

### 33. EARLY OLIGOCENE DIATOMS ON THE CEARA RISE AND THE CENOZOIC EVOLUTION OF BIOGENIC SILICA ACCUMULATION IN THE LOW-LATITUDE ATLANTIC<sup>1</sup>

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#### ABSTRACT

Pronounced biogenic silica accumulation has taken place in the Ceara Rise region during two episodes of the Cenozoic: the early Oligocene (33.5–30.5 Ma) and the early Miocene (23.0–15.5 Ma). The Paleogene deposits are dominated by well preserved assemblages of diatoms and radiolarians representing the early Oligocene *Coscinodiscus excavatus* diatom zone. The rich lower Miocene biosiliceous deposits are dominated by radiolarians and siliceous sponge spicules and deprived of diatoms. Apart from these two conspicuous biosiliceous intervals, siliceous microfossils are rare or absent in the upper Paleocene to Holocene sediments recovered from the Ceara Rise.

The Ceara Rise data point to a very modest silica accumulation in the late Paleocene through late Eocene period in the western equatorial Atlantic. Accumulation of biogenic silica increased during the early Oligocene in a possible response to the global cooling. Following a decline in the late early Oligocene, an observed early Miocene increase in biosiliceous sediments is consistent with the widespread early Miocene biosiliceous productivity increase recorded in other parts of the low-latitude Atlantic. A simple plot of the distribution of biosiliceous sediments from the Ceara Rise and from previously reported occurrences in the low-latitude Atlantic reveals that the early Oligocene and early Miocene periods of increased biosiliceous sedimentation in the Ceara Rise region are representative of the entire low-latitude region of the Atlantic Ocean. The data further suggest that accumulation of biogenic silica terminated across most of the low-latitude Atlantic near the end of early Miocene time, possibly in response to the late early Miocene “silica shift” from the Atlantic Ocean to the Pacific.

#### INTRODUCTION

The Ceara Rise is located in the western part of the equatorial Atlantic (Fig. 1) in a rather infertile area of the present day Atlantic Ocean. Productivity is low and diatoms are rare in the Holocene sediments capping the rise (Lisitzin, 1972; Curry, Shackleton, Richter, et al., 1995). Biogenic silica accumulation in the Ceara Rise region, however, has been significant during two periods of the Cenozoic: the early Oligocene and early Miocene (Fig. 2).

Paleogene and lower Miocene biosiliceous sediments have been described from numerous deep-sea cores in the low-latitude Atlantic. Fenner (1978) reported a rich early Oligocene diatom assemblage from Deep Sea Drilling Project (DSDP) Site 354 on the Ceara Rise. Later, Fenner (1984) summarized the ranges of diatoms in the middle Eocene of Caribbean Site 149, the late Eocene and early Oligocene of eastern equatorial Site 366, and the late Oligocene of Site 369 off northwest Africa. Within the low-latitude Atlantic and eastern Caribbean Sea, biosiliceous sediments have been cored by DSDP Legs 3 (Maxwell, Von Herzen, et al., 1970), 4 (Bader, Gerard, et al., 1970), 15 (Edgar, Saunders, et al., 1973), 39 (Supko, Perch-Nielsen, et al., 1977), 41 (Lancelot, Seibold, et al., 1978), and 78A (Biju-Duval, Moore, et al., 1984), and Ocean Drilling Program (ODP) Legs 108 (Ruddiman, Sarnthein, Baldauf, et al., 1988), 110 (Masclé, Moore, Taylor, et al., 1988), and 159 (Masclé, Lohmann, Clift, et al., 1995).

The present pilot investigation of diatoms was undertaken to document the floral composition of the biosiliceous-rich intervals recovered from the Ceara Rise during Leg 154 and to place this information into a wider context of the paleoceanographic evolution of the Atlantic Ocean.

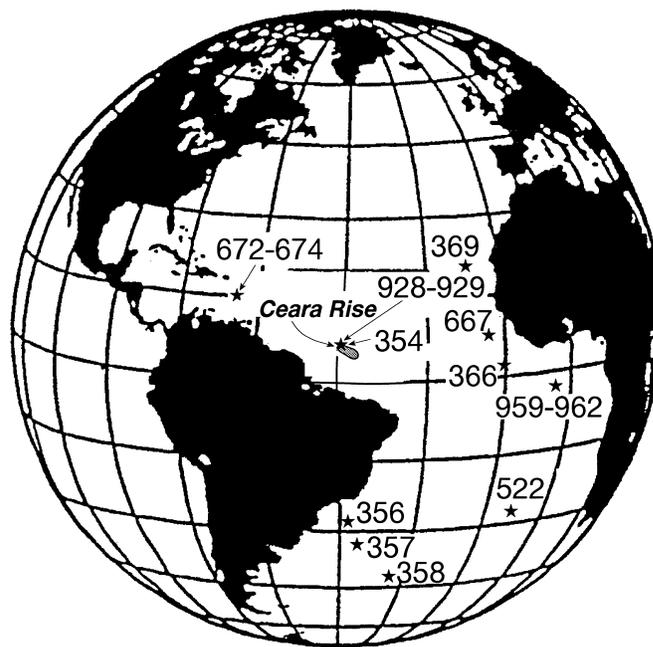


Figure 1. Location of Sites 928 and 929 drilled on the Ceara Rise in the western equatorial Atlantic as well as ODP and DSDP sites with Cenozoic biosiliceous sections referred to in the text.

#### METHODS AND MATERIALS

Samples from Sites 928 and 929 of late Paleocene to Holocene age (Table 1) were prepared after the method described by Barron (1985a). Approximately 0.1 g of sediment was placed in a centrifuge tube and 10% HCl added, followed by 10% H<sub>2</sub>O<sub>2</sub>. The tubes were gently heated until the liquid became light yellow. Distilled water

<sup>1</sup>Shackleton, N.J., Curry, W.B., Richter, C., and Bralower, T.J. (Eds.), 1997. *Proc. ODP, Sci. Results*, 154: College Station, TX (Ocean Drilling Program).

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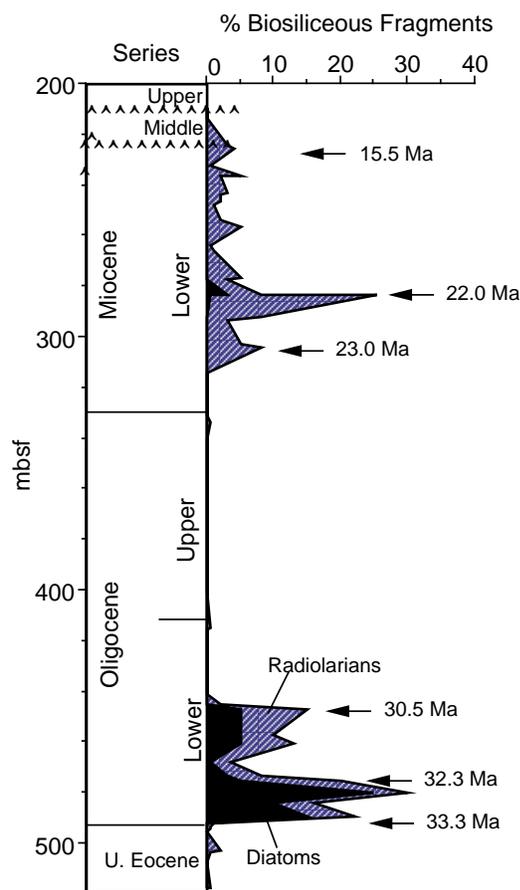


Figure 2. Biosiliceous fragments are notable components of the lower Miocene and lower Oligocene sediments of Site 929. The relative abundances of radiolarians and diatoms are based on smear-slide estimates in Curry, Shackleton, Richter, et al. (1995), and ages are inferred from biostratigraphic data in Curry, Shackleton, Richter, et al. (1995).

was added, and the samples were centrifuged at 2000 rpm for 4 min and then decanted. The centrifugation process was repeated until the suspension was neutralized. Strewn slides were prepared by transferring the material with a disposable pipette to a 22 × 40 mm coverslip, which was dried on a hot plate and mounted with Naphrax on a 22 × 75 mm glass slide.

Assessment of the overall abundance of diatoms was semiquantitative. It was recorded as the coverage of diatom valves on the slide surface relative to other particles (in percent). The abundance of diatoms was listed as absent (–), trace (TR, <1%), rare (R, <5%), few (F, 5%–30%), common (C, 30%–60%), and abundant (A, >60%). The relative abundance of diatom species in an assemblage was estimated under the light microscope at 500× as follows: abundant (A), more than one specimen seen in each field of view; common (C), one specimen observed in two fields of view; few (F), one specimen present in each horizontal traverse; and rare (R), for sparser occurrences. Diatom preservation was noted as good (G) when fine structures of the valves were preserved and weakly silicified forms were present in the assemblage; moderate (M) when the assemblage showed moderate breakage and light dissolution; and poor (P) when more than 30% of all valves were broken and the assemblage was affected by partial dissolution.

The diatom zonation and paleomagnetic age constraints of datums used for this study are the late Oligocene to Holocene zonation com-

plied by Barron (1985a, 1985b), and the Paleogene zonation of Fenner (1984, 1985).

## RESULTS

### Stratigraphy

Leg 154 recovered a stratigraphic interval spanning the late Paleocene to Holocene (Curry, Shackleton, Richter, et al., 1995). Diatoms of stratigraphic importance were found only in the late Paleogene section of Site 929, namely in Cores 154-929A-48X through 52X (Table 2). These diatoms are referred to the early Oligocene *Coscinodiscus excavatus* Zone of Fenner (1984; modified by Barron, 1985a), which covers the total range of *Coscinodiscus excavatus* (Barron, 1985a). This zonal definition is used because of the difficulty in separating *Cestodiscus reticulatus* from *C. gemmifer* (= *C. robustus* sensu Barron, 1985a).

The pronounced increase in biosiliceous fragments occurs in Hole 929A between Samples 154-929A-53X-2, 45–47 cm (495.45 mbsf), and 52X-4, 38–39 cm (489.08 mbsf; Table 2), approximating the Eocene/Oligocene boundary within an interval assignable to undifferentiated calcareous nannofossil Subzones CP16a and CP16b (Curry, Shackleton, Richter, et al., 1995). No hiatus is apparent at this level and sedimentation rates in the overlying lower Oligocene interval average about 18 m/m.y. (Curry, Shackleton, Richter, et al., 1995). The top of the diatom-bearing lower Oligocene interval is also abrupt, lying between Samples 154-929A-48X-1, 41–42 cm (446.11 mbsf), and 47X-3, 42–44 cm (439.52 mbsf), within sediment assigned to the upper part of Zone P19 and the lower part of calcareous nannofossil Zone CP18 (Curry, Shackleton, Richter, et al., 1995). Based on calcareous microfossil datum levels published in Curry, Shackleton, Richter, et al. (1995), this diatom-rich interval begins at about 33.5–33.3 Ma and ends at about 30.5–30.2 Ma.

Biosiliceous microfossils return in lowermost Miocene sediments assignable to planktonic foraminifer Zone N4 and calcareous nannofossil Subzone CN1c (Curry, Shackleton, Richter, et al., 1995). The top of the lower Miocene biosiliceous-rich interval coincides with a hiatus where the lower part of calcareous nannofossil Zone CN4 is missing (Curry, Shackleton, Richter, et al., 1995).

### Abundance of Biogenic Silica

The early Oligocene and early Miocene intervals of Hole 929A are characterized by a relative high abundance of biogenic silica (Curry, Shackleton, Richter, et al., 1995). The percent of diatoms varies from 25% to 3% within the Oligocene and radiolarians from 15% to 2% (smear-slide data in Curry, Shackleton, Richter, et al., 1995) (Fig. 2). Diatoms and radiolarians are missing in Cores 154-929A-47X through 34X (upper part of early Oligocene through earliest Miocene) and vary from 25% to 1% in Cores 154-929A-33X through 25X (23.0–15.5 Ma or early Miocene to earliest middle Miocene), where the assemblages are dominated by radiolarians and siliceous sponge spicules, and poorly preserved diatoms are present only as a minor component.

The late early and middle Miocene sections are nearly barren of biosiliceous microfossils, and the opal content is low (<1%). In comparison, the early Oligocene biogenic opal may reach almost 10% of the bulk sediments (Curry, Shackleton, Richter, et al., 1995).

### Assemblage Composition

Despite the open-ocean location, modern sedimentation on the Ceara Rise is evidenced by the freshwater outflow from the Amazon River, as witnessed by the presence of freshwater diatoms (*Aula-*

**Table 1. Overall abundance of diatoms, radiolarians, and siliceous sponge spicules in samples used in this study.**

Age	Core, section, interval (cm)	Diatoms	Radiolarians	Spicules	Age	Core, section, interval (cm)	Diatoms	Radiolarians	Spicules
Pleistocene	154-929A-					51X-6, 140-141	A	C	F
	2H-1, 120-121	—	—	—	51X-CC	A	C	R	
	3H-3, 40-41	—	—	—	52X-2, 45-47	A	C	R	
Pliocene	6H-3, 120-121	—	—	—	52X-4, 38-39	A	A	F	
	9H-1, 120-121	—	—	—	53X-2, 45-47	—	—	—	
late Miocene	12H-3, 40-41	—	—	—	53X-2, 120-121	—	—	—	
	15H-4, 45-46	—	—	—	54X-1, 40-41	—	—	—	
	18X-3, 120-121	—	—	—	54X-1, 120-121	—	—	—	
early Miocene	21X-5, 40-41	—	—	—	54X-2, 40-41	—	—	—	
	24X-1, 45-47	—	—	—	54X-2, 120-121	—	tr	tr	
	24X-5, 40-41	—	—	—	54X-3, 40-41	—	—	—	
	25X-1, 45-47	—	F	F	54X-3, 120-121	—	—	—	
	25X-4, 45-47	—	F	F	54X-4, 40-41	—	—	—	
	26X-1, 45-47	—	R	R	54X-4, 120-121	—	—	—	
	26X-4, 45-47	—	R	R	54X-5, 20-21	—	—	—	
	27X-1, 40-41	—	R	R	56X-1, 2-3	—	—	—	
	27X-3, 45-47	—	R	R					
	27X-6, 45-47	—	R	R	154-929E-				
late Oligocene	28X-2, 45-47	—	tr	R	early Oligocene	1R-CC	A	F	C
	28X-5, 45-47	—	tr	tr	2R-CC	A	F	C	
	29X-2, 45-47	—	—	tr	late Eocene	3R-CC	—	—	—
	29X-5, 45-47	—	—	tr	4R-CC	—	—	—	
	30X-2, 45-47	—	—	R	5R-CC	—	—	—	
	30X-4, 103-104	—	F	R	6R-CC	—	—	—	
	30X-7, 40-42	tr	R	F	7R-CC	—	—	—	
	31X-3, 45-47	—	tr	R	8R-CC	—	—	—	
	31X-6, 45-47	tr	F	F	9R-CC	—	—	—	
	32X-2, 45-47	—	F	R	middle Eocene	10R-CC	—	—	—
early Oligocene	32X-5, 45-47	—	F-C	F	11R-CC	—	—	—	
	33X-1, 45-47	—	R	R-F	12R-CC	—	—	—	
	33X-3, 47-48	—	F	F	13R-CC	—	—	—	
	33X-5, 45-47	—	tr	tr	14R-CC	—	—	—	
	34X-2, 45-47	—	—	—	15R-CC	—	—	—	
	34X-6, 45-47	—	—	tr	16R-CC	—	—	—	
	35X-1, 120-121	—	—	tr	17R-CC	—	—	—	
	35X-3, 45-47	—	—	tr	18R-CC	—	—	—	
	35X-7, 23-25	—	—	—	19R-CC	—	—	—	
	36X-3, 45-47	—	—	tr	early Eocene	20R-CC	—	—	—
late Paleocene	36X-7, 40-42	—	—	tr	21R-CC	—	—	—	
	37X-2, 45-47	—	—	tr	22R-CC	—	—	—	
	37X-3, 40-41	—	—	tr	23R-CC	—	—	—	
	38X-5, 120-121	—	—	—	24R-CC	—	—	—	
	39X-2, 77-79	—	—	tr	25R-CC	—	—	—	
	40X-2, 84-86	—	—	—	26R-CC	—	—	—	
	41X-5, 10-11	—	—	tr	28R-CC	—	—	—	
	43X-2, 89-91	tr	—	tr	29R-CC	—	—	—	
	44X-5, 40-41	—	—	tr	30R-CC	—	—	—	
	45X-2, 38-40	—	—	tr	late Paleocene	31R-CC	—	—	—
early Miocene	46X-2, 36-38	—	tr	tr	33R-CC	—	—	—	
	47X-3, 42-44	—	—	—	34R-CC	—	—	—	
	47X-5, 105-106	—	F	F					
	48X-1, 41-42	A	C	F	154-928B-				
	48X-3, 115-116	A	F	F	early Miocene	30X-CC	—	R	tr
	48X-4, 42-44	A	A	C	31X-CC	tr	R	C	
	48X-7, 26-28	A	C	F	32X-CC	tr	R	C	
	49X-2, 38-40	A	C	R	33X-CC	—	R	C	
	49X-4, 40-41	C	F	R	34X-CC	tr	R	C	
	49X-6, 38-40	R	C	F	35X-CC	—	tr	tr	
50X-1, 43-45	A	C	R						
50X-2, 116-117	A	F	R						

Notes: Age assignments are from Curry, Shackleton, Richter, et al. (1995). A = abundant, C = common, F = few, R = rare, tr = trace, — = barren, and blank = no data.

*coseira* sp.) in the surface sediments. Freshwater species constitute 5%–10% of the Holocene diatom assemblages.

The Neogene diatom assemblages are very poorly preserved and dominated by a few solution resistant species. Well-preserved diatoms are present only in low abundance in the youngest Holocene sections.

The Paleogene assemblages are characterized by well preserved and heavily silicified diatom species of the early Oligocene *Coscino-discus excavatus* Zone of Fenner (1984) as modified by Barron (1985a; Table 2). These assemblages closely resemble the early Oligocene assemblage described by Fenner (1978) from nearby Site 354 (5°53.95'N, 44°11.78'W; water depth 4052 m), which is also located on the Ceara Rise. The assemblages contain common to abundant *Cestodiscus gemmifer* along with other characteristic Oligocene taxa including *Azpeitia oligocenica*, *Cavitatus miocenicus*, and *Coscino-discus excavatus* (Table 2). As mentioned by Fenner (1978), the flora

is quite similar to that of the upper section of the Oceanic Formation of Barbados. Readers should refer to Fenner (1978) for more detailed documentation and illustration of this flora, but they are cautioned that diatom taxonomy has undergone considerable revision since 1978 (see “Taxonomic Notes” section, this chapter).

## DISCUSSION

Variability of siliceous microfossil accumulation in the Ceara Rise region is mirrored by pore-water silica concentrations and the abundances of siliceous microfossils (Fig. 3). The general close correlation between high abundance of siliceous microfossils and high pore-water concentrations of dissolved silica is used in this study to indicate that the relative flux signal of biogenic silica has not been substantially distorted by dissolution. Therefore, the silica data are

Table 2. Relative abundance of diatom taxa in the early Oligocene of Hole 929A.

Core, Section, Interval (cm)	mbsf	Abundance	Preservation	<i>Actinocyclus octonarius</i>	<i>Asterolampra marylandica</i>	<i>Asteromphalus oligocenicus</i>	<i>Azpeitia oligocena</i>	<i>Cavitatus miocenicus</i>	<i>Cesodiscus gemmifer</i>	<i>Cesodiscus gemmifer (convex)</i>	<i>Cestodiscus reticulatus</i>	<i>Cestodiscus spp.</i>	<i>Coscinodiscus excavatus</i>	<i>Coscinodiscus hajosiae</i>	<i>Coscinodiscus marginatus</i>	<i>Coscinodiscus oculus iridis</i>	<i>Coscinodiscus radiatus</i>	<i>Craspedodiscus elegans</i>	<i>Distephanosira architecturalis</i>	<i>Hemiaulus polycystinorum</i>	<i>Hemiaulus cf. subacutus</i>	<i>Raphoneis sp. 1</i>	<i>Sceptroneis tenue</i>	<i>Thalassiosira bukryi</i>	<i>Triacria subcapitata sp.</i>	<i>Xanthiopyxis spp.</i>
154-929A-47X-3, 42-44	439.52	Barren																								
929A-48X-1, 41-42	446.11	A	M	R	-	-	R	R	A	R	-	-	R	-	-	-	R	-	R	R	R	-	R	R	-	R
929A-48X-3, 115-116	449.85	A	M	-	R	-	F	R	C	R	-	-	R	-	-	-	R	-	R	-	R	-	R	R	-	-
929A-48X-4, 42-44	450.62	A	M	-	-	-	R	-	C	R	-	-	R	-	-	-	-	-	R	-	-	R	R	-	-	R
929A-48X-7, 26-28	454.92	A	G	R	R	R	F	-	A	-	-	-	R	-	-	F	R	-	R	R	R	-	-	R	-	R
929A-49X-2, 38-40	457.18	A	M	-	R	-	R	-	A	F	R	-	F	-	-	R	R	-	R	R	-	-	-	R	R	-
929A-49X-4, 40-41	460.20	C	M	-	R	-	F	F	A	-	-	-	-	-	-	-	-	-	R	-	R	R	-	-	-	-
929A-49X-6, 38-40	463.18	R	P	-	R	-	-	-	R	-	-	-	-	-	-	-	-	-	-	-	-	R	-	-	-	-
929A-50X-1, 116-117	466.16	A	G	R	F	R	C	F	C	R	-	C	R	-	-	R	-	-	R	-	-	-	-	-	R	-
929A-50X-2, 43-45	466.93	A	M	-	R	R	F	C	C	-	-	-	R	-	F	F	-	-	F	F	-	-	-	-	R	F
929A-51X-6, 140-141	483.50	A	G	R	F	R?	F	F	C	R	-	C	R	R	A	R	-	R	C	F	R	-	-	-	R	F
929A-51X, CC	484.20	A	M	-	F	R	F	-	C	-	-	F	R	-	C	-	F	-	C	-	F	-	-	-	-	R
929A-52X-2, 45-47	486.15	A	M	R	R	-	F	-	C	-	-	F	R	-	F	-	C	-	R	R?	F	-	-	-	R	F
929A-52X-4, 38-39	489.08	A	G	-	R	-	R	-	C	-	-	C	F	-	C	-	F	-	R	-	F	-	-	-	-	R
929A-53X-2, 45-47	495.45	Barren																								

Notes: Abundance: A =abundant; C =common; F=few; R =rare; - =barren. Preservation: G =good, M =moderate, P =poor.

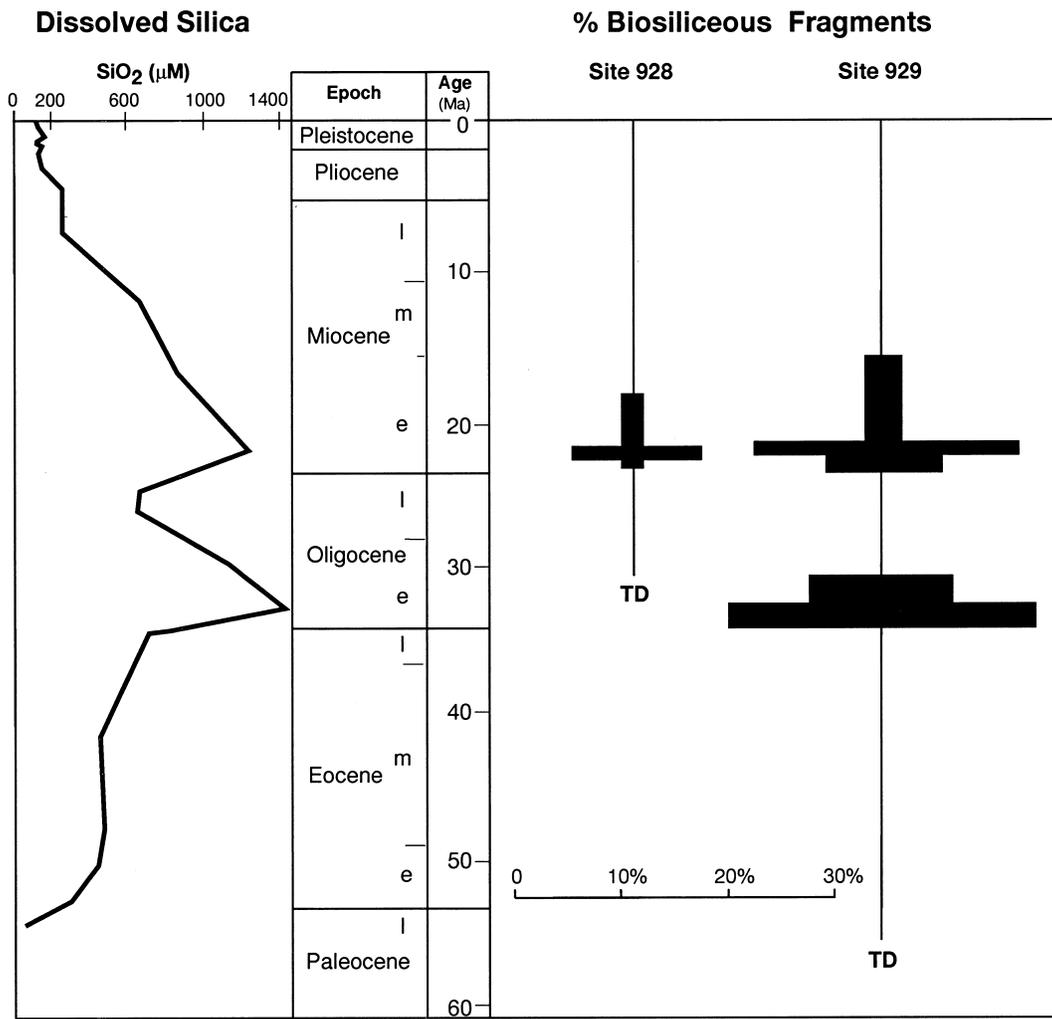


Figure 3. Concentrations of dissolved silica and generalized relative abundance of biosiliceous fragments at Sites 928 (4012 mbsf) and 929 (4356 mbsf) of the Ceara Rise. The early Oligocene and early Miocene intervals of Site 929 and the early Miocene of Site 928 are characterized by high silica concentrations in the pore waters and a high relative abundance of biosiliceous microfossil fragments (diatoms, radiolarians, and siliceous sponge spicules). Percentages are based on smear-slide estimates (adapted from Curry, Shackleton, Richter, et al., 1995), and pore-water silica concentrations are from Curry, Shackleton, Richter, et al. (1995). Total depth (TD) is the deepest stratigraphic interval recovered at the sites.

considered here to be a first proxy to past productivity changes, although postburial processes may often alter the record (Archer et al., 1993).

The very low abundance of diatoms in late Paleocene sediments is mirrored by low silica concentrations in the interstitial pore waters. Similarly, silica pore-water data from the middle and late Eocene sections coincide with only traces of siliceous microfossils, which point to an originally restricted deposition of biosiliceous sediments. In the late Eocene sediments, pore-water silica data and an increasing amount of fragments of siliceous microfossils signal the onset of biosiliceous sedimentation in the equatorial Atlantic, possibly triggered by the polar cooling that intensified the oceanic circulation (Baldauf and Barron, 1990).

Increased primary productivity is indicated by the diverse early Oligocene diatom assemblages of Site 929 and nearby Site 354 (Fenner, 1978). This early Oligocene productivity increase has been documented by an observed increase in opal accumulation and enhanced preservation in the Southern Ocean (Baldauf and Barron, 1990; Baldauf et al., 1992). In low-latitude regions of the world's oceans, it appears to be part of a longer middle Eocene to early Oligocene peri-

od of increased biosiliceous sedimentation (Baldauf and Barron, 1990; Baldauf et al., 1992).

The increase in biosiliceous sedimentation in Leg 154 sites during the early Oligocene also appears to coincide with a global increase in benthic foraminifer oxygen isotope values that is attributed to high-latitude cooling and growth of the East Antarctic ice sheet (Miller et al., 1987; Zachos et al., 1994). Baldauf (1994) and Diester-Haass (1996) have demonstrated that an abrupt early Oligocene increase in biosiliceous productivity in the Southern Ocean coincides with this oxygen isotope shift. It is possible, therefore, that the early Oligocene enhanced biosiliceous sedimentation in low-latitude upwelling regions suggested by the global maps of Baldauf and Barron (1990) is also related to this event. Based on the study of rock magnetism at DSDP Site 522 in the southeast Atlantic, Hartel et al. (1995) hypothesized that the lower proportion of very fine-grained magnetite in lower Oligocene sediments was due to incipient reduction diagenesis that resulted from increased labile carbon transports to sediments during a period of enhanced productivity. They further argued that the enhanced productivity in the early Oligocene was caused by an intensification of thermohaline circulation, implying that increased

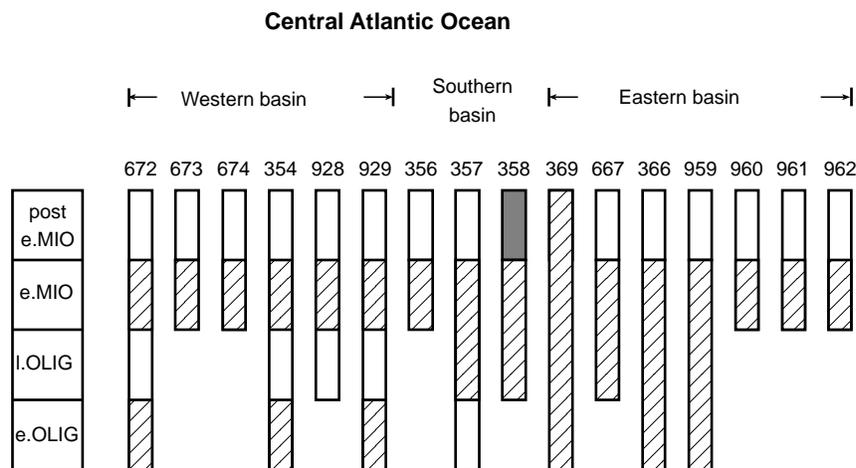


Figure 4. Generalized summary of middle Tertiary biosiliceous sediments recovered by deep-sea drilling from the low-latitude Atlantic. Deposition of biogenic silica was typically terminated near the early/middle Miocene boundary, except off northwest Africa (Site 369), which lies in a present-day upwelling setting. Similar to the present-day accumulation, biogenic silica accumulation during the late Oligocene was confined to the western and southern parts of the low-latitude Atlantic Ocean. References to data are as follows: Sites 672–674 = Mascle, Moore, Taylor, et al. (1988); Sites 354–358 = Supko, Perch-Nielsen, et al. (1977); Sites 366 and 369 = (Lancelot, Seibold, et al., 1977); Site 522 = Hartel et al. (1995); Site 667 = Ruddiman, Sarnthein, Baldauf, et al. (1988); and Sites 959–962 = Mascle, Lohmann, Clift, et al., 1995. Relative abundance of biogenic opal in sediments; hatched = common to abundant, gray = few, and open = rare to absent.

amounts of nutrients were made available in surface waters for phytoplankton growth.

The late Oligocene interval of Site 929 is barren of siliceous microfossils (Fig. 2). Thus, deposition of late Oligocene biogenic silica seems to be confined to the eastern and southern basin of the Atlantic Ocean, similar to the present day pattern. The biosiliceous deposits of early Miocene age in the Ceara Rise region are dominated by radiolarians and siliceous sponge spicules with rare and poorly preserved diatoms. A simple plot of the distribution of the biosiliceous sediments reveals that the early Oligocene and early Miocene periods of increased biosiliceous sedimentation on Ceara Rise are representative of the whole low-latitude region of the Atlantic (Fig. 4).

The abrupt decline in biosiliceous sedimentation in Leg 154 sites at the end of the early Miocene appears to coincide with a previously documented shift in silica accumulation from the low-latitude Atlantic to the Pacific Ocean (Keller and Barron, 1983; Baldauf and Barron, 1990). On a global scale, Keller and Barron (1983) and Baldauf and Barron (1990) show that during most of the early Miocene, biosiliceous sediments were widespread in the low-latitude Atlantic and Caribbean and relatively restricted in the North Pacific. By the middle Miocene, biosiliceous sedimentation in the low-latitude Atlantic ceased and was restricted to the present day upwelling region off western Africa. Similarly, biosiliceous sedimentation was reduced during the middle Miocene in the western equatorial region of the Indian Ocean (Mikkelsen, 1990; Baldauf et al., 1992), but was widespread in the North Pacific (Keller and Barron, 1983) and in the Norwegian Sea (Koç and Scherer, 1996). Keller and Barron (1983) and Baldauf and Barron (1990) argue that an increase in the production of Northern Component Water (NCW) occurred during the late early Miocene. This may have led to enhanced basin-basin fractionation, causing the above-mentioned “silica shift” from the Atlantic to the Pacific Ocean. Syntheses of carbon isotope and benthic foraminiferal data (Woodruff and Savin, 1989; Wright et al., 1992; Wright and Miller, 1993), however, all point to either a cessation or slackening of NCW production at the end of the early Miocene.

Wright et al. (1992) and Wright and Miller (1993) record enhanced NCW production in the North Atlantic between about 20 and 16 Ma during the same early Miocene period when enhanced biosiliceous productivity occurred on the Ceara Rise. Wright et al. (1992) note that diatom preservation was generally poor in the northern

North Atlantic between 19 and 16 Ma, and they argue that the North Atlantic was not really a siliceous basin during the early Miocene. Our compilations, however, show that biosiliceous sediments were more widespread in the low-latitude Atlantic during the early Miocene than during the middle Miocene (Fig. 4).

Woodruff and Savin (1989) found little evidence for NCW production before 12–10 Ma. During the early Miocene, they suggested that Warm Saline Deep Water (WSDW), which originated in the northern Indian Ocean, was an important component of deep-water circulation. Closure of the eastern Mediterranean at the end of the early Miocene caused a reduction or cessation of the production of WSDW between 16 and 15 Ma. It is possible that the resulting reduced overturn of nutrient-rich deep waters, coupled with a deepening of the thermocline during this climatically warm period of the early middle Miocene, led to a reduced nutrient supply to surface waters and a decline in biosiliceous production in the low-latitude Atlantic.

The late Miocene–Pliocene productivity increase seen in many parts of the world's oceans (e.g., Baldauf et al., 1992) is not recorded in the Ceara Rise region. This may be accounted for by the late Miocene–Pliocene decoupling of surface and deep waters in the western equatorial Atlantic caused by the production of NCW (Wright et al., 1992).

#### TAXONOMIC NOTES

*Actinocyclus octonarius* Ehrenberg; Akiba, 1986, pl. 29, fig. 4 = *A. ehrenbergii* Ralfs in Pritchard.

*Asterolampra marylandica* Ehrenberg; Hustedt, 1930, pp. 485–487, fig. 271.

*Asteromphalus oligocenicus* Schrader et Fenner, 1976, p. 965, pl. 21, figs. 8, 1, 14; pl. 28, fig. 1.

*Azpeitia oligocenicica* (Jouse) Sims in Sims et al., 1989, p. 302, pl. 2, figs. 1–3; pl. 3, figs. 8, 9 = *Coscinodiscus oligocenicus* Jouse; Barron, 1983, p. 512, pl. 3, figs. 8, 11.

*Cavitatus miocenicus* (Schrader) Akiba et Yanagisawa in Akiba et al., 1993, p. 29, fig. 9, 1–11 = *Synedra miocenicica* Schrader; Fenner, 1978, pl. 33, fig. 23.

- Cestodiscus gemmifer* Castracane; Fenner and Mikkelsen, 1990, p. 441, pl. 1, fig. 3 = *Coscinodiscus superbus* Hardman; Fenner, 1978, p. 516, pl. 13, figs. 1–5; pl. 14, figs. 1–4 = *Coscinodiscus robustus* Jouse sensu Barron, 1985a, pl. 1, fig. 1.
- Remarks.** Highly convex valves—such as those illustrated by Fenner, 1978, on pl. 13, figs. 1, 2—are tabulated separately on Table 2.
- Cestodiscus reticulatus* Fenner, 1984, p. 331, pl. 1, fig. 10.
- Remarks.** These forms closely resemble *C. gemmifer* except for the reticulate pattern in the center, and it is not clear that they should be separated.
- Cestodiscus* spp. Undifferentiated forms. See Fenner and Mikkelsen, 1990.
- Coscinodiscus excavatus* Greville in Pritchard; Fenner, 1985, p. 728, pl. 7, figs. 26, 28; Barron, 1985a, pl. 1, fig. 8.
- Remarks.** The varieties illustrated by Fenner (1978) have not been separated.
- Coscinodiscus hajosiae* Fenner, 1984, p. 331, pl. 2, fig. 1 = *C. spiralis* sensu Hajos, 1976, p. 826, pl. 7, figs. 1–3.
- Coscinodiscus marginatus* Ehrenberg; Fenner, 1978, p. 515, pl. 8, figs. 3, 7.
- Coscinodiscus oculus iridis* Ehrenberg; Hustedt, 1930, p. 454–459, fig. 252.
- Coscinodiscus radiatus* Ehrenberg; Fenner, 1978, p. 516, pl. 7, fig. 6.
- Craspedodiscus* aff. *elegans* Ehrenberg; Fenner, 1978, p. 518, pl. 9, fig. 3; pl. 37, fig. 6.
- Distephanosira architecturalis* (Brun) Gleser in Gleser et al., 1992, p. 68, table 56; figs. 1–9 = *Melosira architecturalis* Brun; Schrader and Fenner, 1976, p. 989, pl. 14, fig. 13; pl. 29, figs. 7–8; pl. 35, figs. 1–4; Fenner, 1978, p. 524, pl. 16, figs. 7–12.
- Hemiaulus polycystinorum* Ehrenberg; Fenner, 1978, p. 521, pl. 21, figs. 13, 14; pl. 22, figs. 4, 5, 7–10; pl. 23, figs. 1–4.
- Hemiaulus* sp. cf. *H. subacutus* Grunow; Fenner, 1978, p. 522, pl. 244, figs. 8, 14.
- Rhaphoneis* sp. 1 sensu Fenner, 1978, pl. 29, fig. 3.
- Sceptroneis tenue* Schrader et Fenner, 1976, p. 999, pl. 3, figs. 1–4; pl. 25, figs. 12, 22, 24; Fenner, 1978, p. 531, pl. 32, fig. 8.
- Thalassiosira bukryi* Barron, 1983, p. 511, pl. 4, figs. 1–2; pl. 6, fig. 9.
- Trinacria subcapitata* (Greville) Grunow; Fenner, 1978, p. 536, pl. 27, figs. 2, 7, 8.
- Xanthiopyxis* spp. See various forms illustrated by Fenner, 1978, pl. 34, figs. 11–15; pl. 35, figs. 2–22, 25, 26 (undifferentiated).
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