is less important than the record of the cessation of silica sedimentation, which is well controlled by the upward disappearance of a characteristic radiolarian fauna at each site.

The island of Barbados provided an additional site at which Atlantic pelagic sedimentation of the Paleogene could be examined. Samples of the oceanic sediments were analyzed and provided a Si/Al record (Fig. 7) that closely parallels that seen at the pelagic drilled sites of Fig. 6. A sharp decrease in siliceous sedimentation younger than 40 MA is especially clear on this plot.

The record of the rate of accumulation of excess silica in the West Atlantic (Fig. 9) shows close agreement among the sites. However, these western Atlantic sites agree that the cessation of siliceous sedimentation occurred at an earlier age (about 40 MA)

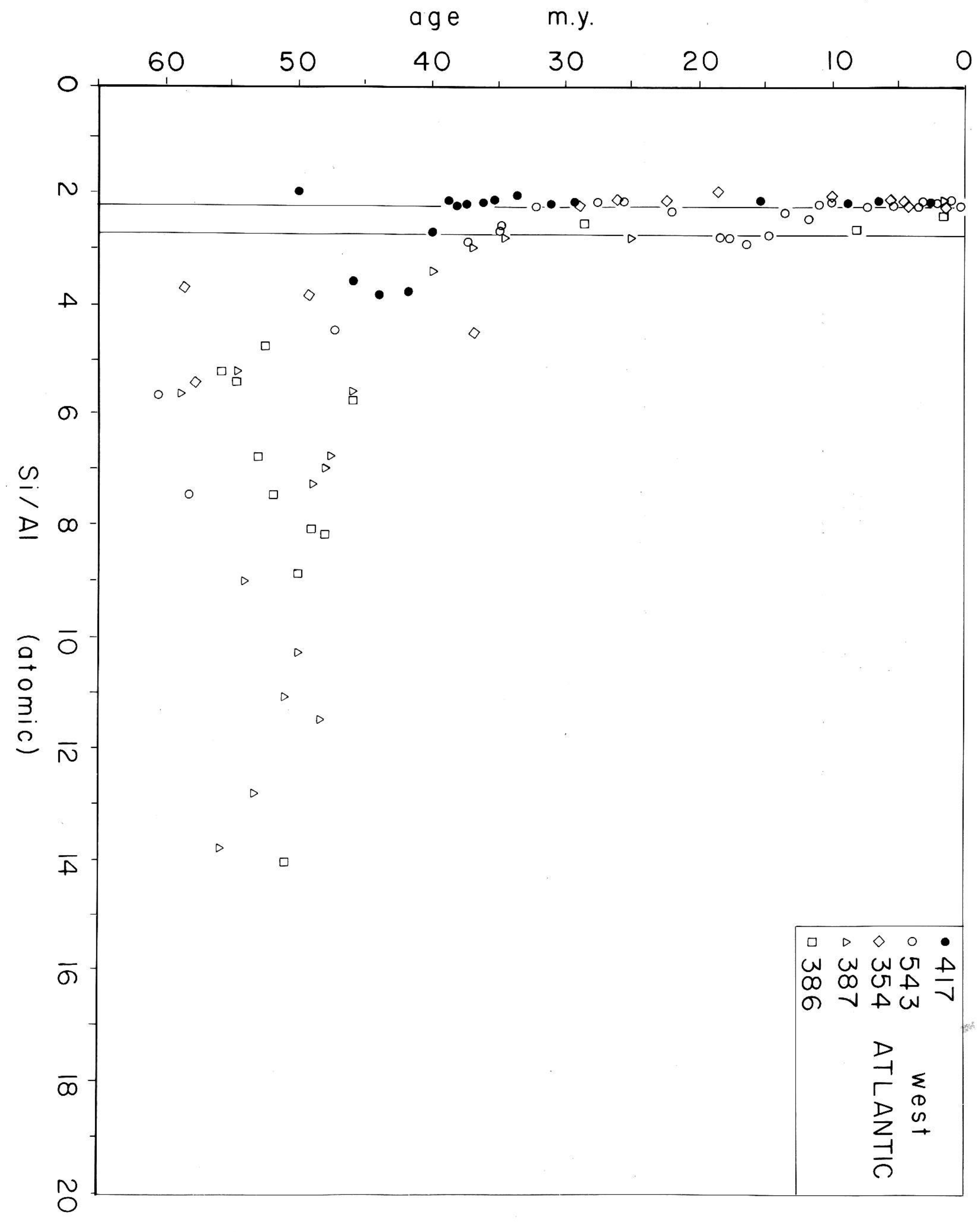

Fig. 6 - Si/Al (atomic) ratios for 5 western Atlantic DSDP Sites, with "range of ambiguity" shown as in Fig. 4.

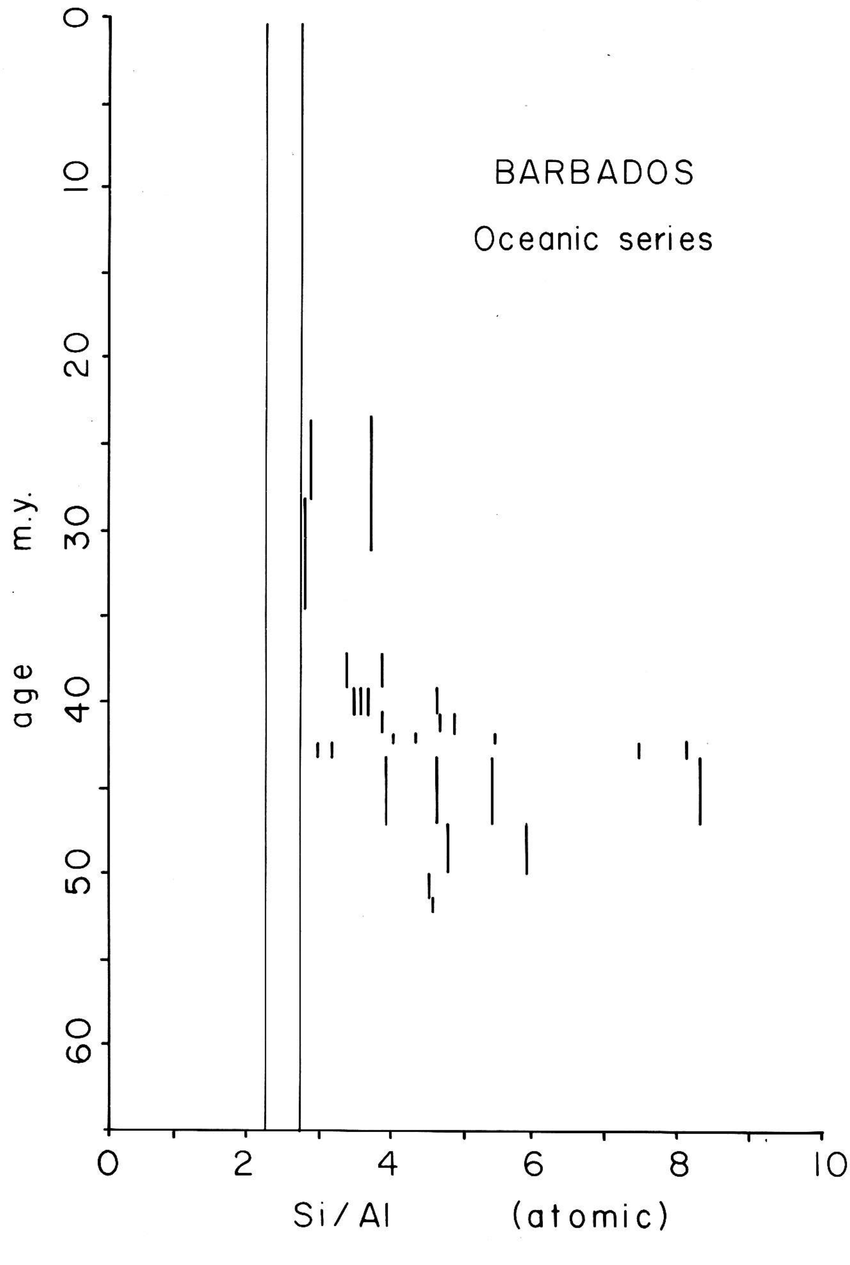

Fig. 7 - Si/Al (atomic) ratios for samples from the oceanic sediments of Barbados, with "range of ambiguity" shown as in Fig. 4. The age ranges of the samples are shown as vertical lines and correspond to radiolarian zones.

than in the Caribbean and seemed to be recorded more abruptly at these sites.

The disappearance in silica in the west Atlantic is clearly not coeval with that of the Caribbean and must indicate the existence of a barrier at 40 MA between these seas. This barrier is some combination of the Aves Ridge and Lesser Antilles, which today enclose the Caribbean and prevent the entry of Atlantic water deeper than about 1600 meters into the Caribbean.

Site 543 stands out among the five sites in showing a renewal in silica sedimentation in the middle Miocene which can be tracked over a time interval of about 5 million years (about 19 to 14 MA). I suggest that this interval marks a breach in the Lesser Antilles - Aves Ridge barrier during this interval. This breach is probably an eastward movement of the Caribbean plate which sheared the Lesser Antilles - Aves Ridge at an unknown place. If the Aves Ridge is composed of Paleogene volcanic materials as is widely believed, then the breach is to the north or south of this remarkably linear feature. The apparent upward disappearance of excess silica at about 14 MA needs not record the healing of this breach, however. At this time the entry of Pacific siliceous intermediate water into the Caribbean has virtually ceased, and would be expected to diminish at an Atlantic site just beyond the barrier synchronously with the Caribbean sites. The final healing of the Lesser Antilles - Aves Ridge breach will be discussed below in connection with the late Neogene CCD variation.

The relatively sharp disappearance of excess silica in the west Atlantic probably marks the first formation of the NADW (Johnson, 1985), and, in fact, may date it more precisely that the commonly given date at the Eocene-Oligocene boundary. The cessation of siliceous sedimentation in the Atlantic at 40 MA should also be recorded in the Caribbean if no barrier to deep water circulation existed between these water masses. These data do not argue with the formation of NADW at about this time, but the continued siliceous sedimentation in the Caribbean shows that if the NADW did form at this time, then it could not have flowed into the Caribbean.

It cannot be determined from these observations alone if a barrier between the Caribbean and west Atlantic existed prior to 40 MA. If a barrier had existed, the deep water supply of silica to the two areas must have had different origins, and the formation of the NADW merely terminated the siliceous sedimentation in one basin without affecting the other. The abundant biogenic siliceous sedimentation in the west Atlantic must have vastly exceeded what could have been supplied through a Caribbean portal and required an Atlantic source for most of the silica. The Caribbean silica must always have been dominantly of Pacific origin; it was certainly so after the 40 MA event.

History of the CCD in the Western Atlantic and the Caribbean.

The stratigraphically recorded upward or downward variation of the CCD (carbonate compensation depth) is the record of the level in sea water at which calcite is severely undersaturated because of the low values of the dissolved carbonate ion (Broecker, 1974). In much of the Atlantic Ocean the CCD was seen to rise dramatically

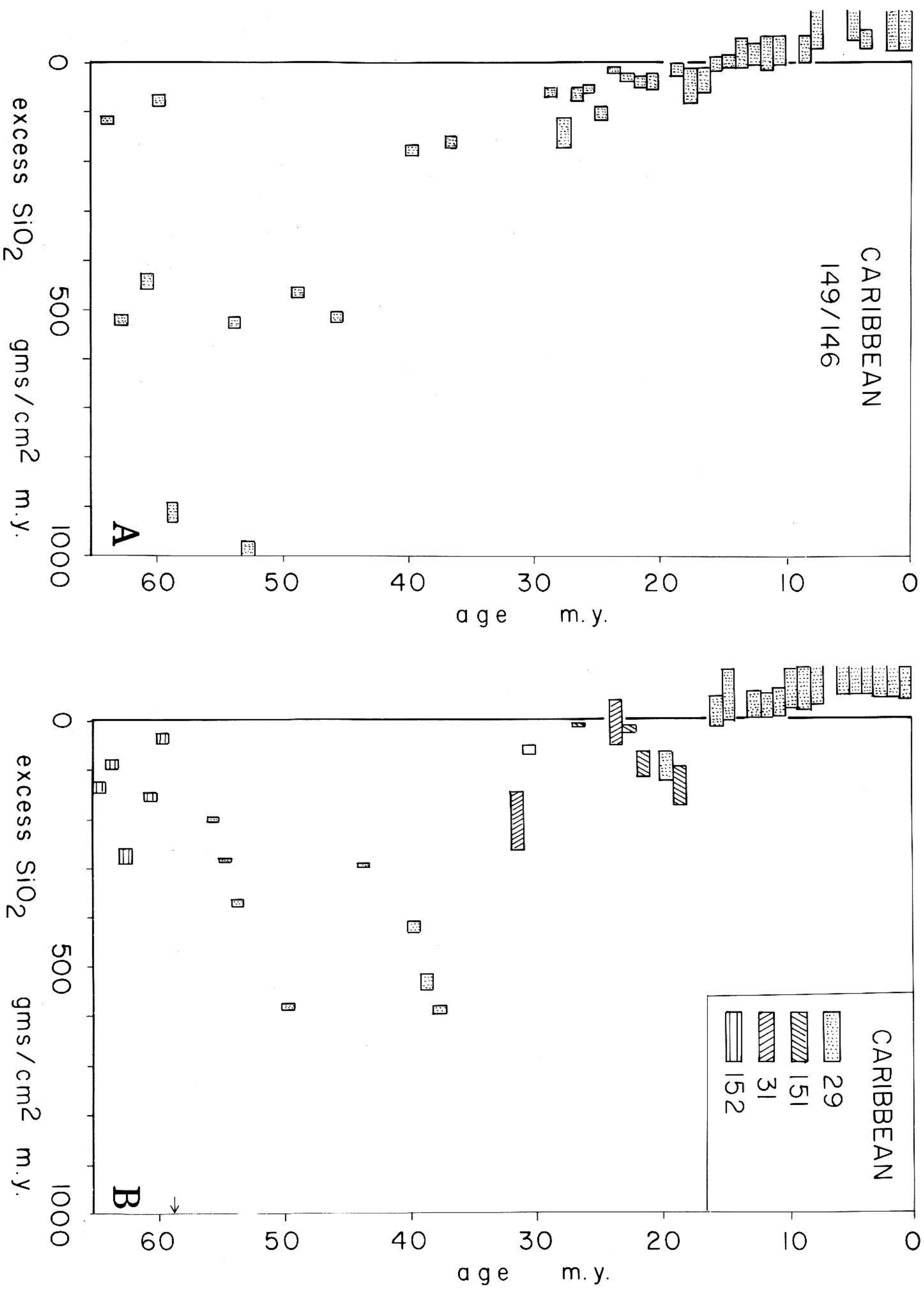

Fig. 8 - Diagrams showing the calculated excess (biological) silica accumulations for Caribbean Sites. The horizontal bars show the "range of ambiguity", with the left side indicating terrigenous sediment with Si/Al=2.75, and the right side with Si/Al=2.25. A) Site 149/146. B) Sites 29, 151, 31, 152, with only Site 29 shown younger than 15 MA.

in the middle Miocene and sink as dramatically in the late Miocene. The present west Atlantic CCD at the latitude of the Caribbean is approximately 5000 meters, as recorded in the carbonate content of surface sediment (Biscaye et al., 1976). The present Caribbean Sea has developed its own unique water chemistry (Worthington, 1966); its present isolation from the Atlantic below the sill depth of 1600 meters must have resulted in its own lysocline and CCD, though these have not been measured by water chemistry. In the present Caribbean the data are too sparse to establish the CCD, but sparse data suggest that it is about 1000 meters shallower than the adjacent Atlantic.

The dramatic variation of the CCD seen in sedimentary sections throughout the south and central Atlantic (Hsü & Wright, 1985), and at Site 541 near Barbados, is seen also at Site 29, within the Caribbean (Fig. 10). The age of this variation at the Atlantic

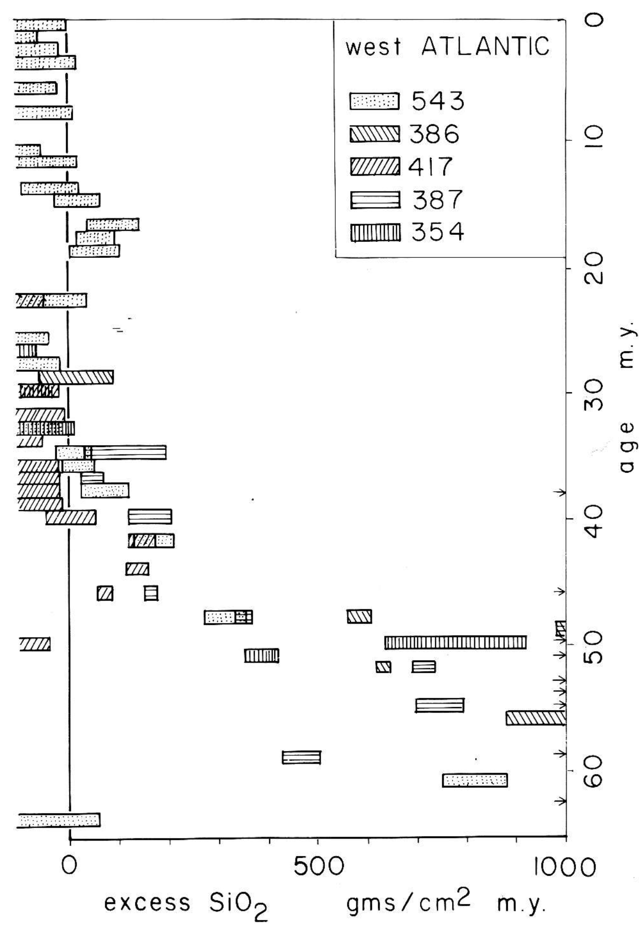

Fig. 9 - Diagram showing the calculated excess (biological) silica accumulations for five west Atlantic Sites. The "range of ambiguity" is shown as in Fig. 8. Only Site 543 is shown younger than 20 MA.

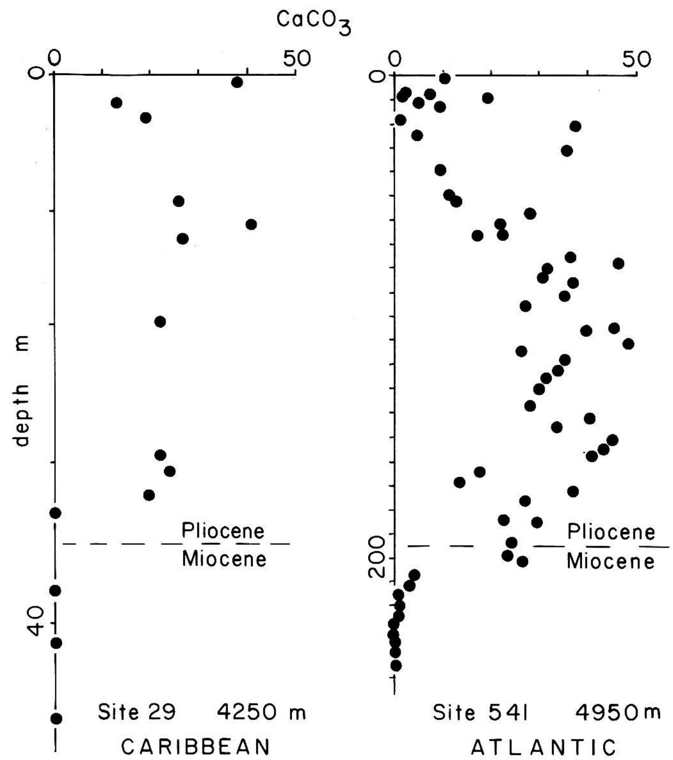

Fig. 10 - Diagrams showing the carbonate content of two drilled Sites, 29 (Caribbean) and 541 (west Atlantic, near Barbados), showing the variation of the CCD recorded as a sudden rise in carbonate at the Miocene-Pliocene boundary. Note that the depth scales are different for the two Sites to bring the Miocene-Pliocene boundary into juxtaposition.

sites is close to the Miocene-Pliocene boundary, which is about 5.3 MA. The age of the variation is not tightly constrained at Site 29, because of the low total accumulation rate, but it is clearly close to this stratigraphic level. Site 29 is slightly shallower than 541 (4250 m vs. 4950 m); paleodepths are not known but assumed to be nearly the same as the present depths for the two sites. For the CCD variation to have been recorded at Site 29 at about the same time as at the Atlantic sites there must have been a deep water connection at that time. Thus, the breach in the Lesser Antilles - Aves Ridge at about 19 MA must have continued until at least 5 MA. Subsequent to that time, the breach has closed again.

Summary and Conclusions.

The difference in the distribution in time of siliceous sediments in the Caribbean, western Atlantic, and eastern Pacific records the formation of barriers to the circulation of intermediate and deep ocean water. Differences between the west Atlantic and Caribbean show that a barrier was present at about 40 MA; this barrier is presumed to be the early Lesser Antilles or Aves Ridge, or both, and must have spanned the gap between the Greater Antilles and South America.

A breach developed in the Lesser Antilles - Aves Ridge barrier at about 19 MA. This breach marked the transition between an earlier arc position spanning the gap across the end of the Caribbean and a later configuration at which existed a deep (or at least intermediate) depth oceanic passage. There are no striking geological events in the Lesser Antilles tied to this date. It represents the nearly the top of the stratigraphic sequence on the Island of Antigua, and is close to the age of the oldest volcanic materials seen in the younger volcanic series of the Lesser Antilles. The breach probably remained open at least until the Miocene-Pliocene boundary (about 5.3 MA). The Miocene breach of the Lesser Antilles - Aves Ridge barrier is consistent with Speed's (1985) collision of the southern Lesser Antilles with the north coast of South America. If other considerations rule out the southern part of the arc, the site of the breach will have to be located at its northern end, where, however, there are no geologic clues for such a feature.

The rise of the Central American isthmus was a gradual shoaling between about 35 MA and 15 MA; continued shoaling finally resulted in cessation of surface water exchange after about 4.2 MA.

The barriers postulated to form and be breached during the Cenozoic are well known barriers today. The pelagic sediment evidence merely gives the timing of the closing, and in the case of the gradual shoaling of the Central American barrier, provides a deeper, older age for the beginning of a shoaling process whose shallower, younger is well established. While pelagic evidence cannot provide a tectonic synthesis for the Caribbean, it does, however, provide important constraints on any proposed models.

The biogeographical significance of barriers to marine circulation is obvious. A fundamental question for biogeographers is the timing of the formation or disruption of island chains or land bridges which allow limited or large-scale exchange of terrestrial faunas. The timing of formation of circum-Caribbean barriers is significant because it suggests that an Antillean island chain surmounting the Lesser Antillean - Aves Ridge barrier would have provided a limited degree of terrestrial faunal exchange prior to the shoaling of the Central American barrier. The use of those aspects of pelagic sedimentation which reflect circulation of intermediate and deep ocean water can have an important place in tectonic history as well as biogeography and should be pursued vigorously.

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