Refinement of late-Early and Middle Miocene diatom biostratigraphy for the East Coast of the United States

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ABSTRACT

Integrated Ocean Drilling Program (IODP) Expedition 313 continuously cored Lower to Middle Miocene sequences at three continental shelf sites off New Jersey, USA. The most seaward of these, Site M29, contains a well-preserved Early and Middle Miocene succession of planktonic diatoms that have been independently correlated with the geomagnetic polarity time scale derived in studies from the equatorial and North Pacific. Shallow water diatoms (species of *Delphineis*, *Rhaphoneis*, and *Sceptroneis*) dominate in onshore sequences in Maryland and Virginia, forming the basis for the East Coast Diatom Zones (ECDZ). Integrated study of both planktonic and shallow water diatoms in Hole M29A as well as in onshore sequences in Maryland (the Baltimore Gas and Electric Company well) and Delaware (the Ocean Drilling Program Bethany Beach corehole) allows the refinement of ECDZ zones into a high-resolution biochronology that can be successfully applied in both onshore and offshore regions of the East Coast of the United States. Strontium isotope stratigraphy supports the diatom biochronology, although for much of the Middle Miocene it suggests ages that are on average 0.4 m.y. older. The ECDZ zonal definitions are updated to include evolutionary events of *Delphineis* species, and regional occurrences of important planktonic diatom marker taxa are included. Updated taxonomy, reference to published figures, and photographic images are provided that will aid in the application of this diatom biostratigraphy.

INTRODUCTION

Marine diatoms have been employed for biostratigraphic correlation of Lower and Middle Miocene sediments deposited on the Atlantic Coastal Plain and offshore between Florida and New Jersey for more than 50 years. Biostratigraphic zonations developed during the 1970s and early 1980s by George W. Andrews (1976, 1978, 1988a) and William H. Abbott (1978, 1980, 1982) relied primarily on benthic and shelf-dwelling diatoms (*Actinoptychus, Delphineis, Rhaphoneis, Sceptroneis*) that are common in these deposits. Limited age control was provided by sporadic occurrences of oceanic planktonic diatoms, calcareous nannofossils, and planktonic foraminifera (Abbott, 1980, 1982) and Sr-isotopic ages (Sugarman et al., 1993).

In both the Pacific and Southern Oceans, however, very reliable biochronologies have been developed for Miocene and younger sediments using evolutionary events of planktonic marine diatoms (Barron, 2003; Scherer et al., 2007), many of which have been tied directly to paleomagnetic stratigraphy. Unlike planktonic foraminifers and calcareous nannoplankton, diatoms are diverse and common in cool waters that are characteristic of both higher latitude regions and coastal regions dominated by coastal upwelling. Planktonic diatoms are common in diatomaceous sediments deposited along the margins of the North Pacific, facilitating the application of planktonic diatom biochronology (Yanagisawa and Akiba, 1998; Scherer et al., 2007). However, planktonic diatoms are scarcer in onshore Miocene diatomaceous sediments of the Atlantic Coastal Plain where the continental shelf-slope gradient is much more gentle than that of Pacific margins, resulting in poorly refined diatom biochronologies (Abbott, 1978, 1980). Abbott (1978, 1980) incorporated some more cosmopolitan planktonic diatoms such as *Annellus californicus, Coscinodiscus lewisianus, C. plicatus* (= *Thalassiosira grunowii*), and *Denticula hustedtii* (= *Denticulopsis simonsenii*) into his biostratigraphic studies; however, their ranges were often found to be sporadic in nearshore sequences, limiting correlation with the geologic time scale.

Andrews (1977, 1988b) recognized an evolutionary succession of *Delphineis* species that are common in onshore sediments of the Atlantic Coastal Plain. Other studies (Abbott, 1978, 1980; Andrews, 1988a) showed that *Delphineis* species are very useful for biostratigraphic correlation. However, only two taxa, *D. penelliptica* and *D. ovata* have been incorporated into diatom zonations (Abbott, 1978; Andrews, 1988a). Typically, the biostratigraphy of Abbott (1978) and Andrews (1988a) has been pieced together from numerous onshore sections that were limited in duration and correlated by lithology, using Shattuck's (1904) lithologic units, (updated by Ward, 1984). In particular, Andrews (1988a) proposed an East Coast Diatom Zonation (ECDZ) that has been widely used. A limited number of continuous onshore and offshore coreholes have been studied for diatom biostragtigraphy (Abbott, 1978, 1982; Burckle, 1998), most notably, the Baltimore Gas and Electric Company (BG&E) corehole (Calvert Cliffs, west shore of Chesapeake Bay, Maryland; Fig. 1; Abbott, 1982); however, detailed documentation of the diatom assemblages has been limited.

A transect of holes cored on the shallow New Jersey shelf during Integrated Ocean Drilling Program (IODP) Expedition 313 provided an opportunity to further develop this East Coast diatom biostratigraphy and to refine its correlation with the geologic time scale. In particular, coring at Site M29, the most seaward of a transect of three coreholes, recovered a nearly continuous succession of diatom-rich sediments between ~695 and 325 m subbottom depth that preliminary strontium and planktonic microfossil assigned to the late early and middle Miocene. Reconnaissance examination of samples from Hole M29A revealed numerous planktonic diatom taxa that have proven useful for diatom biostratigraphy in the equatorial and North Pacific (Barron, 1985, 2003; Yanagisawa and Akiba, 1998), promising an improved correlation of the ECDZ diatom biostratigraphy of the east coast of the United States. Study of the diatom assemblages of Hole M29A along with key stratigraphic successions from onshore drill cores, the Baltimore Gas and Electric well, and the Ocean Drilling Program Leg 174AX Bethany Beach corehole have been initiated with the purpose of refining diatom biostratigraphy.

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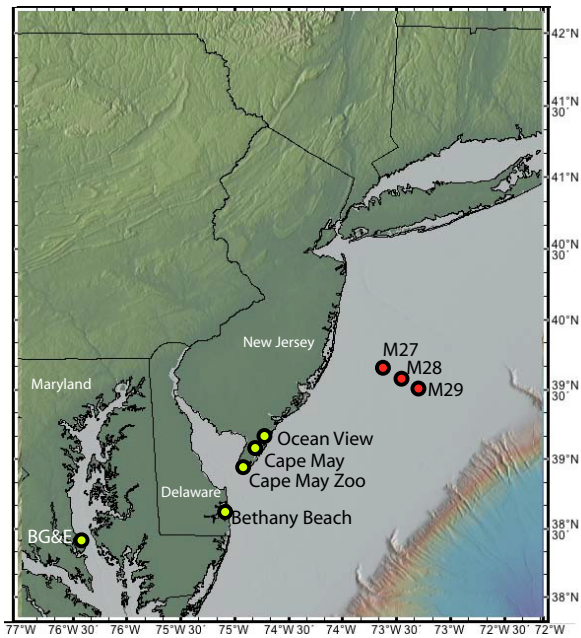

Figure 1. Location map of sections investigated for diatom biostratigraphy (see text).

After the diatom biostratigraphy has been refined, it will be applied to IODP Expedition 313 Holes M27A and M28A, as well as to some additional onshore coreholes.

MATERIALS AND METHODS

IODP Expedition 313 Hole M29A, at 39°31.170′N, 73°24.792′W, 36 m water depth, cored to a depth of 754.44 m lower Miocene to Pleistocene sediments, mostly silts and sandy silts with preliminary estimates provided by calcareous nannofossils, planktonic foraminifers, and dinoflagellates (Mountain et al., 2010) (Fig. 1) and strontium isotopes measured on mollusks and foraminifers (Mountain et al., 2010; Browning et al., 2013). Common diatoms were routinely encountered in smear slides of sediments prepared from Lower and Middle Miocene sediments for routine lithologic descriptions by the IODP Expedition 313 science party. Consequently, material was sent to one of us (J. Barron) for diatom biostratigraphic study.

The BG&E well was drilled to a depth of 103.237 m (338.8 feet) at the company's atomic reactor site at Calvert Cliffs, near the west shore of Chesapeake Bay, Maryland (38.43°N, 76.44°W) (Stefansson and Owens, 1970). The BG&E well was cored continuously from a depth of 3.84 m (12.6 feet) and was studied for diatoms by both Andrews (1978) and Abbott (1982), and therefore is considered a key stratigraphic reference section for Miocene diatom biostratigraphy in the Atlantic Coastal Plain. Microscope slides prepared by Abbott (1982) were obtained from the California Academy of Sciences (by J. Barron) and examined under the light microscope. Andrews (1978) named Miocene Lithologic Units (MLU) after the 24 stratigraphic zones of Shattuck (1904). These include: MLU 1-MLU 3, the Fairhaven Member of the Calvert Formation; MLU 4-MLU 13, the Plum Point Marl Member of the Calvert Formation; MLU 14-MLU 16, the Calvert Beach Member of the Calvert Formation; and MLU 17-MLU 20, the Choptank Formation (Ward, 1984).

The Bethany Beach corehole contains a nearly continuous record of Oligocene-Pleistocene sediments along the coast of eastern Delaware (38.548°N, 75.0625°W) (Miller et al., 2003; Browning et al., 2006; McLaughlin et al., 2008). McLaughlin et al. (2008) provide detailed lithologic descriptions and biostratigraphic correlations utilizing calcareous nannofossil, dinoflagellates, planktonic foraminifers, radiolarians, diatoms, and strontium isotopes, making the Bethany Beach corehole a key stratigraphic reference section for the Atlantic Coastal Plain. Because this corehole contains an extended succession of Lower and Middle Miocene diatom-bearing sediments, it was selected for detailed diatom biostratigraphic study.

Strewn slides of diatoms and silicoflagellates were prepared by placing ~1–2 cm^3 of sediment in a small porcelain mortar and covering it with distilled water. The pestle was then used to disaggregate the samples. To prepare slides, a disposable pipette was used to extract a small amount of the suspension from near the top of the liquid. A drop was then transferred from the pipette to a 40 × 22 mm cover slip and dried at low heat on a hot plate. Slides were then mounted in Naphrax (index of diffraction = 1.74). The entire slide was examined at X920 magnification and the occurrences of stratigraphically important and ecologically significant diatoms were recorded. The overall abundance of diatoms in each sample was listed as abundant (A, >60%), common (C, 30%–60%), few (F, 5%–30%), and rare (R, <5%). The relative abundance of diatom species in an assemblage was estimated at X500 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 of the coverslip; and rare (R), for sparser occurrences.

This study primarily focused on Site M29, which contained an excellent record of stratigraphically important diatoms and silicoflagellates. In general, samples were studied every 5–10 m with fine-grained lithologies preferentially selected. Qualitative estimates of diatom abundance and preservation are included (Table 1). The diatom and silicoflagellate taxonomy applied is shown in Appendix 1.

Fifteen Lower to lower-Middle Miocene (ca. 23–13 Ma) sequence boundaries (m5.8 through m4.1; Fig. 2) were previously recognized using criteria of onlap, downlap, erosional truncation, and toplap and traced through three generations of offshore multichannel seismic data (Monteverde et al., 2008; Mountain et al., 2010). The depths of these seismic sequence boundaries were predicted in the coreholes using a velocity depth function prepared prior to Expedition 313 (Mountain et al., 2010). Sequence boundaries were independently recognized in the cores based on core surfaces, lithostratigraphy (grain size, mineralogy, facies, and paleoenvironments), facies successions, benthic foraminiferal water depths, downhole and core gamma logs, and chronostratigraphic ages (Mountain et al., 2010). Initial correlations were adjusted (by tenss of centemeters to a few meters in vertical position) using revised velocity-depth function and synthetic seismograms based on drilling results (G. Mountain, 2013, written commun.). These new correlations were tested using additional lithologic, benthic foraminiferal, age, and downhole and core log data (Browning et al., 2013; Miller et al., 2013). The placement of the sequence boundaries follows Miller et al. (2013).

RESULTS

Diatom Biostratigraphy of Hole M29A

At Site M29, diatoms are concentrated between ~693 and 336 m composite depth (mcd), with underlying and overlying intervals either being barren or containing only very rare,

TABLE 1. OCCURRENCE OF SELECTED DIATOM AND SILICOFLAGELLATE TAXA IN INTEGRATED OCEAN DRILLING PROGRAM EXCURSION 313 HOLE M29A

Core	Section	Top depth (cm)	Bottom depth (cm)	Meters Compoiste Depth (Top)	Sedimentary sequence	Abundance	Preservation	ECDZ	*Actinocyclus divisus*	*Actinocyclus ingens*	*Actinocyclus radionovae*	*Actinoptychus heliopelta*	*Actinoptychus marylandicus*	*Annellus californicus*	*Azpeitia nodulifera*	*Azpeitia salisburyana*	*Azpeitia* cf. *vetustissima*	*Azpeitia vetustissima* var. *voluta*	*Cavitatus jouseanus*	*Cavitatus rectus*	*Cestodiscus peplum*	*Cestodiscus pulchellus* var. *maculatus*	*Coscinodiscus gigas*	*Coscinodiscus lewisianus*	*Coscinodiscus rhombicus*	*Craspedodiscus coscinodiscus*	*Crucidenticula nicobarcia*	*Crucidenticula paranicobarcia*	*Crucidenticula punctata*	*Crucidenticula sawamurae*	*Cymatogonia amblyoceras*	*Delphineis angustata* s.str.	*Delphineis angustata* sensu Andrews	*Delphineis biseriata*	*Delphineis lineata*	*Delphineis novaecesaraea*	*Delphineis penelliptica*
67	1	80	81	329.71		B	B																														
68	1	43	44	332.39		R	P																			R										R	
69	1	64	65	335.65		F	M			R									R								R					R		R		R	R
69	2	8	9	336.6	m4.1	R	M	7	R										F								R		R			R	R			R	R
70	1	74	75	338.8		R	M			R									R													R		R		R	
71	2	40	41	343.01		F	M						R	R			R		R				R			R						R	R			R	R
72	1	63	64	343.95	m4.2	F	P			R				R					R				R										R	R		R	R
75	1	5	6	353.36		R	P																														
81	2	54	55	370.4		C	M												R								R		R			R	R			R	F
83	1	90	91	375.56	m4.3	A	G	6b	F	F			R		R		F		F				R				R		R			R	R	R		F	F
85	1	74	75	381.5		A	M		R	R			R				R		R				R				R		R			R	R	R		F	C
87	2	44	45	388.8		A	M		R				R				R		F				R				R					R	R	R		R	F
89	1	40	41	393.36	m4.4	A	M			R			R				R		F				R				R					F	R	R		R	R
91	2	52	53	401.08		C	M		R				R			r	F		F				R				R		R			F	F			R	F
94	1	70	71	408.91		A	M		R	R			R				R		R				R	R			R		R			F	F			R	F
97	1	73	74	418.09		A	M		R	R			R						R				R				F		R			F	R			R	F
101	1	62	64	430.18		C	M	6a	R	R			R	R	R				R								R					R	R			F	F
104	1	19	20	438.9		A	M		R	R			R				R		F								F					F	R			R	R
107	2	43	44	445.93	m4.5	A	M		R	R			R						R								R					R	R			F	F
108	2	35	37	449.71		A	M		R	R			R						R								R				r	F	R			F	F
111	2	60	61	459.11		A	M		R	F			R	R		R	R		R							R	R					F	R			F	F
114	1	64	65	466.8		A	M		R				R						R								F					F	R			F	F
118	1	49	50	478.85		A	M		R	R			R			R			F			r					F					R	R			R	F
121	2	115	116	487.12	m5	A	M	5		F			R			R			F								C					R	R			R	F
124	1	43	44	494.04		A	G		R	R				R		R	R		F			R					R					F	R			R	F
124	2	110	111	496.22		A	G		R							F	R		F			R					R					F	F		F	F	F
127	3	43	44	505.47		A	G		R	F						F	R		F		R	R		R			C					F	R		F		F
130	1	114	115	513.05		A	G		R	F						F	R		F			R					C					F	R		R		F
133	1	75	76	521.81		A	G	4	R	F				R		F	R		F			R					C					R	R		R		F
135	1	88	89	528.04		A	M			F						R	R		F			R					F					R			F		C
137	1	51	52	530.72		A	M			F									F							R						R			R		F
139	1	70	71	537.01		A	M			R				R		R		R	F			R					R								R		R
141	1	80	81	543.21		A	M		R	R				R		F		R	R			F													F		R
144	1	31	32	551.87	m5.2	C	M			R						R		R	F		R	R		R			R				R						R
147	1	10	11	557.76		A	M	3						R		R		R	R			R		F					R		R				R		R
149	1	65	66	564.41		A	M		R	R						R		R	R			F		R					R		R				R		R
151	1	61	62	570.47		A	M		R	R						R		R	F	R		R		R							R				R		F
154	1	63	64	579.64		A	M		R	R						R		R	F	R		F		R		R					R				F		R
157	1	70	71	588.86		A	G		R	R				R		R		R	F	R	R	R		R							R				F		R
161	1	68	69	601.04		A	M		R					R		R		R	C	R		R		R							R				R		
167	2	144	145	621.61		A	M							R		R		R	F	R				R						R					R		
169	1	46	47	625.12	m5.3	C	M							R				R	F			R															
171	2	100	102	633.38		C	M							R		R		R	F	R		F				R									R		
176	1	30	32	643.36		A	M	2						R		R			F	R		R								R					R		
179	2	5	6	650.99	m5.4	C	M					R		R					R			R				R				R							
181	1	24	25	655.5		C	M							R										R						R	R				R		
183	1	58	59	661.94		C	M					R				R		R	R			R		R						R					R		
188	1	94	95	672.65	m5.45	C	M												R	R		R		R											R		
191	1	53	54	680.19	m5.47	C	M					R							F			R		R											R		
193	2	80	81	688.07		C	M	1b			R	R							F						R										R		
195	1	94	95	692.8	m5.6	C	M				R																								R		
197	1	50	51	698.46		B	B																														

(*continued*)

TABLE 1. OCCURRENCE OF SELECTED DIATOM AND SILICOFLAGELLATE TAXA IN INTEGRATED OCEAN DRILLING PROGRAM EXCURSION 313 HOLE M29A (*continued*)

Core	*Delphineis ovata*	*"Denticula" norwegica*	*Denticulopsis hyalina*	*Denticulopsis simonsenii*	*Denticulopsis lauta*	*Fragilariopsis maleinterpretaria*	*Koizumia adaroi*	*Mediaria splendida*	*Nitzschia challengeri*	*Nitzschia* cf. *challengerii*	*Proboscia praebarboi*	*Raphidodiscus marylandicus*	*Rhaphoneis* cf. *adamantea*	*Rhaphoneis diamantella*	*Rhaphoneis fossilie*	*Rhaphonies fusiformis*	*Rahphoneis lancettula*	*Rhaphoneis magnapunctata*	*Rhaphoneis parilis*	*Rhaphonies scalaris*	*Rhizosolenia miocenica*	*Rhizosolenia norwegica*	*Rossiella paleacea*	*Rouxia diploneides*	*Sceptroneis caduceus*	*Sceptroneis grandis*	*Sceptronies hungarica*	*Sceptroneis ossiformis?*	*Stephanopyxis* cf. *grunowii*	*Thalassiosira* aff. *eccentrica*	*Thalassiosira fraga*	*Thalassiosira perispinosa*	*Thalassiosira praeyabei*	*Thalassiosira tappanae*	Silicoflagellates	*Bachmannocena quadrangula*	*Naviculopsis lata*	*Distephanus stauracanthus*	*Bachmannocena apiculata curvata*
67																																							
68				R													R																						
69				R													R																						
69				R	R																																R	
70				R	R																																	
71				R										R							R								R										
72				R																									R										
75																																							
81			F	F	R					F																												
83			F	F	F		R	R		F							R		R		R		R						R	R		R				R			
85			C	F	F		R			R																						R	R						
87				F				R		F																				R		R	R						
89				F						F									R		R												R	R					
91				F			R			R											R								R			R	R	R					
94				F			R			F									R														R						
97				R						R																			R	R				R		R			
101				F				R		R											R									R		R							
104				F				R		R																			R	R						R			
107				F						F											R								R			R		R		R			
108				F	R					R	R										R											R		R		R			
111				F						R	R		R																R			R		R					
114				F	F		R		R										F										R	R						R			
118									R		R		R						F		R															R			
121		R						R	R		R								R										R	R		R		R		R			
124		R							R		R								R										R					R					
124									R		R								R										R	R		R		R		R			
127		R						F	F		R	R							R		R		R						R	R		R							R
130		R							F		F							R						R					R	R		R							R
133		R					R		F									R											R	R		R							
135		R						R	R												R								R				R						
137																		R									R		R										
139	F										R									r	R				R	r													
141	F	R									R					R		R				R			R	r	R		R										R
144	F															R		R		r							R												R
147	R				F											R					R									R									R
149	F	R										R						R							R		F		R										
151	F											R				R		R							R														
154	F											R				R							R																
157	C	R			R			R				R				R							R		R		R												
161	F				F							R				R					R						R												
167	F											R													R	R	R				R								
169	R																			R					R	R	R												
171	F											R								R					R						R								
176	F											R										R			R			R		R	R								
179	F																			R	R				R														
181	R																			R					R					R	R								
183	F					R																			R			R		R	R								
188															R										R			R			R								
191	R					R																						R			R								
193						R									R										R			R			R								
195																												cf			R						R		
197																																							

Note: ECDZ—East Coast Diatom Zones; A—abundant; C—common; F—few; R—rare; r—reworked. Preservation: B—barren ; P—poor; M—moderate; G—good.

poorly preserved diatoms. The occurrences of stratigraphically important diatoms and silicoflagellates in Hole M29A are shown in Table 1. Samples studied from Hole M29A contain numerous diatom taxa, in particular species of *Delphineis*, which proved to be useful in the onshore biostratigraphic studies of Abbott (1978, 1980) and Andrews (1988a, 1988b). The succession of first and last occurrences of these diatom taxa in Site M29 (Table 2) has been used to refine the East Coast Diatom Zones (ECDZ) of Andrews (1988a)(Appendix 2).

The recognition of a number of important planktonic diatoms that have been successfully applied in Early and Middle Miocene diatom biostratigraphy in the equatorial and North Pacific (Barron, 1985; Tanimura, 1996; Yanagisawa and Akiba, 1990, 1998; Barron, 2003) allows biostratigraphic ages to be assigned to the section studied in Hole M29A (Table 2). These diatom datum levels are used in Figure 2 to construct an age versus depth plot for Hole M29A. First occurrence datum levels are preferentially used, because they provide constraint on the maximum age of a particular horizon. In the case of last occurrence datum levels, an arrow pointing down the paleomagnetic section has been added to indicate that they may represent reworking. Although both first and last occurrences may be controlled by differential preservation and/or regional ecology, the succession of diatom datum levels for Hole M29A displays a progressive trend of younger ages up section that can be represented by lines of accumulation on an age versus depth plot. Diatom datum levels suggest that M29A sediments at Site M29 accumulated at a rate of ~28 m/m.y. between ca. 18.7 and 15.9 Ma (sedimentary sequences m5.6-m5.3; Miller et al., 2013) with sediment accumulation rates increasing to ~70 m/.y. between ca. 15.9 and 14.6 Ma (sequence m5.2). An unconformity with a hiatus spanning the interval from ca. 14.6–13.8 Ma is inferred at ~502 mcd, corresponding with sequence boundary m5. Above this horizon the interval of sediment containing sequences m5 to m4.1 to the top of preserved diatoms at 336 mcd appears to have been deposited between ca. 13.8 and ca. 13.0 Ma at a sediment accumulation rate close to 180 m/m.y. (Browning et al., 2013).

Strontium isotope stratigraphy (Browning et al., 2013) suggests ages that follow the same up-section trend as the diatom datum levels (green x symbols, Fig. 2), especially for the interval above ~600 mcd (ca. 16–13 Ma), although they indicate ages ca. 0.4 m.y. older than those suggested by diatoms. For detailed discussion of age versus depth relations in Hole M29A based on all of the microfossil groups and strontium isotope stratigraphy, see Browning et al. (2013).

Diatom Biostratigraphy of Key Onshore Sections

In order to test and refine ECDZ biostratigraphy, the BG&E well and the Bethany Beach core were studied (Fig. 1).

The occurrences of stratigraphically useful diatoms in the BG&E well are shown in Table 3, with ECDZ 2–6b being recognized. The Calvert Formation-Choptank Formation boundary, or MLU 16–17 boundary, is recognized at ~34 m depth in the BG&E well (Abbott, 1982), where it coincides with the ECDZ Subzone 6a-6b boundary or first occurrence of *Delphineis biseriata* (Table 3).

The occurrences of stratigraphically useful diatoms in the Bethany Beach corehole are shown in Table 4. ECDZ 1–6b are recognized; the uppermost diatom-bearing sample from a depth of 202 m may represent ECDZ 7. Diatoms suggest that the age equivalent of the boundary between the Calvert and Choptank Formations as recognized by diatoms in the BG&E well (the ECDZ 6a-6b boundary or 13.3 Ma; Table 3) should be placed stratigraphically higher, at ca. 204 m than its reported position at 250 m in the Bethany Beach corehole (McLaughlin et al. (2008) (Table 4). McLaughlin et al. (2008) suggested that the Calvert/Choptank boundary appeared to be significantly older in the Bethany Beach corehole than in the Calvert Cliffs and attributed the difference to a time-transgressive change in the lithologic boundary between the generally finer-grained Calvert Formation and the more clastic-rich Choptank Formation.

In Figure 3 diatom datum levels are combined with strontium isotope stratigraphy (updated here) to suggest an age versus depth plot for the Bethany Beach corehole. We updated the detailed Sr-isotopic ages of Browning et al. (2006) to the Gradstein et al. (2004) time scale (see Browning et al., 2013, for discussion). The interval between ca. 440 m, the lowest sample containing diatoms, and ca. 274 m appears to have accumulated between ca. 20.2 and 17.5 Ma, implying an average sedimentation rate of ~61 m/m.y. Although McLaughlin et al. (2008) suggested the possibility of an unconformity at ca. 351 m corresponding with an upsection shift from coarser to finer grained sediments, the updated strontium and limited diatom data do not reveal a hiatus in deposition. Up section, McLaughlin et al. (2008) identified a heavily burrowed surface upsection at 273.6 m that appears to be an unconformity corresponding with the interval between ca. 17.5 and 16.4 Ma. Above this horizon, the interval up to ca. 218 m coincides with ca. 16.4–15.0 Ma, suggesting a sediment accumulation rate of ca. 36 m/m.y. An unconformity between ca. 218 and 209 m separates ECDZ 4 below from ECDZ 6a above, corresponding to the interval between ca. 15.0 and 13.6 Ma. This unconformity is possibly between a shelly, heavily bioturbated, medium to fine silty sand from 214 to 213 m and a coarsening-upward sequence that begins at 211.6 m (McLaughlin et al., 2008). Above this unconformity, units 4 and 5 of McLaughlin et al. (2008) (ca. 212–185 m) contain diatoms and strontium isotopes ranging in age from ca. 13.6 and 13.0 Ma, implying a sediment accumulation rate of ~48 m/m.y.

Development of a Diatom Biochronology

Diatom biostratigraphic study of Hole M29A, the BG&E well, and the Bethany Beach corehole has allowed refinement of the ECDZ (see Appendix 2). The construction of age-depth plots for Site M29 and the Bethany Beach corehole as constrained by diatom datum levels and strontium isotope stratigraphy (Figs. 2 and 3) makes it possible to propose a diatom range chart for the East Coast of the United States (Figure 4). As concluded by Abbott (1978, 1980) and Andrews (1988a), the ranges of benthic and shallow shelf-dwelling diatoms (*Actinoptychus, Delphineis, Rhaphoneis, Sceptroneis*) are most useful for biostratigraphic correlations of onshore strata, and they form the basis for the ECDZ zonations (Appendix 2). However, the ranges of planktonic diatom taxa that have proven to be useful for biochronology in the equatorial and North Pacific (Barron, 1985, 2003; Yanagisawa and Akiba, 1998) in Hole M29A provide a means of correlation (Barron, 2003) with the paleomagnetic time scale of Gradstein et al. (2004). These age assignments are largely supported by strontium isotope stratigraphy in Hole 29A of Site M29 and the Bethany Beach corehole (Figs. 2, 3; Browning et al., 2013). Stratigraphically useful diatoms and silicoflagellates for the ECDZ zonation are illustrated in Plates 1–4.

Correlation of Other IODP 313 Holes and Onshore Sections

Diatom preservation is not as good or consistent at Sites M27 and M28, which contain coarser-grained sediments than Site M29; 34 samples were examined for diatoms from Hole M27A, 23 of which yielded diatoms that were preserved well enough to be assignable to ECDZ 1 (482.34 mcd) to ECDZ 6b (210.535 mcd) (Supplemental Table 1[1]).

[1]Supplemental Table 1. Samples studied for diatoms from Hole M27A. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00864.S1 or the full-text article on www.gsapubs.org to view Supplemental Table 1.

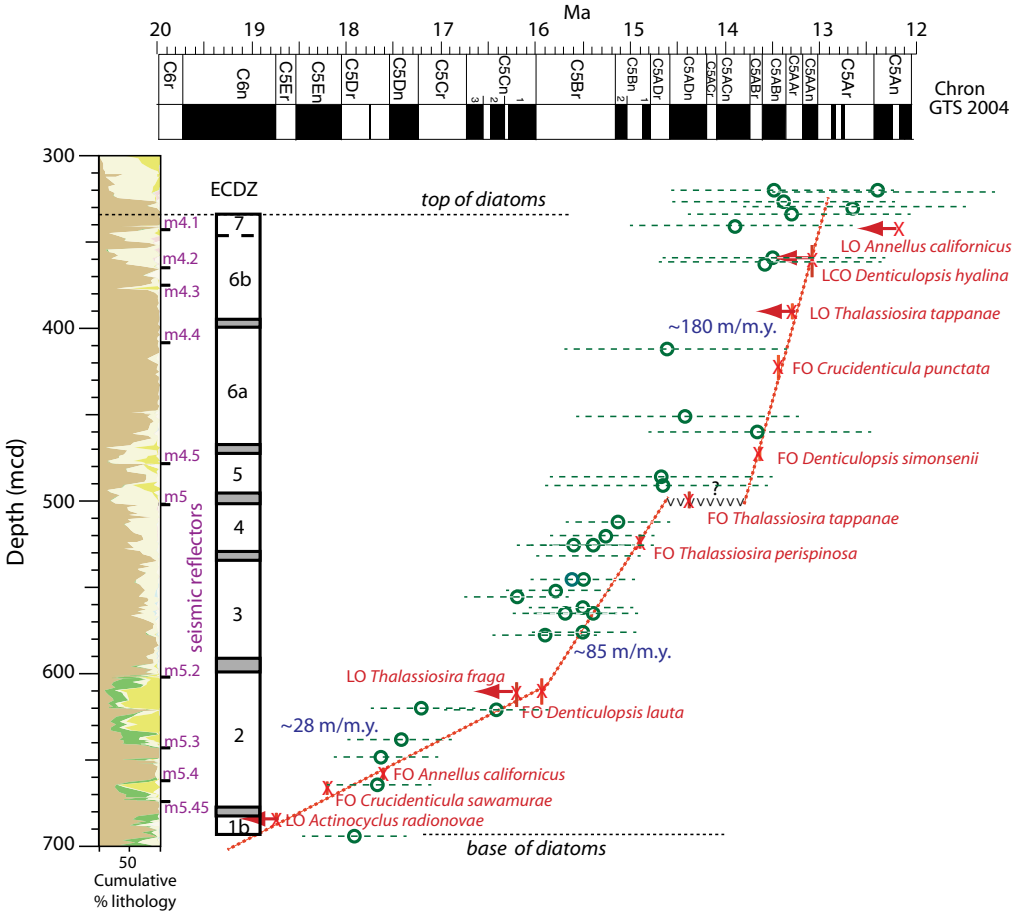

Figure 2. Age-depth (mcd—meters composite depth) plot for Integrated Ocean Drilling Program Expedition 313 Site M29 constructed from diatom biostratigraphic markers (red X's) compared with strontium isotope stratigraphy (green dots; Browning et al., 2013; dashed lines = errors ± 0.6 m.y. for >15.5 Ma, ± 1.17 m.y. for younger) Paleomagnetic time scale of Gradstein et al. (2004; GTS—geologic time scale). Questions marks indicate hiatus duration estimated by extrapolation of sedimentation rates. ECDZ—East Coast Diatom Zone; FO—first occurrence; LO—last occurrence; LCO—last common occurrence. Cumulative percent lithology data is after Miller et al. (2013).

TABLE 2. STRATIGRAPHIC CONSTRAINTS ON DIATOM DATUM LEVELS IN INTEGRATED OCEAN DRILLING PROGRAM EXPEDITION 313 HOLE M29A

	Species	Top depth (mcd)	Bottom depth (mcd)	Ma	Source	Zone
LO	*Crucidenticula nicobarica*	?	336.6	12.3	Barron (2003)	
LO	*Annellus californicus*	336.6	343.01	12.5	Barron (2003)	ECDZ 7?
FO	*Rhaphoneis diamantella?*	343	353.06			
LCO	*Denticulopsis hyalina*	353.1	370.4	13.1	Yanagisawa and Akiba (1998)	
LO	*Thalassiosira tappanae*	388.8	393.36	13.2	Barron (2003)	ECDZ 6b
FO	*Delphineis biseriata*	393.4	401.08	(13.3)		
FO	*Coscinodiscus gigas*	418.1	430.18	13.4	Barron (1985)	
FO	*Crucidenticula punctata*	418.1	430.18	13.4	Barron (1985)	ECDZ6a
FO	*Denticulopsis simonsenii*	466.8	478.85	13.6	Barron (1985) (update)	
LO	*Denticula norwegica*	478.9	487.12	13.4		
LO	*Cestodiscus pulchellus maculatus*	487.1	494.04	13.9	Barron (2003)	ECDZ 5
LO	*Cestodiscus peplum*	496.2	505.47	14.1	Barron (2003)	
FO	*Thalassiosira tappanae*	496.2	505.47	14.4	Barron (2003)	
FO	*Delphineis novaecesarae*	496.2	505.47	(14.6)		
FO	*Thalassiosira perispinosa*	521.8	528.72	14.9	Tanimura (1996)	
FO	*Delphineis angustata* sensu Andrews	521.8	528.72	(14.9)		ECDZ 4
FO	*Delphineis angustata*	530.7	537.01	(15.0)		
LO	*Delphineis ovata*	530.7	537.01	(15.0)		
FO	*Delphineis penelliptica*	588.9	601.4	(15.8)		ECDZ 3
FO	*Actinocyclus ingens*	588.9	601.4	15.5	Barron (1985)	
FO	*Denticulopsis lauta*	601	621.61	15.9	Yanagisawa and Akiba (1998)	
LO	*Thalassiosira fraga*	601	621.61	16.2	Barron (1985)	
LO	*Crucidenticula sawamurae*	601	621.61	16.2	Yanagisawa and Akiba (1990)	ECDZ 2
FO	*Annellus californicus*	655.5	661.94	17.6	Barron (2006)	
FO	*Azpeitia salisburyana*	661.9	672.65	17.4	Barron (2006)	
FO	*Crucidenticula sawamurae*	661.9	672.65	18.2	Barron (2006)	
LO	*Rhaphonies fossile*	661.9	672.65	(18.2)		
LO	*Actinoptychus heliopelta*	672.7	680.19			ECDZ 1
FO	*Cestodiscus pulchellus maculatus*	680.2	688.07	18.7	Barron (2006)	
FO	*Delphineis ovata*	680.2	688.07			
LO	*Actinocyclus radionovae*	680.2	688.07	18.7	Barron (2006)	

Note: ECDZ—East Coast Diatom Zones; FO—first occurrence; LO—last occurrence; LCO—last common occurrence; mcd—meters composite depth. Parentheses around dates derived from the age-depth plot.

TABLE 3. OCCURRENCE OF SELECTED DIATOM TAXA IN THE BALTIMORE GAS AND ELECTRIC COMPANY (BG&E) WELL

CAS Accession #	Interval (ft)	Poor preservation	MLU	Formation/Member	ECDZ Zone	*Actinocyclus ellipticus*	*Actinocyclus ingens*	*Actinoptychus heliopelta*	*Actinoptychus marylandicus*	*Annellus californicus*	*Azpeitia salisburyana*	*Azpeitia vetustissima*	*Azpeitia vetustissima* var. *voluta*	*Cestodiscus pulchellus* var. *maculatus*	*Coscinodiscus gigas* var. *diorama*	*Coscinodiscus lewisianus*	*Craspedodiscus coscinodiscus*	*Crucidenticula sawamurae*	*Cymatogonia amblyoceras*	*Delphineis angustata* s.str.	*Delphineis angustata* sensu Andrews	*Delphineis biseriata*	*Delphineis lineata*	*Delphineis novaecesaraea*	*Delphineis penelliptica*	*Delphineis ovata*	*"Denticula" norwegica*	*Denticulopsis simonsenii*	*Koizumia adaroi*	*Paralia sulcata* (shallow diatom)	*Rhaphoneis diamantella*	*Rhaphoneis fossilie*	*Rhaphonies fusiformis*	*Rhaphoneis margaritata*	*Rhaphoneis magnapunctata*	*Rhaphoneis lancettulla*	*Rhaphoneis parilis*	*Rhaphonies scalaris*	*Sceptroneis caduceus*	*Sceptroneis grandis*	*Sceptronies hungarica*	*Thalassiosira fraga*	*Thalassiosira grunowii*	*Thalassiosira perispinosa*	*Thalassiosira tappanae*
614841	75.7–76.7	quartz	20	Choptank																										F						F										
614834	80.7–81.7																													C						C										
614840	90.9	quartz																																												
613521	100		18		6b		F								R				R			R		R				F	F						C								F		
614829	103.6–104.6						R															R						R	R						F	F							R		
613522	106		18				F								R				R	R		R		R				R	F						C	R							F		
614835	109.6–110.6						R															R		R				R	R						F	F									
614828	121.8–122.8	quartz																																												
614836	123.8–124.8	v poor		Calvert Beach																																							R		
613524	124.8		16		6a		R			R										R	R			R	F			R	R						R	R									
614831	129.8–130.8																			R	R				R				R						R	R									
	131	quartz					R													R	R			R	R				R							R									R
613525	136		15			R	R				R								R	R	F			R	R			R							F	R							R		
617432	139.5		15						R							R	R		R	R	F			F	F										F	R									
614827	141.3–142.3																R			R	F			R	F										R	F							R		
614832	144.3–145.3				5				R											R	F		R	R	F										R	R									
613526	146.3		15			R			R											F	F			R	C					A					R	F							R		
614852	151.3–152.3	poor																																												
613528	156.6	coarse	13	Plum Point										R											R					C																
614849	159.1–160.1						F					R								R	R		R		F					A					R		R									
613529	162.1		13				F				R						R			R			R		F					A					R											
614859	170.6–171.6	quartz					F													R					R					F					R											
613531	174.1	quartz	13		4		F				R		R							R					R					C					R		R									
613532	178.8		13				F		R		F		F							F			R		C										F		R									
613533	183.8		12				F		R		F		R	R						R					F		R								R		R								R	
	186.6	quartz					R				R		R										R		R					C					R											
614851	188.1–189.1						F						R	R						R			R		F										R		R									
613534	189.2		11				F				R		R	R											F	R							R		R											
614853	194.7–195.7	quartz												R											R	R									R		R									
613535	196.9	quartz																																												
613536	202.1	quartz	10		3					R				R											R	R							R					R	F	R	R					
613537	207.1		9-10					R			R			R		R			R				R		R	R				C			F				R	F	R	R					
613538	215.1		4-8				R	R			R		R	F		R			R						R	R							R				F	F	F	F					
614838	215.1–216.1	poor	4-8																																			R							
613539	221.8		3					R					R			R			R						R	C							R	R			F	F							
614839	224.4–225.8		3	Falrhaven																			R			F								R			R	F				R			
619045	225.8		3					R			R		R						R				R			F				C			R	F			R	F			R	R			
614837	230.8–231.8		3					R								R							R			R							R	F			R	F				R			
614868	240.8–241.8		3								R							R								R								R			R	F							
619046	248.8		3					F			R		R	R												R				C				R			R	F							
614862	250.8–251.8		3					F					R					R					R			R				C							R	F				R			
614865	259.8–260.8		3					R			R		R	R									R			F				C				R			F	R				R			
614863	269.8–270.8		3		2					R			R	R				R					R			F								R			F	F							
614867	279.8–280.8		3							R	R		R				R						R			R											R	F				R			
614866	290.8–291.8		3							R													R			F	R			C								F							
619047	294.8		3					R		R			R	R		F	F	R	R				R			F				C							R	C				cf			
614861	298–299		3							R			R	R			F	R	R				R			F								R			R	C				cf			
614864	309–310		3					R			R			R			R	R	R							R								R			R	R				R			
614855	321–322		3					R						R												R						R		R				R							

Note: CAS—California Academy of Sceince; MLU—Miocene Lithologic Unit; ECDZ—East Coast Diatom Zones; R—rare; F—few; C—common.

TABLE 4. OCCURRENCE OF SELECTED DIATOM AND SILICOFLAGELLATE TAXA IN THE ODP BETHANY BEACH COREHOLE

Interval of Bethany Beach corehole (ft)	Preservation	Abundance	ECDZ	*Actinocyclus ingens*	*Actinoptychus heliopelta*	*Annellus californicus*	*Azpeitia bukryi*	*Azpeitia nodulifera*	*Azpeitia salisburyana*	*Azpeitia vetustissima*	*Cavitatus jouseanus*	*Cavitatus rectus*	*Cestodiscus* sp (resembles *Ac.ingens*)	*Cestodiscus pulchellus* var. *maculatus*	*Coscinodiscus gigas* var. *diorama*	*Coscinodiscus lewisianus*	*Craspedodiscus barronii*	*Craspedodiscus elegans*	*Cymatogonia amblyoceras*	*Delphineis angustata* s.str.	*Delphineis angustata* sensu Andrews	*Delphineis biseriata*	*Delphineis lineata*	*Delphineis novaecesaraea*	*Delphineis penelliptica*	*Delphineis ovata*	*“Denticula” norwegica*	*Denticulopsis lauta*	*Denticulopsis simonsenii*	*Koizumia adaroi*	*Paralia sulcata*	*Raphidodiscus marylandicus*	*Rhaphoneis fossilie*	*Rhaphonies fusiformis*	*Rahphoneis lancettula*	*Rhaphoneis margaritata*	*Rhaphoneis magnapunctata*	*Rhaphoneis lancettulla*	*Rhaphoneis parilis*	*Rhaphonies scalaris*	*Rouxia californica*	*Sceptronies caducea* (short)	*Sceptroneis caduceus*	*Sceptroneis grandis*	*Sceptronies hungarica*	*Thalassiosira* aff. *eccentrica*	*Thalassiosira fraga*	*Thalassiosira grunowii*	*Thalassiosira irregulata*	*Thalassiosira praefraga*	*Thalassiosira tappanae*	*Trinacria solenoceros*	Silicoflagellates	*Naviculopsis ponticula*	*Naviculopsis biapiculata*	*Naviculopsis navicula*	*Naviculopsis lata*	*Naviculopsis quadrata*	*Bachmannocena quadrangula*	*Bachmannocena apiculata curvata*
587.4	B																																																											
602	VP	VR	?																																																							
622	P	F	7?																											F																												
642.5	M	C	6b																	R		F												F			R	F																				
662.5	P	F																											R	R																												
682	G	A	6a	R				R							R					R	R			R	R				F	R	F	R					R		F		F					R		R			R									
702	VP	VR																																																								
722	M	A	4						R											R			R		F						A						F		R																				R	
742	M	A	4	R						R										R			R		F					R	C						F		R																					
762	M	C	3	R		R								R											F	R				R	C								R					R							R									
782.5	M	C	3		R									R									R		R	R					F			R									F	R	R															
802	P	VR																													F																													
822.3	M	C	2		R				R					R					R				R			F	R	R		R	F	R		F									R	R																
842	MG	A	2			R			R	R				R					R				R			F	R	R			C	R		F									F	R		R						R								
862	MG	A	2		R				R	R				R		R			R							C					C			F									F	F																
882.4	MG	A	2		R				R	R				F		R			R							C					C			R									F	F	R		R													R
902.4	VP	VR																																																								
922	M	A	2						R					F									R			C					C					R				R			F									R								
942	M	A	2											R												F					F					R				R			F																	
962	M	C	2	R										R									R			R					C					R				R			R																	
983	M	C	2		R				R					R									R			R					C					R				R							R		R			R								
1002.3	M	C	2		R									F					R				R			R					C	R				F				R							R													
1022	M	C	2											R									R			R					C					F				R			R									R								
1042	M	C	2		R									R												R					C					R				R			R									R		R						
1062	M	C	2		R						R			R									R			R					C					C							R				R					R								
1082	M	A	2		F								R	R									R								C		cf			F																R								
1102	M	A	2		F						R			F									R								C		R			R											R													
1122	G	A	2		F									F									F			R					C		R			C							F				R					R		R						
1142.3	G	A	2		F				R				R	F									F			R					F					F							F				R					R								
1165.5	P	F	1		R									R									R								R					R							R																	
1182	VP	VR																																																								
1200.7	VP	VR												VR																																												
1222	A	G	1				R		R		F																				C		R			R						R	R				R			R						R	R			
1242	A	G	1		F		R		R		F	R		F																	C	R	F			C						R	F				R			R		R		R						
1262.3	A	G	1		R		R						R	F																	C		F			C						F	F				R		R	R										
1282	A	G	1		R		R							F																	C		R			F						F	F				R					R								
1302	A	G	1		R		R				F			R																	F		F			F						R	C				F			F										
1322	A	G	1		F						F			F																	C		F									R	C				R													
1342.5	A	G	1		R		R				F			F			R														C	R	R									R	F				R		R	R										
1362.5	A	M	1								R	R																			C		R										F						R											
1382.5	A	M	1																												C	R?	R									R	F				R													
1402	A	M	1		R		R				F	R																			F		R									R	R				cf			F										
1422.5	A	M	1		R						F						R	R													C											F							R						cf		R			
1442	A	M	1								F																				C																			R							R		
1462.3	B	B																																																								

Note: ODP—Ocean Drilling Program; ECDZ—East Coast Diatom Zones; A—abundant; C—common; F—few; R—rare; cf—questionable identification. Preservation: G—good; M—moderate; P—poor; VP—very poor.

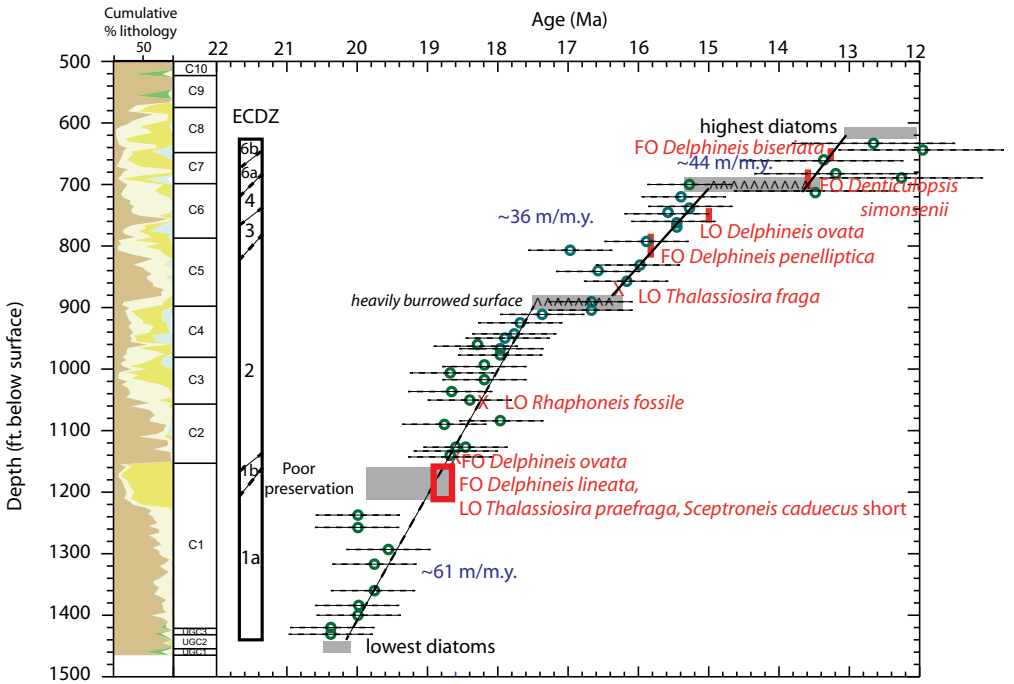

Figure 3. Age-depth plot for the Bethany Beach corehole. Red—diatom events, green dots—strontium isotope stratigraphy with age constraints, gray boxes—poor diatom preservation possibly at unconformities. Abbreviations as in Figure 2.

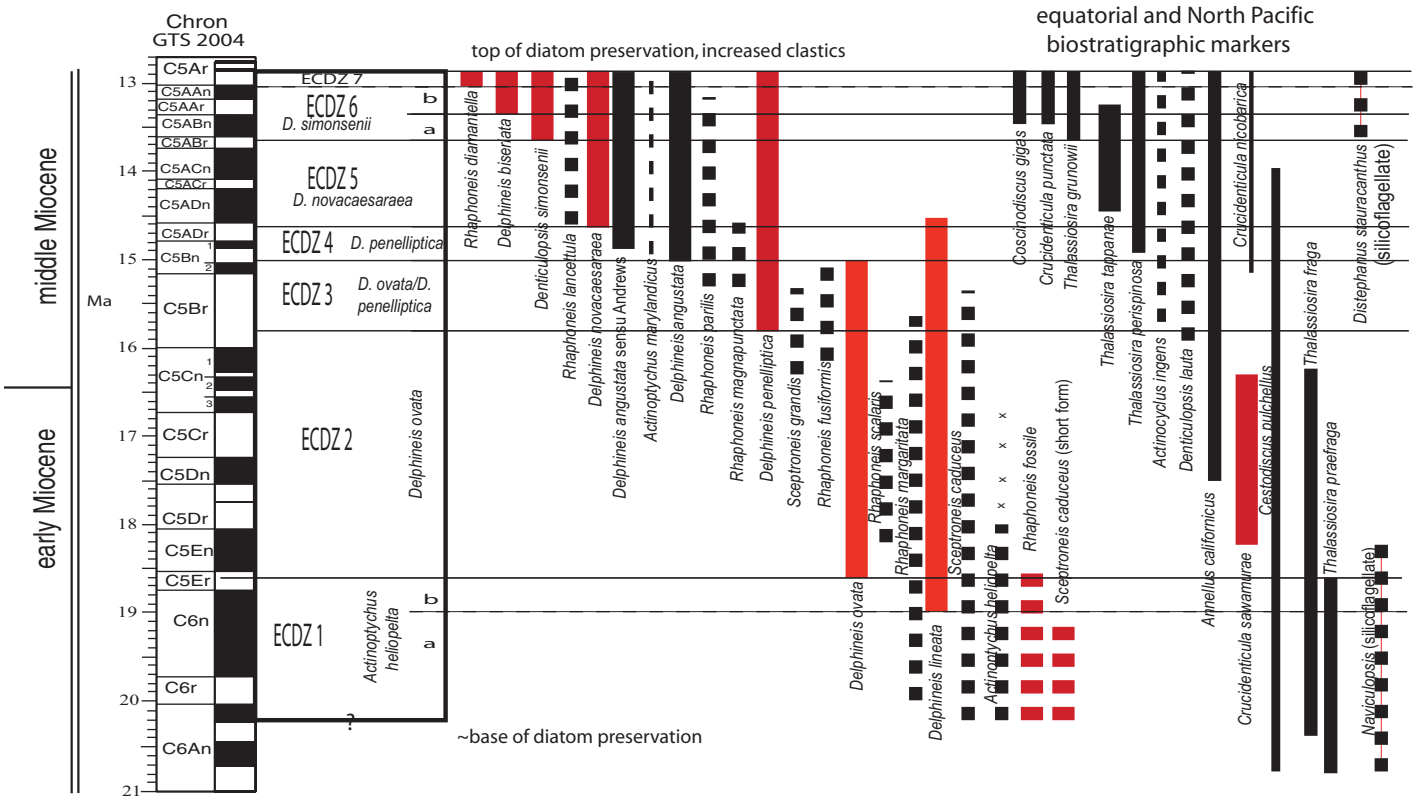

Figure 4. Age ranges of East Coast Diatom zonal markers (red bars) determined from ranges of planktonic diatom marker taxa (black bars) and the age versus depth model for Integrated Ocean Drilling Program Expedition Hole M29A (Fig. 2) (Table 2). Dashed lines show inferred ranges of secondary marker taxa. Abbreviations as in Figure 2.

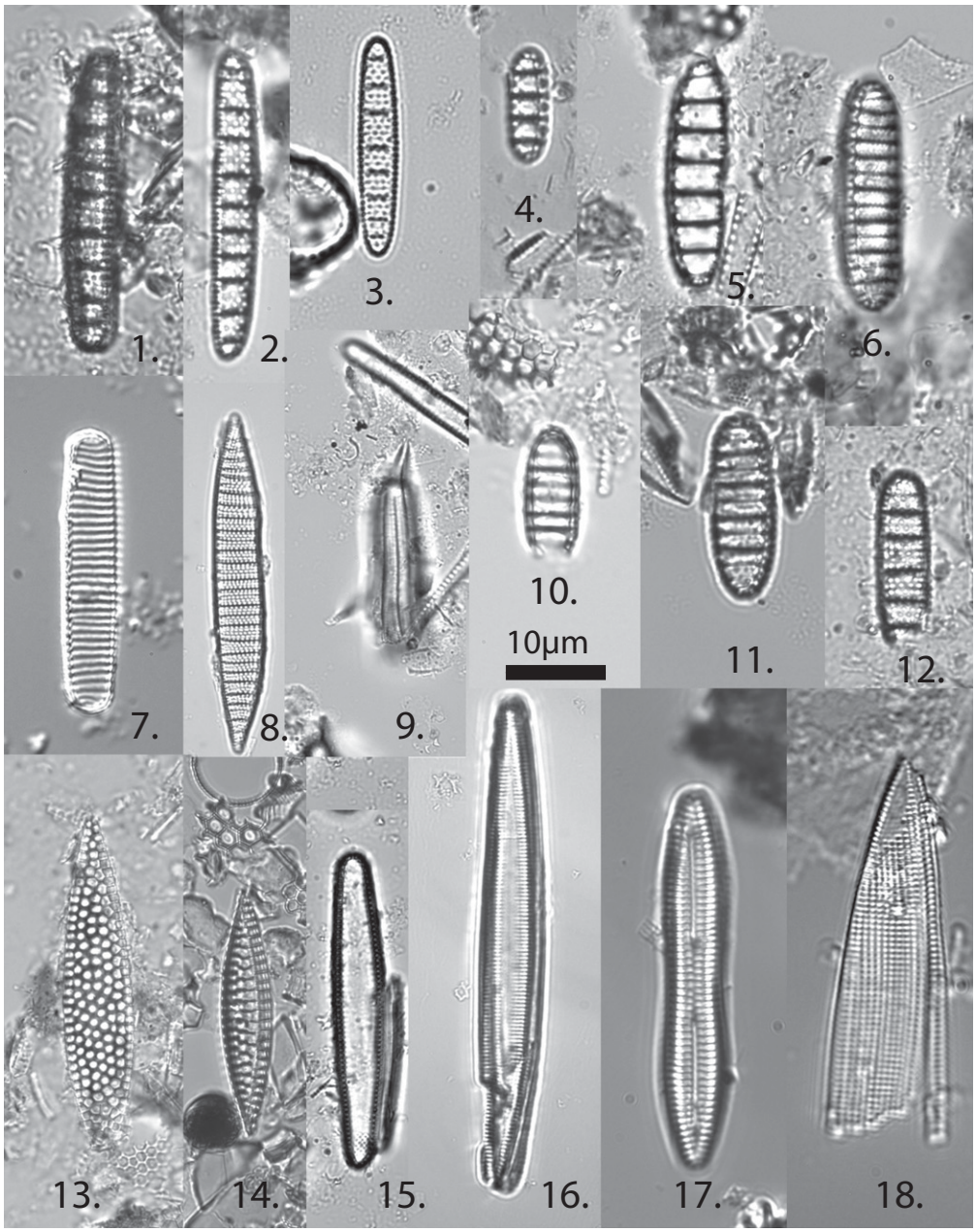

Plate 1. 1—*Crucidenticula sawarmurae* Yanagisawa and Akiba, sample 29A-183R-1, 58 cm. 2 and 3—*Crucidenticula nicobarica* (Grunow) Akiba and Yanagisawa, 2 is sample 29A-83R-1, 90 cm; 3 is sample 29A-130R-1, 114 cm. 4—*Denticulopsis lauta* (Bailey) Simonsen, sample 29A-157R-1, 70 cm. 5—*Denticulopsis hyalina* (Schrader) Simonsen, sample 29A-83R-1, 90 cm. 6, 10, and 11—*Denticulopsis simonsenii* Yanagisawa and Akiba, 6 and 11 are sample 29A-85R-1, 74 cm; 10 is sample 29A-101R-1, 62 cm. 7—*Nitzschia* cf. *N. challengerii* Schrader, sample 29A-83R-1, 90 cm. 8—*"Denticula" norwegica* Schrader and Fenner, sample 29A-130R-1, 114 cm. 9—*Rhizosolenia miocenica* Schrader, sample 29A-83R-1, 90 cm. 12—*Crucidenticula punctata* (Schrader) Akiba and Yanagisawa, sample 29A-83R-1, 90 cm. 13—*Rossiella paleacea* (Grunow) Desikachary and Maheswari, sample 29A-157R-1, 70 cm. 14—*Koizumi adaroi* Yanagisawa, sample BG&E (Baltimore Gas and Electric Company), 100 ft. 15—*Cavitatus rectus* Akiba and Hiramatsu, sample 29A-167R-2, 144 cm. 16—*Cavitatus jouseanus* (Shesukova-Poretzkaya) Williams, sample 29A-130R-1, 114 cm. 17—*Rouxia diploneides* Schrader, sample 29A-130R-1, 114 cm. 18—*Mediaria splendida* Sheshukova-Poretzkaya, sample 29A-130R-1, 114 cm.

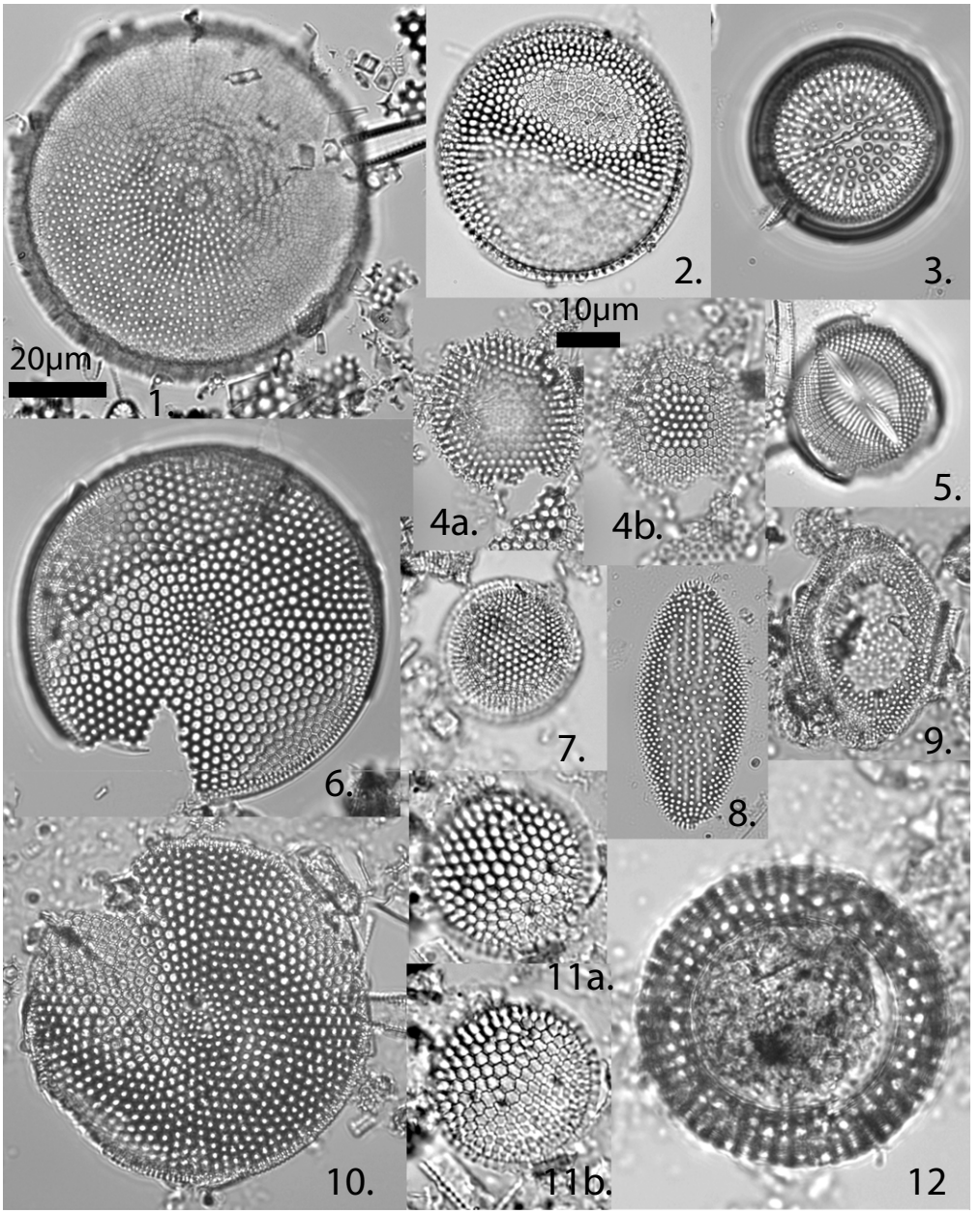

Plate 2. 1—*Cestodiscus pulchellus* var. *maculatus* Kolbe, sample BG&E (Baltimore Gas and Electric Company), 269.8–270.8 ft. 2—*Thalassiosira perispinosa* Tanimura, sample 29A-130R-1, 114 cm. 3—*Actinocyclus ingens* Rattray, sample 29A-130R-1, 114 cm. 4a, 4b, and 7—*Thalassiosira fraga* Schrader, 4a and 4b, low and high focus, sample BG&E, 259–260 ft.; 7, sample 29A-191R-1, 53 cm. 5—*Raphidodiscus marylandicus* Christian, sample 29A-167R-2, 114 cm. 6—*Azpeitia salisburyana* (Lohman) P.A. Sims, sample 29A-130R-1, 114 cm. 8—*Coscinodiscus lewisianus* Greville, sample 29A-157R-1, 70 cm. 9—*Cestodiscus peplum* Brun, sample 29A-157R-1, 70 cm. 10—*Azpeitia vetustissima* var. *voluta* (Baldauf), Sims, Fryxell, and Baldauf, sample 29A-157R-1, 70 cm. 11a and 11b—*Thalassiosira tappanae* Barron, high and low focus, sample 29A-124R-2, 110 cm. 12—*Annellus californicus* Tempère, sample 29A-171R-2, 100 cm.

Plate 3. 1 and 2—*Delphineis ovata* Andrews, sample 29A-157R-1, 70 cm. 3, 4, and 5—*Delphineis penelliptica* Andrews, 3 is sample 29A-157R-1, 70 cm; 4 is sample 29A-130R-1, 114 cm; 5 is sample 29A-91R-2, 52 cm. 6, 14, and 19—*Delphineis angustata* sensu Andrews, 6 is sample 29A-83R-1, 90 cm; 14 is sample 29A-91R-2, 52 cm; 19 is sample 29A-124R-2, 110 cm. 7 and 15—*Delphineis biserialata* (Grunow) Hendy, sample 29A-87R-2, 44 cm. 8, 10, 16, and 17—*Delphineis lineata* Andrews, 8 is sample 29A-130R-1, 114 cm; 10 is sample 29A-124R-2, 110 cm; 16 is sample 29A-147R-1, 10 cm; 17 is sample 29A-135R-1, 88 cm. 9, 25, and 26—*Delphineis angustata* (Pantocsek) Andrews s. str., 9 is sample 29A-130R-1, 114 cm; 25 and 26 are sample BG&E (Baltimore Gas and Electric Company), 139.5 ft. 11–13—*Delphineis novaecaesaraea* (Kain and Schultze) Andrews, 11 is sample 29A-91R-2, 52 cm; 12 and 13 are sample 29A-111R-2, 60 cm. 18—*Rhaphoneis diamantella* Andrews, sample 29A-71R-2, 40 cm. 20—*Rhaphoneis lancettulla* Grunow, sample BG&E, 80.7–81.7 ft. 2—*Rhaphoneis fossile* (Grunow) Andrews, sample BG&E, 323–324 ft. 22 and 23—*Rhaphoneis fusiformis,* 22 is sample 29A-157R-1, 70 cm; 23 is sample BG&E, 207.1 ft. 24—*Rhaphoneis parilis* Hanna sensu Andrews and Abbott, 1985, sample 29A-130R-1, 114 cm.

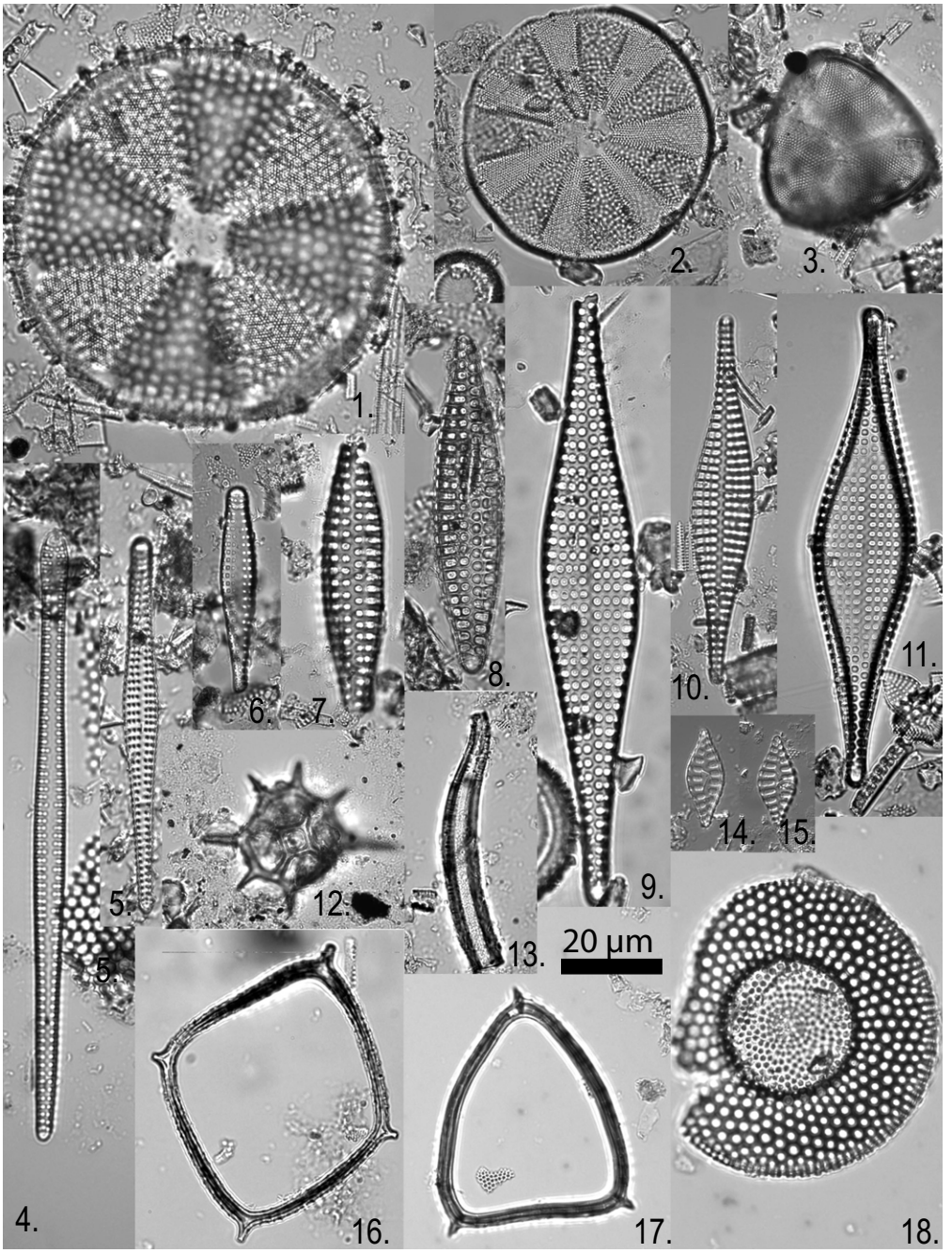

Plate 4. 1—*Actinoptychus heliopelta* Grunow, sample Bethany Beach, 1142.3 ft. 2—*Actinoptychus marylandicus* Andrews, sample BG&E (Baltimore Gas and Electric Company), 139.5 ft. 3—*Cymatogonia amblyoceras* (Ehrenberg) Hanna, sample 29A-157R-1, 70 cm. 4—*Sceptroneis caduceus* Ehrenberg, sample BG&E, 323–324 ft. 5—*Sceptroneis* sp. cf. *S. caduceus* Ehrenberg, sample Bethany Beach, 1342.5 ft. 6—*Sceptroneis* sp. cf. *S. caduceus* Ehrenberg (short form), sample Bethany Beach, 1342.5 ft. 7, 8—*Sceptroneis hungarica* (Pantocsek) Andrews, 7 is sample 29A-167R-2, 144 cm; 8 is sample 29A-149R-1, 65 cm. 9—*Rhaphoneis margaritata* Andrews, sample BG&E, 221.8 ft. 10—*Rhaphoneis scalaris*, Ehrenberg, sample BG&E, 221.8 ft. 11—*Rhaphoneis magnapunctata* Andrews, sample BG&E, 162.1 ft. 12—*Distephanus stauracanthus* Ehrenberg, sample 29A-69R-2, 8 cm (silicoflagellate). 13—*Proboscia praebarboi* (Schrader) Jordan and Priddle, sample 29A-141R-1, 80 cm. 14, 15—*Rhaphoneis fossile* (Grunow) Andrews, sample Bethany Beach, 1242 ft. 16—*Bachmannocena quadrangula* (Ehrenberg ex Haeckel) Locker, sample 29A-87R-2, 44 cm (silicoflagellate). 17—*Bachmannocena apiculata curvata* (Schulz) Bukry, sample 29A-130R-1, 114 cm (silicoflagellate). 18—*Craspedodiscus coscinodiscus* Ehrenberg, sample 29A-130R-1, 114 cm.

TABLE 5. STRATIGRAPHIC CONSTRAINTS ON EAST COAST DIATOM ZONE BOUNDARIES IN SECTIONS STUDIED

Zone	Age (Ma)	M29A* (mcd)	M28A* (mcd)	M27A* (mcd)	Bethany Beach† (ft)	BG&E well (ft)	Cape May† (ft)	Cape May Zoo† (ft)	Ocean View† (ft)
top of diatoms	ca. 12.8	329.71/332.39	246.32/249.84	208.03/210.54	602/622	<75.7	392.5/461.7	<282.1	260.6/300.6
base ECDZ7	13.0	343.01/343.95						313.1/321.6	
base ECDZ6b	13.3	393/36/401.08	249.84/253.22	211.26/217	642.5/682	110.6/123.8	485.1/511.2	340.0/370.9	310.7/374.7
base ECDZ6a	13.6	466.8/478.85	272.4/287.39	219.8/225.99	682/722	136/139.5	485.1/511.2	399.1/453.9	386.8/414.4
base ECDZ5	14.6	496.22/505.47	287.39/297.4	225.99/227.25	682/722	146.3/156.6	485.1/511.2	399.1/453.9	386.8/414.4
base ECDZ4	15.0	530.72/537.01	297.4/304.27	225.99/227.25	742/762	188.1/189.2	511.2/654.5	399.1/453.9	386.8/414.4
base ECDZ3	15.8	588.86/601.04	324.1/361.07	247.63/252	782.5/822.3	221.8/224.4	511.2/654.5	453.9/487.8	425.7/481
base ECDZ2	18.6	680.19/688.07	507.5/520.05	316.46/323.88	1062/1082	>322	1025.3/1079.8?	>611.7	>721.6
base ECDZ1b	19.4	>692.8	548.92/668.95	323.88/421.78	1165.5/1222				

Note: ECDZ—East Coast Diatom Zone; mcd—meters composite depth; BG&E—Baltimore Gas and Electric Company.
*IODP—Integrated Ocean Drilling Program Expedition 313.
†ODP—Ocean Drilling Program site.

Of the 44 samples that were examined for diatoms between cores 7 and 171 of Hole M28A, only 23 could be assigned to ECDZ zones (Supplemental Table 2[2]), ranging from ECDZ 1 at 668.65 mcd to ECDZ 6b 248.84 mcd. Initial reconnaissance study of samples with finer-grained lithologies was supplemented by the study of additional samples that were chosen with the aim of refining zonal boundaries.

The revised ECDZ zones can also be applied to other onshore cores that were previously studied for microfossil biostratigraphy and strontium isotope stratigraphy (Fig. 1). With this in mind, 17, 13, and 20 samples were examined for diatoms, respectively, from the Cape May (Miller et al., 1996), Cape May Zoo (Sugarman et al., 2007), and Ocean View (Miller et al., 2001) cores, respectively (Supplemental Table 3[3]). Table 5 provides a summary of the ECDZ biostratigraphy of Holes M27A, M28A, and M29A, the Bethany Beach corehole, the BG&E well, and cores from Cape May, Cape May Zoo, and Ocean View Site.

CONCLUSIONS

The Lower and Middle Miocene section cored at Site M29, the outermost of the IODP 313 sites on the shallow New Jersey shelf, contains a succession of planktonic marine diatoms that allows detailed correlation with diatom biochronologies developed in the equatorial and North Pacific. Coupled with the regular occurrence of shallow water diatoms of the genera *Delphineis*, *Rhaphoneis*, *Sceptroneis*, and *Actinoptychus* that have been used for correlation of onshore strata in Maryland, Virginia, and New Jersey, detailed study of the diatom biostratigraphy of Site M29 makes possible the refinement of East Coast Diatom Zones (ECDZ). Detailed study of key onshore reference sections, the BG&E well in Maryland and the Bethany Beach corehole in Delaware, is used for further refinement of this diatom biostratigraphy for the interval from ca. 20–13 Ma. Regionally along the New Jersey to Virginia coastal margin of the United States, diatoms are most common in sediments younger than ca. 20 Ma and older than ca. 13 Ma. Age-depth models for Site M29 and the Bethany Beach corehole are constructed and compared with strontium isotope stratigraphy, which mostly supports the age assignment of the refined ECDZ diatom biochronology. Hole M29 provides the best opportunity yet to determine the age of the margin-wide sequence boundary m5 (Monteverde et al., 2008). Diatom biostratigraphy suggests this m5 sequence boundary corresponds with an unconformity at Site M29 dated at ~14.6–13.8 Ma. A correlative unconformity in the Bethany Beach corehole is dated by diatoms at ~15.0–13.6 Ma.

ACKNOWLEDGMENTS

Holly Olson of the US Geological Survey prepared excellent microscope slides. We thank Jean DeMouthe, collections manager of the diatom collection at the California Academy of Sciences, for the loan of William Abbott's microscope slides from the BG&E (Baltimore Gas and Electric Company) well. Lucy Edwards and David Bukry of the US Geological Survey provided helpful comments and advice throughout this study. Funding was supplied by the Consortium of Ocean Leadership/U.S. Science Support Program, and samples were provided by the Integrated Ocean Drilling Program and the International Continental Scientific Drilling Program. We thank Scott W. Starratt and two anonymous reviewers for their reviews, as well as Greg Mountain (Associate Editor) and Carol Frost (Science Editor) for their comments.

APPENDIX 1. TAXA DISCUSSED–REFERENCE TO SYNONYMY AND FIGURES

Actinocyclus divisus (Grunow) Hustedt, as *Coscinodiscus divisus* Grunow (Abbott and Andrews, 1979, Plate 2, fig. 13; as Coscinodiscus curvatulus Grunow, Andrews and Abbott, 1985, Plate 7, fig. 9; *Coscinodiscus rothii* sensu Andrews, 1976, Plate 3, figs. 1, 2.

Actinocyclus ellipticus Grunow, Abbott, 1980, Plate 2, figs. 2, 3.

Actinocyclus ingens Rattray, Andrews, 1976, Plate 3, fig. 10. (Plate 2, image 3, herein)

Actinocyclus radionovae Barron, Barron, 2006, Plate 3, figs. 2, 3. Note: First recorded occurrence in East Coast Miocene sections.

Actinoptychus heliopelta Grunow, Andrews, 1988a, Plate 1, figs. 1, 2; Plate 5, figs. 1, 2; Wetmore and Andrews, 1990, Plate 1, figs. 6, 7. (Plate 4, image 1 herein)

Actinoptychus marylandicus Andrews, 1976, Plate 4, figs. 3–6; Andrews, 1988a, Plate 1, fig. 4.; Plate 5, figs. 3. (Plate 4, fig. 2) Note: Occurrence charts include *A. virginicus* (Grunow) Andrews).

Annellus californicus Tempère in J. Tempère & H. Peragallo, Abbott, 1978, Plate 2, fig. 1; Barron, 1985, Plate 2, fig. 5. (Plate 2, image 12 herein)

Azpeitia bukryi (Barron) Barron, Barron, 2006, Plate 8, fig. 4.

Azpeitia sp. cf. *A. nodulifera* (Schmidt) G. Fryxell & P.A. Sims, compare *Coscinodiscus hirosakiensis* Kanaya sensu Abbott and Andrews, 1979, Plate 2, fig. 15.

Azpeitia salisburyana (Lohman) P.A. Sims in Fryxell, Sims & Watkins, Barron, 2006, Plate 1, fig. 2; as *Coscinodiscus salisburyanus* Lohman, Lohman, 1974, Plate 2, figs. 5, 7; compare *Coscinodiscus curvatulus* sensu Abbott and Andrews, 1979, Plate 4, fig. 10. (Plate 2, image 6 herein)

Azpeitia vetustissima (Pantocsek) P.A. Sims in Fryxell, Sims & Watkins, as *Coscinodiscus vetustissimus* Pantocesek sensu Andrews, 1976, Plate 3, fig. 3.

Azpeitia vetustissima var. *voluta* (Baldauf) Sims, Fryxell, & Baldauf, 1989, p. 303. (Plate 2, image 10 herein). Note: First recorded occurrence in East Coast Miocene sections.

Cavitatus jouseanus (Shesukova-Poretzkaya) Williams, Barron, 2006, Plate 9, fig. 6. (Plate 1, image 16 herein)

Cavitatus rectus Akiba & Hiramatsu, Barron, 2006, Plate 9, fig. 6. (Plate 1, image 15 herein)

Cestodiscus peplum Brun, Lohman, 1974, Plate 3, fig. 2; Barron, 1985, Plate 7, figs. 7, 8 (Plate 2, image 9 herein). Note: First recorded occurrence in East Coast Miocene section

[2]Supplemental Table 2. Samples studied for diatoms from Hole M28A. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00864.S2 or the full-text article on www.gsapubs.org to view Supplemental Table 2.

[3]Supplemental Table 3. Samples studied for diatoms from the Cape May, Cape May Zoo, and Ocean View wells. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00864.S3 or the full-text article on www.gsapubs.org to view Supplemental Table 3.

Cestodiscus pulchellus var. *maculatus* Kolbe, Barron, 1985, Plate 1, fig. 4; as *C. pulchellus* Greville, Lohman, 1974, Plate 3, fig. 4. (Plate 2, image 1 herein)

Coscinodiscus gigas var. *diorama* (Schmidt) Grunow, Abbott and Andrews, 1979, Plate 2, fig. 14; Abbott, 1980, Plate 2, fig. 10; Barron, 1985, Plate 9, fig. 6; –compare *C. apiculatus* Ehrenberg, sensu Andrews, 1976, Plate 2, fig. 3

Coscinodiscus lewisianus Greville, Andrews, 1988a, Plate 1, figs. 8, 9. (Plate 2, image 8 herein)

Coscinodiscus rhombicus Castracane, Barron, 1985, Plate 7, fig. 1; Barron, 2006, Plate 9, figs. 17, 23. Note: First recorded occurrence in East Coast Miocene sections.

Craspedodiscus barronii Bukry, Barron, 2006, Plate 1, figs. 6a, 6b.

Craspedodiscus coscinodiscus Ehrenberg, Andrews, 1976, Plate 3, fig. 4; Abbott, 1980, Plate 2, fig. 11; Barron, 1985, Plate 2, fig. 7. (Plate 4, image 18 herein)

Craspedodiscus elegans Ehrenberg, Barron, 2006, Plate 1, fig. 7.

Crucidenticula nicobarcia (Grunow) Akiba & Yanagisawa, Yanagisawa and Akiba, 1990, Plate 1, figs. 23–29; as *Denticula nicobarica* Abbott, 1980, Plate 1, fig. 18. (Plate 1, images 2, 3 herein)

Crucidenticula paranicobarcia Akiba & Yanagisawa, Yanagisawa and Akiba, 1990, Plate 1, figs. 13–16. Note: First recorded occurrence in East Coast Miocene sections.

Crucidenticula punctata (Schrader) Akiba & Yanagisawa, Yanagisawa and Akiba, 1990, Plate 1, figs. 30–32 (Plate 1, fig. 12) Note: Recorded by Abbott and Ernisee (1983) as *Denticula punctata* Akiba.

Crucidenticula sawamurae Yanagisawa & Akiba, Barron, 2006, Plate 9, fig. 2 (Plate 1, fig. 1 herein)

Cymatogonia amblyoceras (Ehrenberg) Hanna, Andrews and Abbott, 1985, Plate 8, figs. 2, (Plate 4, image 3 herein)

Delphineis angustata (Pantocsek) Andrews s. str., as *Rhaphoneis angustata* Pantocsek, Andrews, 1975, Plate 1, figs. 5, 6, Andrews, 1976, Plate 7, figs. 1, (Plate 3, images 9, 25, 26 herein)

Delphineis angustata (Pantocsek) Andrews sensu Andrews, 1977, Plate 1, figs. 1–4, Plate 2, figs. 21?, 22; Andrews, 1988a, Plate 2, figs. 1, (Plate 3, images 14, 19 herein)

Delphineis biseriata (Grunow) Hendy, Andrews, 1988a, Plate 2, figs. 3. (Plate 3, images 7, 15 herein)

Delphineis lineata Andrews, Andrews, 1988a, Plate 2, figs. 6–8. (Plate 3, images 8, 16, 17 herein)

Delphineis novaecaesaraea (Kain & Schultze) Andrews, Andrews, 1988a, Plate 2, figs. 9–12. (Plate 3, images 11–13 herein)

Delphineis ovata Andrews, Andrews, 1988a, Plate 2, figs. 13–16; Wetmore and Andrews, 1990. Plate 1, fig. 13. (Plate 3, images 1, 2 herein)

Delphineis penelliptica Andrews, Andrews and Abbott, 1985, Plate 8, figs 11–13; Andrews, 1988a, Plate 2, figs. 17–19. (Plate 3, images 3–5 herein) Note: ranges younger than recorded by Andrews, 1988a.

"Denticula" norwegica Schrader & Fenner, Abbott and Ernisee, 1983; Yanagisawa and Akiba, 1990, Plate 1, fig. 40; Plate 8, fig. 18. (Plate 1, image 8 herein)

Denticulopsis hyalina (Schrader) Simonsen, Yanagisawa and Akiba, 1990, Plate 2, figs. 14, 33, 34; Plate 9, figs. 8, 9. (Plate 1, image 5 herein) Note: First recorded occurrence in East Coast Miocene sections.

Denticulopsis lauta (Bailey) Simonsen, Yanagisawa and Akiba, 1990, Plate 2, figs. 6–8; Plate 5, figs. 1–3; Plate 9, fig. 1; Abbott, 1980, Plate 1, fig. 17? (Plate 1, image 4 herein)

Denticulopsis simonsenii Yanagisawa and Akiba, 1990, Plate 3, figs. 1–3; Plate 11, figs. 1, 5; as *Denticulopsis hustedtii* (Simonsen & Kanaya) Simonsen, Abbott and Andrews, 1979, Plate 4, fig. 4; Abbott, 1980, Plate 1, fig. 16; Andrews, 1988a, Plate 2, figs. 21–24. (Plate 1, images 6, 10, 11 herein)

Fragilariopsis maleinterpretaria (Schrader) Censarek & Gersonde, as *Nitzschia maleinterpretaria* Schrader, Barron, 2006, Plate 9, figs. 20, 21. Note: First recorded occurrence in East Coast Miocene sections.

Koizumia adaroi Yanagisawa, 1994, Plate 8, figs. 1–7, 12, 13; Plate 9, figs. 1–3, as *Rossiella paleacea* sensu Andrews and Abbott, 1985, Plate 9, figs. 20–22. (Plate 1, image 14 herein)

Mediaria splendida Sheshukova-Poretzkaya, Abbott and Andrews, 1979, Plate 4, fig. 22. (Plate 4, image 18 herein)

Nitzschia challengeri Schrader, 1973, Plate 5, figs. 10–16, 34; Yanagisawa and Akiba, 1990, Plate 2, figs. 1, 2, 10; Plate 9, figs. 12–16; Plate 10, figs. 1, 2. (Plate 1, image 7 herein)

Paralia sulcata (Ehrenberg) Cleve, Andrews, 1976, Plate 1, figs. 5, 6.

Proboscia praebarboi (Schrader) Jordan & Priddle, as *Rhizosolenia praebarboi* Schrader, 1973, Plate 24, figs. 1–3. (Plate 4, image 13 herein)

Raphidodiscus marylandicus Christian, Andrews, 1988a, Plate 2, figs. 25, 26. (Plate 2, image 5 herein)

Rhaphoneis cf. *adamantea* Andrews, 1988a, p. 2, figs. 27–29, Plate 6, fig. 14.

Rhaphoneis diamantella Andrews, 1976, Plate 6, figs. 15–18; Andrews, 1988a, Plate 2, figs. 27–29, 36–38. (Plate 3, image 18 herein)

Rhaphoneis fossile (Grunow) Andrews, Abbott, 1978, Plate 2, fig. 7; Andrews, 1988a, Plate 4, figs. 4–6; Wetmore and Andrews, 1990, Plate 1, fig. 8; as *Dimerogramma fossile* Grunow sensu Schrader and Fenner, 1976, Plate 5, figs. 12, 13, 22. (Plate 3, image 21; Plate 4, images 14, 15 herein)

Rhaphonies fusiformis Andrews, Andrews, 1988a, Plate 4, figs. 7–10. (Plate 3, images 22, 23 herein)

Rhaphoneis lancettulla Grunow, Andrews, 1988a, Plate 4, figs. 15–17. (Plate 3, images 20 herein)

Rhaphonies magnapunctata Andrews, Andrews and Abbott, 1985, Plate 9, figs. 14–16; Andrews, 1988a, Plate 3, figs. 1–4. (Plate 4, image 11 herein)

Rhaphoneis margaritata Andrews 1988a, Plate 3, figs. 5–9, p. 7, fig. 10; Wetmore and Andrews, 1990, Plate 1, fig. 12. (Plate 4, image 9 herein)

Rhaphoneis parilis Hanna, sensu Andrews and Abbott, 1985, Plate 9, figs. 17–19; Andrews, 1988a, Plate 4, figs. 18, 19. (Plate 3, image 24 herein)

Rhaphonies scalaris Ehrenberg, Andrews, 1988a, Plate 4, figs. 20, 21; Wetmore and Andrews, 1990, Plate 1, fig. 11 (Plate 4, image10 herein)

Rhizosolenia miocenica Schrader, Abbott and Andrews, 1979, Plate 5, fig. 23 (Plate 1, image 9 herein)

Rhizosolenia norwegica Schrader in Schrader & Fenner, 1976, p. 996, Plate 9, figs. 4, 10.

Rossiella paleacea (Grunow) Desikachary & Maheswari, Andrews and Abbott, 1985, Plate 9, figs. 20–22 (Plate 1, image 13 herein)

Rouxia californica M. Peragallo in Tempere and Peragallo, Schrader, 1973, Plate 3, figs. 18–20, 22?, 26.

Rouxia diploneides Schrader, 1973, p. 710, Plate 3. Figs. 24, 25; Abbott, 1978, Plate 2, fig. 8; Abbott, 1980, Plate 1, fig. 19 (Plate 1, image 17 herein)

Sceptroneis caduceus Ehrenberg, Andrews, 1988a, Plate 4, figs. 29–32; Wetmore and Andrews, 1990, Plate 1, fig. 5 (Plate 4, images 4, 5? herein)

Sceptroneis cf. *caduceus* short form; compare *S.* sp, aff. *S. caduceus* sensu Schrader and Fenner, 1976, p. 998, Plate 4, figs. 11–16. (Plate 4, image 6 herein)

Sceptroneis grandis Abbott, Andrews, 1988a, Plate 4, figs. 33, 34.

Sceptroneis hungarica (Pantocsek) Andrews, Andrews, 1988a, Plate 4, figs. 35. 36. (Plate 4, images 7, 8 herein)

Sceptroneis ossiformis Schrader in Schrader and Fenner, 1976, p. 998, Plate 2, figs. 14–17.

Stephanopyxis grunowii Grove & Sturt, Abbott and Andrews, 1979, Plate 5, fig. 29; Abbott and Ernisee, 1983, Plate 9, fig. 1.

Thalassiosira eccentrica (Ehrenberg) Cleve, Abbott, 1980, Plate 4, fig. 4; Andrews and Abbott, 1985, Plate 9, fig. 28.

Thalassiosira fraga Schrader, Barron, 2006, Plate 8, fig. 1 (Plate 2, images. 4, 7 herein). Note: First recorded occurrence in East Coast Miocene sections.

Thalassiosira grunowii Akiba & Yanagisawa, Andrews, 1988a, Plate 1, fig. 6?, 7; as *Coscinodiscus plicatus* Grunow, Abbott, 1978, Plate 1, fig. 1; Abbott, 1980, Plate 1, fig. 4; Abbott and Ernisee, 1983, Plate 4, fig. 1.

Thalassiosira irregulata Schrader in Schrader & Fenner, 1976, Plate 20, figs. 10–12.

Thalassiosira perispinosa Tanimura, 1996, p.181, Figs. 35–39, as *Coscinodiscus lacustris* Grunow sensu Abbott and Andrews, 1979, Plate 2, fig. 17; Andrews and Abbott, 1985, Plate 7, fig. 10. (Plate 2, image 2 herein)

Thalassiosira praefraga Gladenkov & Barron, Barron, 2006, Plate 8, figs. 2a, 2b, 6?

Thalassiosira praeyabei (Schrader) Akiba &Yanagisawa, Tanimura, 1996, Figs. 40–42; as *Coscinodiscus praeyabei* Schrader, Abbott, 1978, Plate II, fig. 3.

Thalassiosira tappanae Barron, 1985, Plate 6, figs. 1–5, 7. (Plate 2, image 11 herein) Note: First recorded occurrence in East Coast Miocene sections.

Trinacria solnoceros (Ehrenberg) VanLandingham; Andrews, 1988a, Plate 8, figs. 6–8

Silicoflagellates:

Bachmannocena quadrangula (Ehrenberg ex Haeckel) Locker, as *Mesocena quadrata*, Perch-Nielsen, 1985, Plate 23, fig. 22. (Plate 4, image 16 herein)

Bachmannocena apiculata curvata (Schulz) Bukry, as *Mesocena apiculata* Bukry, Perch-Nielsen, 1985, Plate 23, fig. 2. (Plate 4, image 17 herein)

Distephanus stauracanthus Ehrenberg, Abbott, 1978, Plate I, fig. 7; Abbott, 1980, Plate 3, fig. 12. (Plate 4, image 12 herein)

Naviculopsis biapiculata (Lemmermann) Frenguelli, Perch-Nielsen, 1985, Plate 25, figs. 3, 4.

Naviculopsis lata (Deflandre) Frenguelli, Perch-Nielsen, 1985, Plate 25, fig. 21.

Naviculopsis navicula (Ehrenberg), Deflandre Wetmore and Andrews, 1990, Plate 1, fig. 3.

Naviculopsis ponticula (Ehrenberg) Bukry, Wetmore and Andrews, 1990, Plate 1, fig. 2.

Naviculopsis quadrata (Ehrenberg) Locker, Wetmore and Andrews, 1990, Plate 1, fig. 1.

APPENDIX 2. PROPOSED CHANGES IN EAST COAST DIATOM ZONES

ECDZ 1: *Actinoptychus heliopelta* Assemblage Zone

Andrews (1988a) defined the base of ECDZ 1 by the first occurrence of *A. heliopelta* and its top by the last occurrence of *A. heliopelta*. Current studies reveal that *A. heliopelta*, a rare, large diatom that is commonly fragmented, is commonly reworked into overlying ECDZ 2. It is proposed here that the first occurrence of *Delphineis ovata* be used to recognize the top of ECDZ 1. Therefore, ECDZ 1 can be recognized by the presence of *A. heliopelta* and the absence of *D. ovata*. The last occurrence of *Rhaphoneis fossile* also approximates the top of ECDZ 1. Two new subzones are proposed—the first occurrence of *Delphineis lineata* defines the top of subzone a and the base of overlying Subzone b.

ECDZ 2: *Delphineis ovata* Partial Range Zone

Andrews (1988a) defined the base of ECDZ 2 by the first occurrence of *D. ovata* and its top by the last occurrence of *D. ovata*. Abbott's (1978) proposal to use the first occurrence of *Delphineis penelliptica* to define the top of ECDZ 2, however, is accepted here. ECDZ 2 thus becomes the *Delphineis ovata* Partial Range Zone (Abbott, 1978). Notes: *D. ovata* ranges slightly below the first occurrence of *Crucidenticula sawamurae* in Integrated Ocean Drilling Program Expedition 313 Site M29 and the Baltimore Gas and Electric Company (BG&E) well (Tables 1 and 3). In the Bethany Beach corehole, *C. sawamurae* is not present, but the first *D. ovata* is easily recognizable (Table 4).

ECDZ 3-4

Andrews (1988a) proposed the *Rhaphoneis magnapuncta* Range Zone to represent a combined ECDZ 3-4 interval. This zone was defined as the interval between first occurrence of *R. magnapunctata* and the last occurrence of *R. magnapunctata*.

ECDZ 3: *Delphineis ovata-D. penelliptica* Concurrent Range Zone

It is proposed here that ECDZ 3 be redefined to be equivalent to Abbott's (1978) *Delphineis ovata/ D. penelliptica* Concurrent Range Zone. This means that the base of ECDZ 3 is defined by first occurrence of *Delphineis penelliptica* and its top is the last occurrence of *Delphineis ovata*.

ECDZ 4: *Delphineis penelliptica* Partial Range Zone

The base of ECDZ 4 is defined by the last occurrence of *D. ovata*. However, rather than following Abbott (1978) in using the first occurrence of *Coscinodiscus plicatus* (*Thalassiosira grunowii*) to define the top of this zone, the top of ECDZ 4 and the base of overlying ECDZ 5 are redefined here to coincide with the first occurrence of *D. novaecaesaraea*, in keeping with Andrews' (1977, 1988b) recognition of the stratigraphic usefulness of the evolutionary succession of *Delphineis* species.

ECDZ 5: *Delphineis novaecaesaraea* Partial Range Zone

Andrews (1988a) defined the base of ECDZ 5 as the last occurrence of *Rhaphoneis magnapunctata* and its top by the first occurrence of *R. clavata*. These large benthic diatoms are often rare and fragmented in diatom assemblages. It is proposed here that ECDZ 5 be redefined to be the interval from the first occurrence of *D. novaecaesaraea* to the first occurrence of *Denticulopsis simonsenii* (=*D. hustedtii* of Andrews, 1988a). ECDZ 5 therefore becomes the *Delphineis novaecaesaraea* Partial Range Zone.

ECDZ 6: *Denticulopsis simonsenii* Partial Range Zone

Andrews (1988a) defined the base of ECDZ 6 by first occurrence of *Rhaphoneis clavata* and its top by the last occurrence of *R. gemmifera*. It is proposed that the first occurrence of *Denticulopsis simonsenii* be used to define the base of ECDZ 6 and the first occurrence of *Rhaphoneis diamantella* be used to define its top. The first occurrence of *Delphineis biseriata* is proposed here to define the base of new subzone b and the top of new subzone a. Note: Figure 2 of Andrews (1988a) suggests that the first occurrence of *Denticulopsis hustedtii* (=*D. simonsenii*) occurs just above the base of his ECDZ 6. Andrew's Figure 2 also shows that the first occurrence of *Rhaphoneis diamantella* coincides with the top of ECDZ 6.

Abbott (1978) proposed the *Coscinodiscus plicatus* Partial Range Zone as the interval coinciding with the range of *C. plicatus* (*Thalassiosira grunowii*) above the last *Delphineis penelliptica*; however, this biostratigraphic zone does not seem practical based on the long range of *D. penelliptica* in Hole M29 (Table 1). It is possible that *D. penelliptica* disappears earlier in more nearshore sections, such as the BG&E well (Table 3), because it is restricted by falling sea level.

ECDZ 7: *Rhaphoneis diamantella* Partial Range Zone

Andrews (1988a) defined the base of his ECDZ 7 by the last occurrence of *Rhaphoneis gemmifera* and its top by the last occurrence of *R. diamantella*.

The first occurrence of *R. diamantella* is proposed here to define the base of ECDZ 7. Increasing clastic debris, probably due to falling sea level, upsection characterizes ECDZ 7. Therefore, the top of ECDZ is not defined.

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