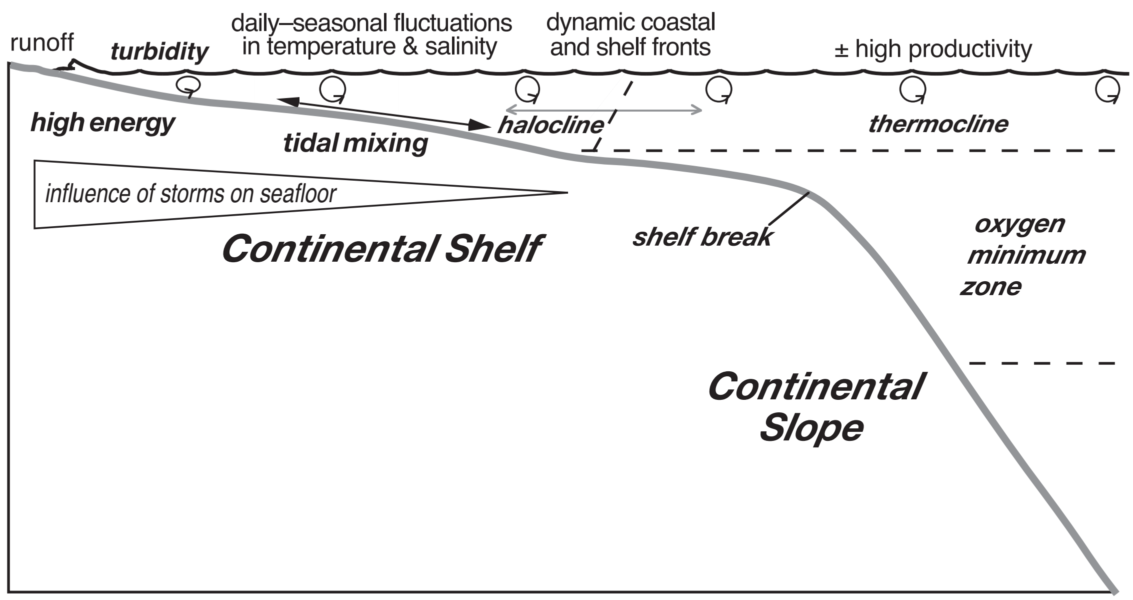
MICROPALEONTOLOGIC PROXIES FOR SEA-LEVEL CHANGE AND STRATIGRAPHIC DISCONTINUITIES



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BIOFACIES AND LITHOFACIES EVIDENCE FOR PALEOENVIRONMENTAL INTERPRETATIONS OF UPPER NEOGENE SEQUENCES ON THE NEW JERSEY CONTINENTAL SHELF (ODP LEG 174A)

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ABSTRACT: We evaluate late Miocene–Recent paleoenvironments, paleobathymetry, and depositional facies recovered at two sites drilled by Ocean Drilling Program Leg 174A on the New Jersey continental shelf. Based on seismic stratigraphy, previous studies suggested that the New Jersey margin sequences are primarily either highstand deposits or lowstand systems tracts. However, benthic foraminiferal biofacies and planktonic foraminiferal abundances proved to be key to deciphering systems tract development. By integrating foraminiferal, lithologic, and downhole logging evidence within a seismically defined sequence stratigraphic framework, we show that Pleistocene sequences cored by Leg 174A are characterized by transgressive and highstand deposits, whereas Miocene sequences consist of lowstand, transgressive, and highstand deposits, with repeated flooding surfaces indicating parasequences. We propose that the erosion responsible for the shelf sequence boundaries can be attributed to mean lowerings of base level in response to changes in the mean states of glaciation that marked: (1) the Miocene increase in ice volume and glacioeustatic lowering; (2) the transition to Northern Hemisphere–dominated glaciation; and (3) the transition to the large eustatic fluctuations of the middle–late Pleistocene.

INTRODUCTION

Variations in global sea level (eustasy), tectonism, and sediment supply control the distribution of sediments, stratal geometries, and stacking patterns within depositional sequences on continental margins, particularly on passive margins (Vail et al., 1977; Vail et al., 1991; Haq et al., 1987; Weimer and Posamentier, 1993; Christie-Blick and Driscoll, 1995). However, the links among these processes, the formation of unconformity-bounded sequences, and facies variations within sequences remain controversial.

Pioneering work by Exxon Production Research Company (EPR; Vail et al., 1977; Haq et al., 1987; Posamentier et al., 1988) laid the groundwork for modern sequence stratigraphy, using it to extract eustatic records from passive-margin sequences and to predict facies distributions (and attendant control on fluid resources, both oil and water). Whereas several studies have supported the chronology of the EPR eustatic variations (e.g., Miller et al., 1996; Eberli et al., 1996), it is clear that the amplitude and shape of the EPR curve is incorrect (Christie-Blick et al., 1992; Miall, 1991; Miller et al., 1998). Nevertheless, EPR documented that depositional sequences can be used objectively to partition the stratigraphic record. (We follow Mitchum, 1977, as modified by Christie-Blick, 1995, in defining a depositional sequence as an unconformity-bounded unit associated with baselevel lowering.) In addition, EPR provided several generations of depositional models for facies variations within sequences, such as the systems tracts of Posamentier et al. (1988). These have wide applicability (e.g., Winn et al., 1995; Abreu and Haddad, 1998; West et al., 1998), although many aspects of the models remain controversial or untested.

A critical component of deciphering sequence-stratigraphic architecture and evaluating systems-tract models is determining and interpreting the vertical succession of biofacies with regard to paleobathymetric changes. Benthic foraminiferal faunal changes can be used to interpret paleobathymetric changes and the provenance of transported sediments (e.g., Natland, 1933; Bandy 1960). Changes in abundances of planktonic and benthic foraminiferal provide an additional proxy for water-depth variations (e.g., Grimsdale and van Morkhoven, 1955), although this index can be influenced by other effects (e.g., productivity and dissolution). Lithofacies variations provide the basis for interpreting paleoenvironmental changes, although inferences using lithofacies alone are notoriously non-unique. The reliability of paleoenvironmental interpretations can be greatly improved by integrating biofacies, lithofacies, seismic, and downhole geophysical log measurements.

Although many studies have applied the concept of systems tracts to sequence interpretations (e.g., Abbott and Carter, 1994; Kolla et al., 2000), few studies of offshore marine sections have targeted sequences that display the classic prograding clinoform geometry on a siliciclastic passive margin. In this paper, we use Ocean Drilling Program (ODP) Leg 174A drilling results (Austin et al., 1998) from upper Neogene (upper Miocene to Recent) sequences to link microfaunal and sedimentologic data with prograding clinoform geometries along the outer edge of the New Jersey passive margin.

Miller and Mountain (1994) outlined why the New Jersey margin (Fig. 1) is an ideal setting for a rigorous sequence stratigraphic study, including: (1) a thick accumulation of Oligocene to Recent "icehouse" sediments (Poag, 1977; Schlee, 1981; Greenlee et al., 1988; Greenlee et al., 1992) deposited during a time of known glacioeustatic oscillations (see Miller and Mountain, 1994 and Austin et al., 1998); (2) a stable passive-margin setting in a late stage of thermal cooling; (3) a mid-latitude location with excellent chronostratigraphic control (Miller et al., 1996); and (4) a substantial body of existing data that range from seismic lines to wells to outcrops (Figs. 1–3).

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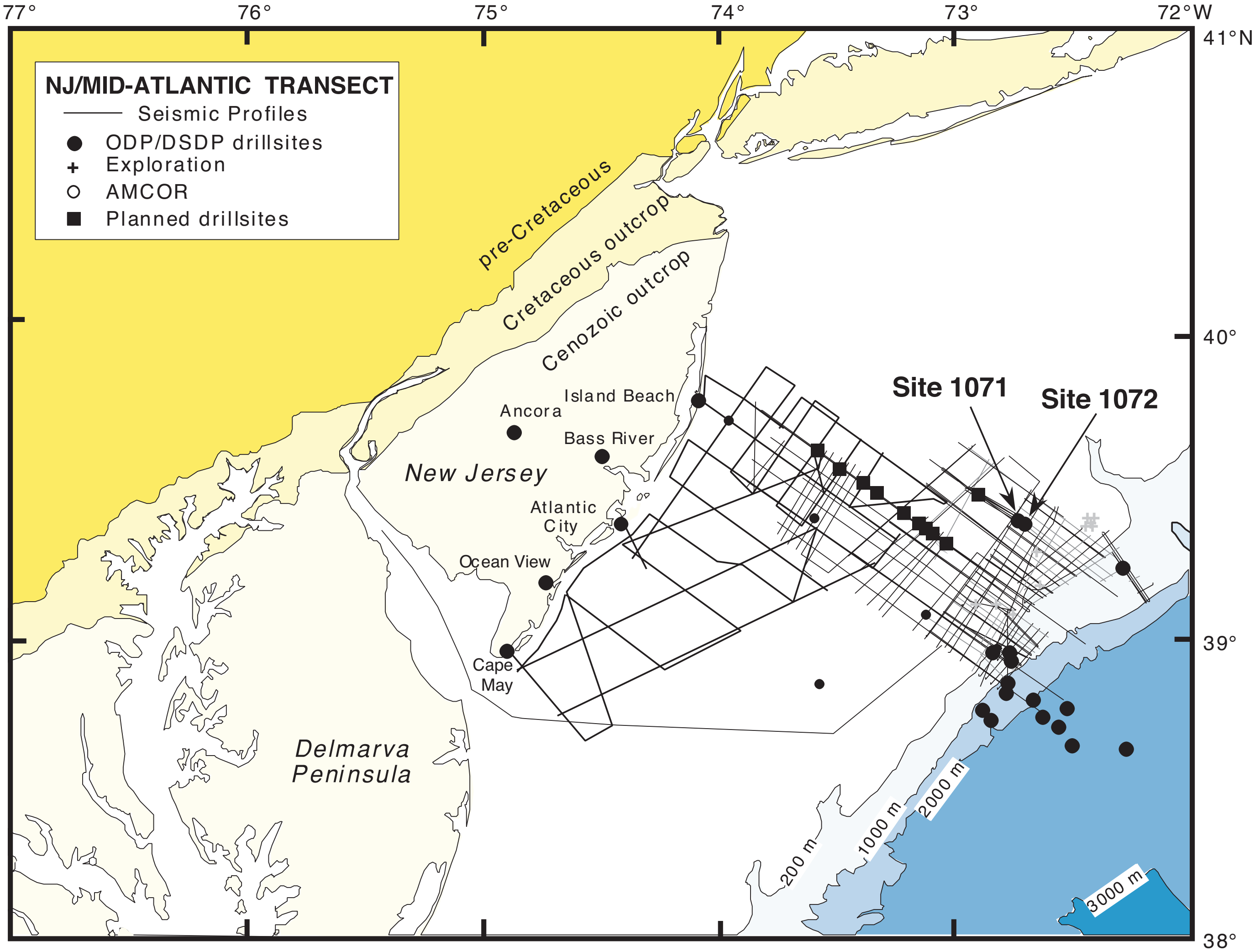

FIG. 1.—Location map showing the New Jersey / mid-Atlantic sea-level transect including onshore, offshore, and proposed boreholes and seismic line track charts (cruises Ch0698, Ew9009, and Oc270).

ODP Leg 174A drilled two sites on the New Jersey continental shelf (Austin et al., 1998). Sites 1071 and 1072 (present water depths 88 m and 98 m, respectively) recovered sediments deposited no deeper than neritic paleodepths (shelf; <200 m) during the late middle Miocene to Holocene on the New Jersey margin, and thus are in the setting that is most sensitive to sea-level change.

This study investigates sequence architecture by integrating foraminiferal, lithofacies, and seismic stratigraphic data at Sites 1071 (Holes A–C) and 1072 (Hole A), and downhole LWD (logging-while-drilling) at Holes 1071G and 1072D. Biofacies changes have proven to be successful in deciphering stratigraphic sequences deposited in shallow water on the New Jersey margin (e.g., Olsson and Wise, 1987; Miller et al., 1997). Changes in benthic foraminiferal biofacies and planktonic foraminiferal abundances at Sites 1071 and 1072 are documented and integrated with seismic profiles, downhole logs, lithofacies, and biostratigraphy in order to evaluate the sequence stratigraphic architecture on the New Jersey shelf at the Leg 174A sites.

These integrated results can be used to test the validity of several proposed models of sedimentation within sequences on this margin. For example, Greenlee et al. (1992) used commercial seismic data to conclude that the New Jersey shelf sequences consist primarily of highstand deposits (the highstand systems tracts of Posamentier et al., 1988). With improved multichannel seismic data, Christie-Blick et al. (1992) interpreted these same sequences as primarily lowstand systems tracts. However, successions within the upper Miocene sands drilled at Sites 1071 and 1072 fit neither interpretation; rather, sedimentary facies indicate that these sequences are largely transgressive systems tracts (Austin 1998; Metzger et al., 2000). Changes in benthic foraminiferal biofacies, planktonic foraminiferal abundances, and lithofacies are the key to evaluating these models of sequence stratigraphic architecture. This study integrates foraminiferal records with seismic profiles, downhole logs, lithofacies, and biostratigraphy to provide the means to assess these systems-tracts interpretations.

METHODS

Biofacies and Paleobathymetry

In general, one sample per 1.5 m of section was examined for foraminifera. Poor to moderate core recovery in some sections

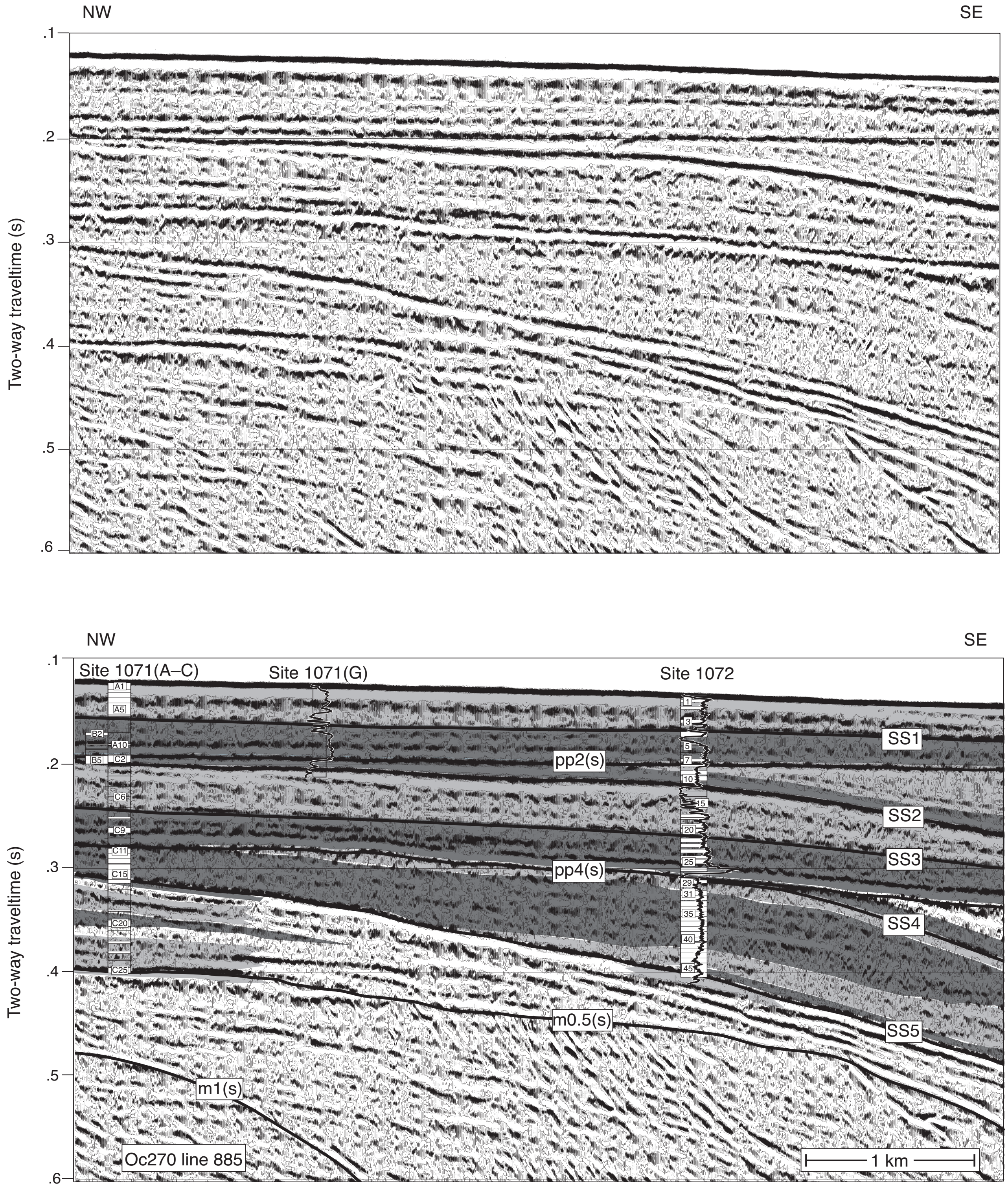

FIG. 2.—Seismic dip section from Oc270 line 885 with seismic and stratal surfaces indicated (after Austin et al., 1998). Surfaces m0.5(s), pp4(s), and pp2(s) are sequence boundaries; intra-sequence reflections are labeled as stratal surfaces SS1(s)–SS5(s). The upper panel shows the uninterpreted seismic line. The lower panel includes seismic and facies interpretations, drillsite locations, and downhole logs. Generalized facies interpretations (based on foraminiferal and lithologic data) compare deep (middle to outer shelf; dark shading) vs. shallow (inner shelf; light shading) to illustrate a simplified relationship between depositional facies and sequence stratigraphy. Core recovery (white boxes) for Sites 1071 and 1072 has been adjusted to concur with log character (see text) and displayed in two-way traveltime based on VSP measurements (see text). LWD gamma-ray logs are shown for Holes 1071G and 1072D.

resulted in a variable sampling resolution (see *Results* for sample frequency within each sequence). Samples from Sites 1071 and 1072 were soaked overnight and then washed with sodium metaphosphate (5.5 g/l) and/or hydrogen peroxide (3% solution) in tap water through a 63 μm sieve and air-dried. All foraminifera were picked from the > 150 μm fraction; foraminifera were rare or absent in the 63 μm to 150 μm fraction. Data on relative species abundance are inadequate for quantitative biofacies analysis because foraminifera were sparse in or absent from some samples. Therefore, we calculate the numbers of planktonic and benthic foraminifera (separately) per gram as approximations of foraminiferal fluxes. Changes in benthic foraminiferal biofacies are described qualitatively. Percent coarse fraction is based on > 63 μm weight vs. total dry sample weight prior to processing. Faunal and lithologic patterns are discernible in spite of poor to moderate core recovery in many sections.

The neritic zone (0–200 m) is split into three standard subzones: inner (0–50 m), middle (50–100 m), and outer (100–200 m). Taxonomic concepts and paleobathymetric estimates are based on multiple references for the Pleistocene (Parker, 1948; Loeblich and Tappan, 1953; Buzas, 1965; Murray, 1969; Gevirtz et al., 1971; Ellison and Nichols, 1976; Cronin, 1979; Poag et al., 1980; Poag, 1981; Vilks et al., 1982; van Morkhoven et al., 1986; Culver and Buzas, 1980; Brunner and Culver, 1992; Matoba and Fukasawa, 1992; Culver and Snedden, 1996; Lagoe et al., 1997) and Miocene sections (Cushman and Cahill, 1933; Schnitker, 1970; Gibson, 1983; van Morkhoven et al., 1986; Olsson et al., 1987; Snyder et al., 1988; Miller et al, 1996) (Table 1).

Paleobathymetry was estimated by integrating benthic foraminiferal biofacies, number of benthic foraminifera per gram, number of planktonic foraminifera per gram, and percent coarse fraction. Integration of these datasets provides paleobathymetric estimates to at least the subzone level. Estimates of fluctuations within a subzone are relative to other samples in that subzone rather than to an absolute water depth. Paleobathymetric reconstructions in paleoshelf settings (such as drilled by Leg 174A) can be hampered by poor core recovery and downhole contamination by coarse sediments. Samples dominated by coarse sediment are often devoid of foraminifera, making it difficult to estimate paleobathymetry. These barren sediments may be downhole contaminants, *in situ* mid-shelf sands, *in situ* extremely shallow-water deposits, or terrigenous sediments. Because we cannot distinguish among these possibilities, samples without foraminifera are plotted at 0 m water depth and connected with dashed lines.

Benthic and planktonic foraminiferal evidence for shallowing-upward and deepening-upward successions provide our primary means of recognizing systems tracts. Each tract is bounded by key surfaces that are defined by seismic character. The transgressive systems tract (TST) is recognized by a deepening-upward succession that is bounded by a transgressive surface (TS) below and a maximum flooding surface (MFS) above (Posamentier et al., 1988). The highstand systems tract (HST) overlies the MFS and shallows upward to the overlying sequence boundary (Posamentier et al., 1988). Thus, we interpret deepening-upward successions as TST and overlying shallowing-upward sections as HST. Sedimentological criteria typically can support water-depth inferences derived from foraminifera; for example, HST sediments coarsen upward in general. Lowstand systems tracts (LST) are more difficult to recognize in Leg 174A shelf boreholes using paleontological criteria alone. By definition, LST sediments should contain transported foraminifera. However, at our relatively shallow-water shelf sites, the potential sources of transported foraminifera in lowstand deposits are also shallow-water environments. Therefore, it can be difficult to differentiate shallow-water *in situ* foraminifera from shallow-water transported foraminifera in the absence of deeper-water indicators. We use stratal relationships to recognize the LST as shallow-water deposits between a sequence boundary and an overlying TS. In general, LSTs should shallow upward as a result of progradation or show relatively constant water depths during aggradation (Posamentier et al., 1988).

Correlations Between Core Data and Seismic Profile

As is typically encountered in ODP operations, fine-grained, clay-dominated sediments at the Leg 174A sites were recovered more readily than were unconsolidated sands and gravels. Total recovery was 40.7% at Holes 1071A–C and 49.5% at 1072A. Few core barrels were completely filled (Austin et al., 1998). The true position of recovered sediment within any 9.5 m range of a cored interval is unknown; by ODP convention, all material is measured from the top of a cored interval, as though the unrecovered sediment is from a single gap at the base of each cored interval.

In this study, we correct these core depths using LWD gamma-ray logs at Site 1072. The gamma-ray tool measures the natural radioactivity of the formation, providing an indication of overall clay content. Assuming that core recovery of finer-grained, clay-rich sediments was better than recovery of unconsolidated, sandier sediments, we adjusted the depths of incompletely recovered sections within each cored interval to correspond to the finer-grained intervals indicated by the gamma-ray logs. Because gamma-ray logs were not generated at Site 1071, core depths at this site remain unadjusted.

A vertical seismic profile (VSP) was conducted at Hole 1072B. This technique provides a reasonably quick and accurate method for matching features measured in depth (such as core-based or log-based data) to features measured in acoustic traveltime (such as reflectors in a seismic profile). It is accomplished by lowering an acoustic receiver into a borehole, remotely clamping it to the borehole wall, and measuring the traveltime of sound pulses generated just below the waterline. This yields depth–time pairs that are precisely accurate at the clamped locations; interpolation at other locations provides additional conversions from depth to time. All holes drilled at Sites 1071 and 1072 were judged to be sufficiently close to each other so that depth–time measurements at Hole 1072B could be applied to each of the other holes (Austin et al., 1998).

Seismic and Age Control

We focus on three surfaces, m0.5(s), pp4(s), and pp2(s), that have been identified as sequence-bounding unconformities on the basis of marked offlap landward of a clinoform inflection point and a hiatus associated with the surface. (The point of maximum inflection in a clinform has been called a rollover, clinoform breakpoint, shelf edge, depositional coastal break, and clinoform inflection point. We use the last term because it is the most descriptive.) Each surface has been correlated to Sites 1071 and 1072 (Austin et al., 1998; Mountain and Monteverde, 2000). We also investigate stratal surfaces named SS1(s) through SS5(s) (Austin et al., 1998) that we interpret as either transgressive surfaces or maximum flooding surfaces (TS or MFS, respectively) (Fig. 2). The designation "(s)" is used to denote seismic and stratal surfaces identified on the New Jersey continental shelf (to avoid confusion with seismic and stratal surfaces defined on the continental slope). Our age–depth interpretations define the sequences overlying m0.5(s), pp4(s), and pp2(s) as primarily Messinian, lower Pleistocene, and middle–upper Pleistocene (Fig. 3).

Shipboard studies (Austin et al., 1998) identified reflector pp3(s) in the vicinity of Sites 1071 and 1072 (Fig. 3). Subsequent study of seismic profiles (Mountain and Monteverde, 2000) indicates that

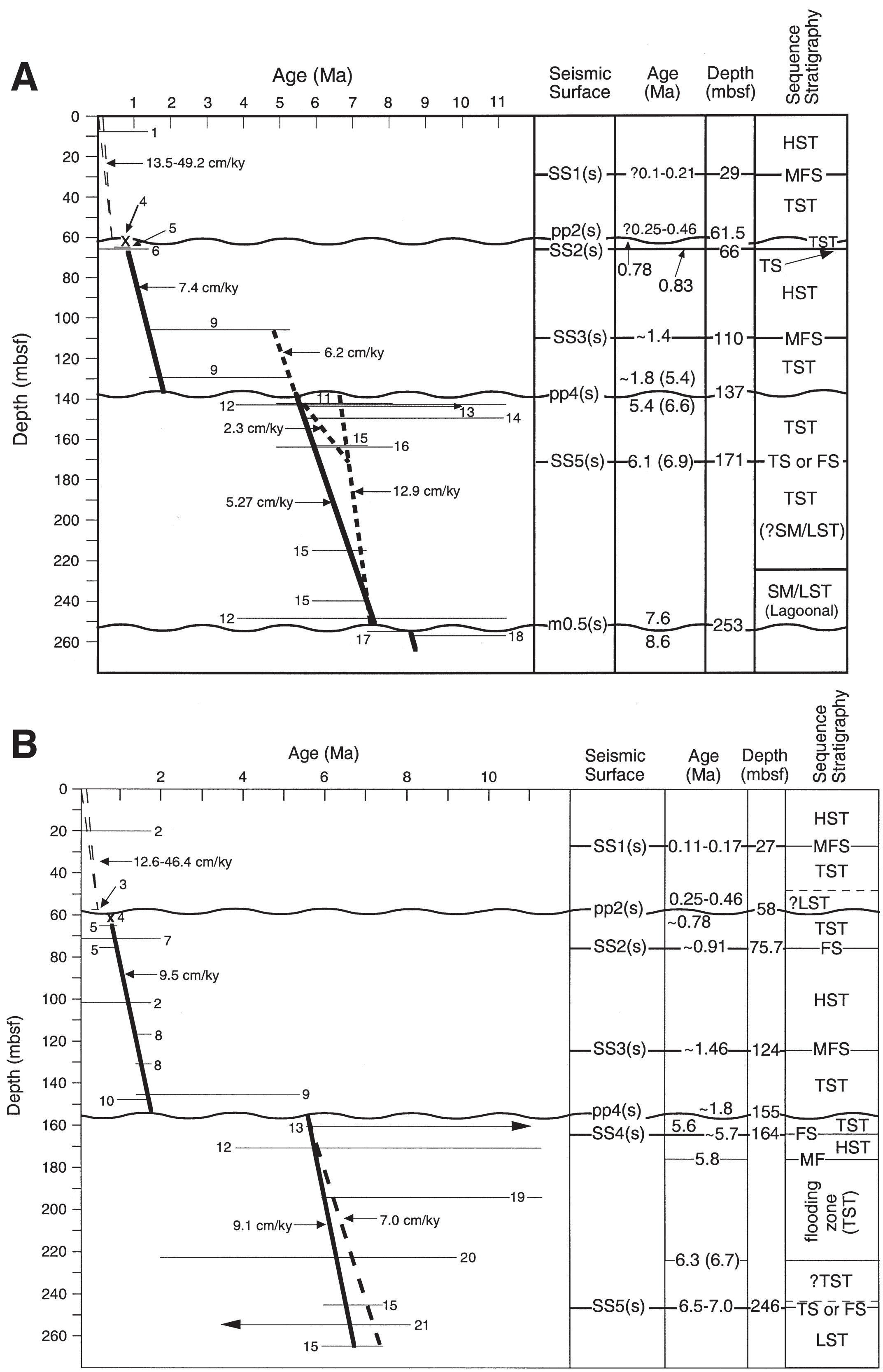

FIG. 3.—Age–depth plots with reinterpreted chronology based on previously published datum levels provided by dinocyst, pollen, nannofossil, and foraminiferal biostratigraphy and magnetostratigraphy (Austin et al., 1998; McCarthy and Gostlin, 2000; McCarthy et al., 2000). **A)** Site 1071 (Holes A–C). **B)** Site 1072 (Hole A). See Table 2 for datums.

TABLE 1.—References and depth ranges of species that provided the basis for the paleobathymetric estimates for the Pleistocene and Miocene sections in this study.

Reference	*Ammonia beccarii*	*Angulogerina angulosa*	*Bolivina striathula*	*Bolivina subaenariensis*	*Buccella frigida*	*Buliminella exilis*	*Bulimina marginata*	*Bulimina* & *Cassidulina*	*Cassidulina laevigata*	*Cassidulina crassa*	*Cassidulina norcrossi*	*Cibicides lobatulus*
Bartlett & Molinsky, 1971				outer shelf			outer shelf					
Brunner & Culver, 1992					shallow neritic						outer neritic	
Buzas, 1965												
Cronin, 1979										30–100 m		
Culver & Buzas, 1980											< 200 m	< 200 m
Culver & Snedden, 1996	inner shelf											middle shelf
Gevirtz et al., 1971		>100 m					80–100 m peak					
Lagoe et al., 1997		70–90 m peak					70–90 m peak		70–90 m peak			
Loeblich & Tappan, 1953					20–135 m	20–65 m					40–50 m	
Matoba & Fukasawa, 1992	0–50 m		0–75 m		50–100 m peak, < 150 m		> 45 m; 70–150 m peak					0–50 m
Parker, 1948		90–680 m		90–680 m			90–680 m		90–300 m peak	90–300 m peak	90–680 m	
Poag, 1981												
Poag et al., 1980								60–180 m				
Schnitker, 1970					inner shelf							
Vilks et al., 1982												

Reference	*Cibicides* spp.	*Elphidium advenum*	*Elphidium excavatum*	*E. excavatum clavatum*	*Elphidium subarcticum*	*Elphidium* spp.	*Fursenkoina fusiformis*	*Globobulimina auriculata*	*Hanzawaia concentrica*	*Hanzawaia strattoni*	*Hanzawaia nipponica*	*Islandiella teretis*	*Oridorsalis* spp.
Bartlett & Molinsky, 1971													
Brunner & Culver, 1992	middle to outer neritic		inner to middle neritic							middle to outer neritic			
Buzas, 1965				90% ——> < 15 m									
Cronin, 1979												30–100 m	
Culver & Buzas, 1980							< 200 m	< 200 m	< 200 m				
Culver & Snedden, 1996		inner shelf	marginal marine							middle shelf			
Gevirtz et al., 1971						0–20 m peak							
Lagoe et al., 1997			30–40 m peak			< 90 m	30–40 m peak						
Loeblich & Tappan, 1953					> 35 m			> 35 m				> 20 m	
Matoba & Fukasawa, 1992				0–120 m peak, < 200 m							0–50 m		
Parker, 1948						0–15 m							90–300 m
Poag, 1981													
Poag et al., 1980	60–100 m			0–45 m		0–60 m							
Schnitker, 1970				90% ——> <15 m	inner shelf								
Vilks et al., 1982				30–100 m								inner shelf	

TABLE 1 (continued).—References and depth ranges of species that provided the basis for the paleobathymetric estimates for the Pleistocene and Miocene sections in this study.

Reference	*Lenticulina americana*	*Nonionella atlantica*	*Nonionella labradoricum*	*Nonionella pulchella*	*Nonionella stella*	*Nonionella turgida*	*Nonionella* spp.	*Quinqueloculina seminulum*	*Quinqueloculina stalkeri*	*Quinqueloculina* spp.	*Sphaeroidina bulloides*	*Stainforthia complanata*	*Textularia* spp.
Bartlett & Molinsky, 1971												outer shelf	
Brunner & Culver, 1992							shallow neritic						
Buzas, 1965													
Cronin, 1979													
Culver & Buzas, 1980								< 200 m					
Culver & Snedden, 1996		middle shelf											
Gevirtz et al., 1971													
Lagoe et al., 1997										0–40 m			
Loeblich & Tappan, 1953			> 20 m						< 50 m				
Matoba & Fukasawa, 1992				0–80 m peak, < 150m	30–150 m peak, < 200 m			0–65 m			> 140 m		0–100 m peak
Parker, 1948	90–300 m					90–300 m		0–90 m				90–300 m	
Poag, 1981													
Poag et al., 1980													
Schnitker, 1970													
Vilks et al., 1982													

Reference	*Triloculina tricarinata*	*Triloculina trigonula*	*Valvulineria laevigata*	planktonics	*Ammonia beccarii*	*Ammonia & Elphidium*	*Asterigerina* spp.	*Rosalina* spp.	*Hanzawaia* spp.	*Planulina* spp.	*Cibicidoides* spp.
Bartlett & Molinsky, 1971											
Brunner & Culver, 1992											
Buzas, 1965											
Cronin, 1979											
Culver & Buzas, 1980	< 200 m										
Culver & Snedden, 1996											
Gevirtz et al., 1971											
Lagoe et al., 1997				> 65 m							
Loeblich & Tappan, 1953	< 43 m										
Matoba & Fukasawa, 1992		0–50 m									
Parker, 1948	145–680 m		300–680 m								
Poag, 1981					nearshore, saline	nearshore	middle shelf	middle shelf	outer shelf	outer shelf	shelf edge
Poag et al., 1980											
Schnitker, 1970				> 20 m							
Vilks et al., 1982											

pp3(s) is truncated by an overlying sequence boundary 8 km southeast of Site 1072, and that the surface identified at Sites 1071 and 1072 as pp3(s) by shipboard investigators in actually an amalgamation of pp3(s) and overlying pp2(s). Thus, the sequence dated here is actually pp2(s), following the convention that the base of the sequence defines the name of the overlying stratigraphic unit. Mountain and Monteverde (2000) also identified a thin (~ 5–10 m thick) uppermost sequence pp1(s)-seafloor that corresponds to the "outer shelf wedge" above reflector "R" mapped by Milliman et al. (1990). Seismic correlations tie these shelf sites to Site 1073 on the adjacent slope, where it has been demonstrated that the pp1(s) surface is no younger than marine oxygen isotope stage (MIS) 5 (McHugh and Olson, 1999; Mountain and Monteverde, 2000). Furthermore, these same data indicate that strata between MIS 3 and 5 are exposed on the seafloor at Sites 1071 and 1072, although there may be a veneer (< 5 m) of Holocene strata that are too thin to resolve with Oc270 MCS data. We cannot differentiate between Holocene and MIS 5 sediments with the data available.

Previous studies of seismic profiles have not interpreted SS5(s) as a sequence boundary, for several reasons (Austin et al., 1998; Metzger et al., 2000). Seismic character changes across SS5(s) from laterally persistent high-amplitude reflections below to a comparatively featureless unit above, where subhorizontal pegleg multiples tend to obscure the true stratal geometry (for

TABLE 2—Datums used in age-depth plots (Fig. 3). Datums were provided by Austin et al. (1998), McCarthy and Gostlin (2000), and McCarthy et al. (2000).

Site 1071 depth (mbsf)	Site 1072 depth (mbsf)	key #	age (Ma}	fossil group	datum
7.83		1	< 1.4	pollen/dinoflagellates	see IR (p. 63) for assemblages
	19.6	2	< 1.77	dinoflagellates	see IR (p. 118–119) for assemblages
	101.96	2	< 1.77	dinoflagellates	see IR (p. 118–119) for assemblages
	57.79	3	.25–.46	nannofossils	absence of *P. huxleyi* & presence of *G. parallela*
62.30	62.3	4	0.78	paleomagnetics	Brunhes/Matyama
65.69	65, 75.2	5	.46–.9	nannofossils	co-occurrence of *G. parallela* & *P. lacunosa*
65.69		6	< 1.4	pollen/dinoflagellates	see IR (p. 63) for assemblages
	71.12	7	< 2.0	planktonic foraminifera	occurrence of *G. truncatulinoides*
	116.8	8	1.4–2.0	dinoflagellates	see IR (p. 118–119) for assemblages
	130.8	8	1.4–2.0	dinoflagellates	see IR (p. 118–119) for assemblages
105.97	145.36	9	1.4–5.3	pollen/dinoflagellates	see IR (p. 63) for assemblages
129.15		9	1.4–5.3	pollen/dinoflagellates	see IR (p. 63) for assemblages
	147.65	10	.9–1.7	nannofossils	co-occurrence of *G. caribbeanica* & *P. lacunosa*
143.69		11	4.9–8.1	planktonic foraminifera	presence of *G. juanai*
143.70	170.59	12	3.8–11.2	nannofossils	*C. floridanus* absent; *R. pseudoumbilicus* & *Sphenolithus* spp. present
143.69	163.17	13		benthic foraminifera	Miocene; see IR (p. 63, 118) for assemblages
149.45		14	5.3–11.2	dinoflagellates	see IR (p. 63) for assemblages
163.11	244.4	15	5.9–7.4	dinoflagellates	Zone DN10
	263.78	15	5.9–7.4	dinoflagellates	Zone DN10
163.11		16	4.9–8.1	planktonic foraminifera	presence of *G. juanai*
214.90		15	5.9–7.4	dinoflagellates	Zone DN10
239.77		15	5.9–7.4	dinoflagellates	Zone DN10
248.00		12	3.8–11.2	nannofossils	*C. floridanus* absent; *R. pseudoumbilicus* & *Sphenolithus* spp. present
254.74		17	7.4–8.6	dinoflagellates	Zone DN9
256.36		18	8.6–11.2	dinoflagellates	Zone DN8
	193.99	19	5.9–11.2	dinoflagellates	Zone DN8–10
	222.48	20	< 9.2	planktonic foraminifera	occurrence of *N. pachyderma*
	254.65	21	< 8.1	planktonic foraminifera	occurrence of *C. nitida*

detailed discussion, see Austin et al., 1998; Metzger et al., 2000). Intersecting seismic features above SS5(s) cannot both be real, which means that some apparent onlap is not true onlap (N. Christie-Blick, personal communication). Furthermore, there is no offlap associated with SS5(s). Therefore, SS5(s) is not a sequence boundary (Austin et al., 1998; Metzger et al., 2000).

A sequence boundary corresponds to a single physical surface that separates two sequences, accompanied by evidence of base-level lowering across the boundary. This physical surface is actually two merged surfaces with an associated time gap, or hiatus (Aubry, 1991). The upper surface is associated with the lower limit of the overlying sequence, and the lower surface is associated with the upper limit of the underlying sequence. The duration of the hiatus is determined by dating the sediments both overlying and underlying the physical surface of the sequence boundary (Aubry, 1991). Thus, age control at Sites 1071 and 1072 is provided by dating the sediments immediately overlying and underlying the seismic and stratal surfaces. We use previously published datum levels provided by dinocyst, pollen, nannofossil, and foraminiferal biostratigraphy and magnetostratigraphy (Austin et al., 1998; McCarthy and Gostlin, 2000; McCarthy et al., 2000) to reevaluate the age–depth relationships, interpolate sedimentation rates, and estimate ages of seismic and stratal surfaces (Fig. 3; Table 2).

The age of the sediments immediately overlying sequence boundary pp2(s) at Site 1072 is constrained to younger than 0.25–0.46 Ma (Fig. 3A), on the basis of the absence of *Emiliani huxleyi* (first occurrence in MIS 8; 0.25 Ma), the absence of *Pseudoemiliani lacunosa* (last occurrence in MIS 12; 0.46 Ma), and the presence of *Gephyrocapsa parallela* (Austin et al., 1998). There is no age control on the corresponding sediments at Site 1071; nonetheless, there is no apparent truncation of seismic reflections against pp2(s) between Sites 1071 and 1072 (Fig. 2), indicating that < 0.25–0.46 Ma is a reasonable maximum age estimate for the sediments overlying pp2(s) at both sites (Fig. 3). A sample examined from Site 1071 (0.15 meters below sea floor; mbsf) yielded ?Holocene/MIS 5e benthic foraminifera (see below). Therefore, the age of the sequence overlying pp2(s) is 0.0–0.125 to 0.25–0.46 Ma (middle to late Pleistocene; Fig. 3). Based on sedimentation rates, we estimate the age of SS1(s) as ~ 0.1–0.2 Ma at both sites (Fig. 3).

There may be several concatenated sequences above the pp2(s) surface. $\delta^{18}O$ records (Imbrie et al., 1984) show that at least four large sea-level lowerings (~ 100 m) occurred during the middle Pleistocene (MIS 2/3, 6/7, 8/9, and 10/11). On the New Jersey continental slope, the pp2–pp1 sequence has been dated as post–MIS 9 and pre–MIS 5 at Site 1073 (~ 300–240 ka) and is probably entirely within MIS 8 (McHugh and Olson, 1999). Therefore, the pp2(s) sequence boundary may correlate with the MIS 8/9 glacioeustatic lowering. However, poor to moderate core recovery make it impossible to demonstrate this on the basis of age or stratal stacking patterns. Although there are several prominent reflections above the pp2(s) surface seaward of Sites 1071 and 1072, they lack the defining criteria of seismic sequence boundaries and they merge downslope from the shelf sites (Mountain and Monteverde, 2000). Thus, we identify pp2(s)–seafloor as the sole middle–upper Pleistocene sequence on the basis of our data.

The Brunhes–Matuyama boundary (62.3 mbsf; ~ 0.78 Ma) lies below pp2(s) (58 mbsf) at Site 1072 (Fig. 3B). At Site 1071, the Brunhes–Matuyama datum was placed at 61.5 mbsf, whereas pp2(s) was placed at 62 mbsf (Austin et al., 1998). However, a 0.5 m difference between a core datum depth and a seismic surface is not resolvable in seismic–borehole correlations. To maintain consistency between Sites 1071 and 1072, we suggest that pp2(s) actually lies above the Brunhes–Matuyama datum, at or shallower than 61.5 mbsf. Accordingly, the sediments that immediately underlie sequence boundary pp2(s) are estimated as ~ 0.78 Ma at both Sites 1071 and 1072.

At Site 1072, the age of the sediments that immediately overlie sequence boundary pp4(s) is well constrained to ~ 1.8 Ma, on the basis of our sedimentation-rate interpretation (Fig. 3B). Our best estimate of the corresponding sedimentation rate at Site 1071 also yields ~ 1.8 Ma for the sediments that immediately overlie pp4(s), although it cannot be ruled out conclusively that these sediments are older (< 5.4 Ma). Therefore, our best age estimate of the pp4(s)–pp2(s) sequence is 1.8–0.78 Ma (lower Pleistocene; Fig. 3). Again, given our core and seismic resolution, it is possible that there are several concatenated sequences within the lower Pleistocene pp4(s)–pp2(s) sequence.

Two stratal surfaces occur within the pp4(s)–pp2(s) sequence (Fig. 2). On the basis of sedimentation rates, we estimate the age of SS2(s) as 0.83 Ma (66 mbsf) at Site 1071 and 0.91 Ma (66 mbsf) at Site 1072 (Fig. 3). Similarly, we estimate the age of SS3(s) as ~ 1.4 Ma at both sites.

At both Sites 1071 and 1072, the age of the sediments immediately underlying pp4(s) is older than ~ 5.5 Ma (Fig. 3). This sequence overlies the m0.5(s) surface; we estimate that the basal sediments are ~ 7.6 Ma on the basis of sedimentation rates extrapolated from biostratigraphic datum levels at Hole 1071C (Fig. 3A, Table 2). The sediments underlying m0.5(s) at Hole 1071C are dated at ~ 8.6 Ma on the basis of sedimentation rates determined from tightly constrained dinoflagellate datum levels. This is consistent with a previous estimate of ca. 8 Ma for m0.5 from Leg 150 drilling (Mountain et al., 1994). Thus, we adopt an age for the m0.5(s)–pp4(s) sequence that is largely Messinian. Within the m0.5(s)–pp4(s) sequence, SS5(s) may be coeval or even slightly diachronous (6.1–6.9 Ma at Site 1071; 6.5–7.0 Ma at Site 1072) (Fig. 3). Within this sequence, we estimate that the age of SS4(s) (164 mbsf) at Site 1072 is ~ 5.7 Ma (Fig. 3B).

RESULTS

Site 1071

m0.5(s)–pp4(s) Sequence.—

The sampling interval in this sequence is ~ 53 ky. Lowstand and transgressive deposits at Site 1071 are recognized on the basis of integrated biofacies and lithofacies in the Miocene sequence bounded below by m0.5(s) and above by pp4(s); highstand deposits are probably truncated (Fig. 4). Core recovery was poor below SS5(s) (~ 170 mbsf) (Fig. 4), and no downhole log data were acquired below 88 mbsf at this site. Samples below ~ 225 mbsf are characterized by coarse-grained sediments that lack foraminifera, indicating very shallow water depths; this section is interpreted as a lowstand deposit. This is supported by lagoonal sediments that overlie sequence boundary m0.5 (Austin et al., 1998).

Above this lowstand deposit, two thin intervals (~ 175.08 mbsf and 209.80–214.30 mbsf) yield sparse planktonic foraminifera and benthic foraminiferal biofacies characterized by *Cibicidoides*, *Lenticulina*, *Nonionella*, *Uvigerina*, and *Bolivina;* these biofacies indicate middle neritic environments (50–100 m). We tentatively interpret the section from ~ 175–215 mbsf as TST and SS5(s) as a FS, with the absence of foraminifera from ~ 180–210 msbf reflecting variability in shelf sedimentation. Alternatively, the entire section below SS5(s) may be part of the lowstand system tracts (LST), in which case SS5(s) would be a TS.

Deeper-water biofacies and planktonic foraminiferal abundances indicate that the water depth increases immediately above SS5(s) (Fig. 4). Planktonic foraminiferal abundances increase again immediately below pp4(s). Benthic foraminifera indicate depths within the middle neritic zone (50–100 m), with the intervening section (~ 154–160 mbsf) at lower inner neritic depths (~ 30–50 m) (Fig. 4). We identify the interval between SS5(s) and pp4(s) as a TST with no evidence for regressive sediments of a HST. Sequence boundary pp4(s) represents a gap of ~ 3.6 My; it cannot be determined how much of the m0.5(s) sequence may have been removed by erosion. On the basis of this interpretation of the interval between SS5(s) and pp4(s), we suggest that the MFS merged with the overlying sequence boundary.

pp4(s)–pp2(s) Sequence.—

Core recovery was extremely poor at Site 1071 in the lower Pleistocene sequence bounded below by pp4(s) and above by pp2(s), with a sampling interval of ~ 170 ky. Nonetheless, faunal and lithologic patterns are clearly discernible (Fig. 4) and transgressive deposits, MFS, and regressive HST deposits are recognized. Benthic foraminiferal biofacies (dominated by *Cibicidoides*, *Elphidium*, *Siphonina*, and *Uvigerina*) indicate greatest water depths (outer neritic; 100–150 m) at ~ 125 msbf, comprising the TST. Declining *Cibicidoides, Siphonina,* and *Cassidulina* abundances coupled with increasing *Elphidium* abundances immediately below SS3(s) indicate a shallowing from the outer neritic zone to the middle neritic zone, with shallowing continuing to inner neritic depths above SS3(s) (Fig. 4). This indicates either that SS3(s) is not a MFS or that its traveltime-to-depth calculation is incorrect and should be ~ 5 m lower, below the level where the water depth shallows. If SS3(s) is moved down to ~ 115 mbsf in this manner at Site 1071 (which is within the uncertainties in the VSP technique), then the facies patterns indicate that it is a MFS. This would be consistent with Site 1072, where SS3(s) is a MFS (see below; Fig. 5).

Above SS3(s), samples are nearly devoid of foraminifera, indicating very shallow water depths and deposition in the regressive HST (Fig. 4). SS2(s) occurs near the top of the pp4(s)–pp2(s) sequence; planktonic and benthic foraminiferal abundances increase and indicate a deepening associated with this surface, identifying it as a flooding surface. LWD gamma-ray data were collected (with no coring) to 88 mbsf at Hole 1071G; the continuity of strata imaged in the seismic data allow this LWD data to be compared with core data from Holes 1071A–C, ~ 1 km west of Hole 1071G. LWD data indicate a slight fining upward across SS2, consistent with the water-depth increase indicated by the biofacies (Figs. 2, 4). The logs indicate a return to coarser sediments just below the pp2(s) surface, although there is no corresponding water-depth shallowing indicated by the biofacies.

pp2(s)–Seafloor Sequence.—

The sampling interval in this sequence is ~ 18–32 ky. Biofacies indicate a middle neritic water depth (50–100 m) at the base of the

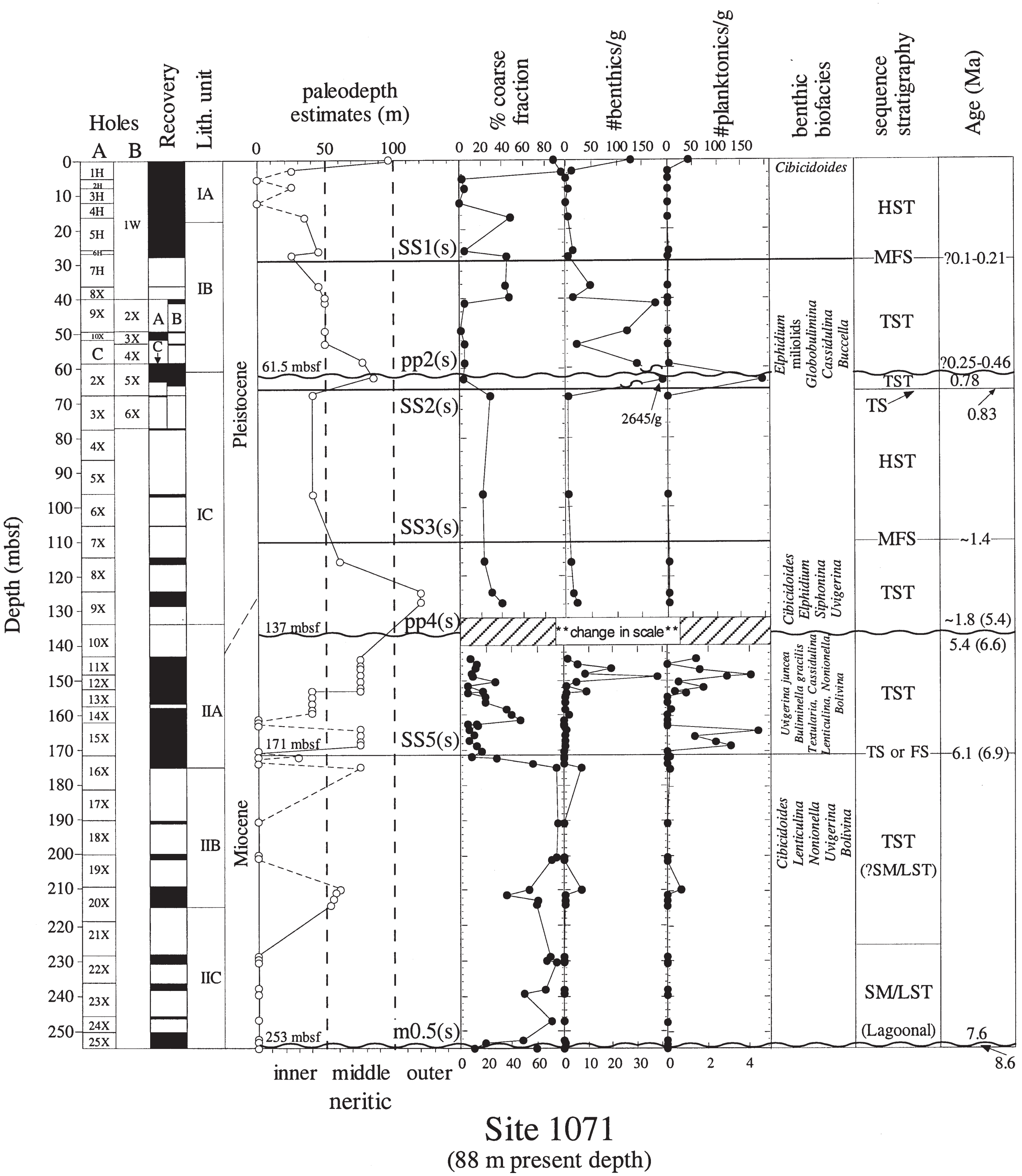

FIG. 4.—Site 1071 data (percent coarse fraction, numbers of planktonic and benthic foraminifera per gram, and benthic foraminiferal biofacies changes), paleobathymetric estimates, and sequence stratigraphic interpretations. Samples devoid of foraminifera with uncertain paleobathymetric estimates are connected with dashed lines. Note changes in scale at ~ 65 and 135 mbsf. Seismic and stratal surfaces are indicated (after Austin et al., 1998), as are boundary ages (see text).

youngest sequence bounded below by pp2(s), with a shallowing upsection to about 50 m paleodepth below SS1(s) (Fig. 4). There is an abrupt upward increase in LWD values across the pp2(s) surface, although the biofacies indicate middle neritic water depths (50–100 m) both immediately above and below pp2(s) (Fig. 2) (see the corresponding sequence at Site 1072 for comparison).

Paleowater depths decrease above SS1(s) to 30–50 m (based on fluctuating abundances of *Elphidium*, miliolids, *Globobulimina*, *Cassidulina*, and *Buccella*). A gap in core recovery immediately below SS1(s) precludes paleodepth interpretations based on biofacies; LWD values fluctuate here, indicating that water depths may have been variable in this section. The TST at this site is overlain by HST regressive deposits, and SS1(s) is interpreted as the MFS separating the TST from HST (analogous to the coeval section at Site 1072; see below). Alternatively, this sequence may record a very thin TST overlain by thick regressive HST, with the LST and most of the TST not represented (Fig. 4). Moderately high LWD gamma-ray values immediately above the pp2(s) surface indicate the presence of fine-grained sediments, which is consistent with the paleodepth estimates.

Holocene or MIS 5e.—

The uppermost sample examined (0.15 mbsf) is dominated almost exclusively by *Cibicidoides* with planktonic foraminifera, indicating a paleodepth in the deepest part of the middle neritic zone (~ 90–100 m). This is consistent with the present water depth at this site (88 m) (Fig. 4). This, together with the presence of *Globorotalia menardii* at 0.15 mbsf indicating interglacial conditions (Fig. 4), suggests a Holocene age, though it does not rule out isotope stage 5. Roughly 5 m of sand constitutes the uppermost lithologic unit at this site, as indicated by low gamma-ray log values and the sandy lithology of Core 1071A-1H (Austin et al., 1998). Available seismic data cannot distinguish this sand unit, but studies from elsewhere on the middle and outer shelf report that sands dominate the first 5 to 10 m below seafloor (Knebel and Spiker, 1977; Milliman et al., 1990; Duncan et al., 2000). We conclude that these sands are interglacial MIS 5e or 1 (Holocene) (see "Seismic and Age Control" above).

Site 1072

m0.5(s)–pp4(s) Sequence.—

Drilling and LWD measurements at Site 1072 extended to 355.9 mbsf, but very little core was recovered below SS5(s) at 255 mbsf. The sampling interval in this sequence is ~ 17–21 ky. LWD gamma-ray log data indicates that coarse-grained sediments dominate the interval below SS5(s) (Figs. 2, 5). Core samples from below SS5(s) are coarse-grained and devoid of foraminifera, indicating shallow-water deposition. Biofacies and finer-grained sediments immediately overlying SS5(s) indicate that sediments were deposited in the middle neritic zone (50–100 m), with faunas dominated by *Uvigerina juncea* and *Buliminella gracilis*. Gamma-ray log character indicates an upsection increase in clay content at this surface, consistent with this paleodepth increase (Fig. 5). These water-depth variations indicate that SS5(s) is a TS or FS, as it is at Site 1071.

The overlying sandy unit (242.24 to 225.43 mbsf) is virtually barren of foraminifera and was deposited in a very shallow-water environment (Fig. 5). Above this, ~ 50 m of deeper-water sediment yields common planktonic foraminifera; water depths fluctuated within the middle neritic zone (50–100 m), indicated by varying abundances of *Uvigerina juncea*, *Buliminella gracilis*, *Textularia*, *Cassidulina*, *Cibicidoides*, and *Nonionella*, punctuated by barren samples (Fig. 5; Table 1). Gamma-ray log data show a subtle and parallel trend; moderate values between 240 and 225 mbsf increase to uniformly higher (more clay-rich) values between 225 and 170 mbsf (Fig. 5). The sequence stratigraphic interpretation of this water-depth variation is enigmatic, going from deep (immediately above the SS5(s) surface) to shallow (sandy section) and back to deep again (Fig. 5). We tentatively interpret SS5(s) as a flooding surface (as it is at Site 1071) related to parasequence deposition, with the zone of maximum flooding associated with the section from 177.04–222.45 mbsf. The maximum flooding interval (Fig. 5) does not yield a diagnostic seismic signature such as downlapping or prograding geometries. This flooding reflects a time when the rate of subsidence exceeded the rate of sediment supply and available accommodation space was large.

A shallowing occurs (174.80–163.22 msbf) near the upper part of the m0.5(s)–pp4(s) sequence, where foraminifera disappear (Fig. 5) and gamma-ray log values decrease. We interpret this as a thin HST. An increase in planktonic foraminiferal abundances and benthic foraminiferal biofacies (160.96–162.54) dominated by *Buliminella gracilis*, *Cassidulina*, and *Textularia* indicate a deepening associated with SS4(s) at the very top of this sequence, consistent with an increase in gamma-ray log values (Fig. 5). Therefore, SS4(s) is a flooding surface and the SS4(s)–pp4(s) section is a thin parasequence.

pp4(s)–pp2(s) Sequence.—

The sampling interval in this sequence is ~ 4 ky. The lower Pleistocene sequence at Site 1072 bounded below by pp4(s) and above by pp2(s) yields common planktonic foraminifera and benthic foraminiferal faunas below SS3 (~ 123 mbsf) (Fig. 5). Biofacies are characterized by *Cibicidoides*, *Cassidulina*, *Elphidium*, *Hanzawaia*, *Gyroidinoides*, and *Uvigerina*, indicating that sediments were deposited in the outer-neritic zone (100–200 m). Above SS3(s), an abrupt shallowing to the inner-neritic zone (0–50 m) is indicated by a sharp decrease in planktonic foraminiferal abundances and scattered benthic foraminiferal occurrences. Gamma-ray log data do not show a corresponding upsection increase in grain size; rather, gamma-ray log values decrease at ~ 100 mbsf, consistent with an increase in coarse-fraction sediments (Fig. 5). The poor core recovery for ~ 15 m below SS2 is further indication of sand-dominated sediments. This pattern indicates that a thick TST (147.04–124.44 mbsf) is overlain by a thick HST (122.91–84.73 mbsf), separated by the MFS SS3(s).

Water depth increased to the middle-neritic zone (50–100 m) above SS2(s) (~ 76 mbsf), with increased planktonic foraminiferal abundances and biofacies dominated by *Elphidium*, miliolids, and *Cassidulina* (71.20–66.44 mbsf), improved core recovery, and gamma-ray log values consistent with a return to more clay-rich sediments. Decreased foraminiferal abundances in overlying sediments indicate a shallowing (Fig. 5). Thus, SS2(s) represents a flooding surface within the sequence (although not the MFS), showing that SS2(s)–pp2(s) is a parasequence.

pp2(s)–Seafloor Sequence.—

The sampling interval in this sequence is ~ 25–46 ky. Biofacies indicate that sediments immediately above pp2(s) were deposited in inner-neritic environments (0–50 m) (Fig. 5). The middle part of the sequence (~ 40–30 mbsf) was deposited in middle-neritic water depths (50–100 m), with a return to inner-neritic settings in the rest of the cored interval up to the seafloor (Fig. 5). A thin portion of the LST may be preserved at the base of this sequence, where paleodepths are shallowest (~ 52–57 mbsf). However, no LST

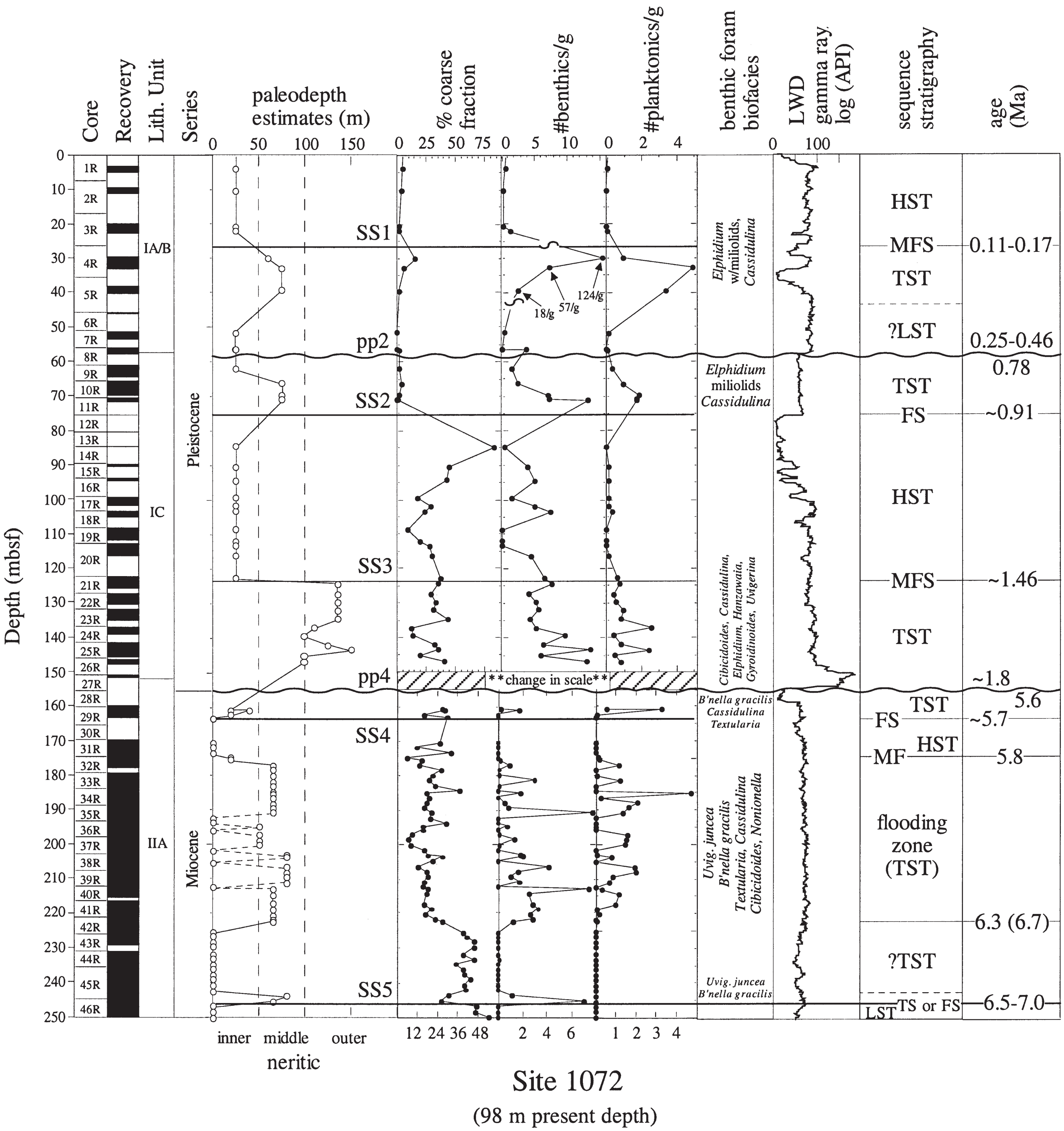

FIG. 5.—Site 1072 data (percent coarse fraction, numbers of planktonic and benthic foraminifera per gram, and benthic foraminiferal biofacies changes), downhole LWD gamma-ray log (Hole 1072D), paleobathymetric estimates, and sequence stratigraphic interpretations. Samples devoid of foraminifera with uncertain paleobathymetric estimates are connected with dashed lines. Note changes in scale at ~ 30 and 155 mbsf. Seismic and stratal surfaces are indicated (after Austin et al., 1998), as are boundary ages (see text). Sediment recovery depths have been adjusted on the basis of log character (see text).

sediments were preserved in the corresponding section at the shallower Site 1071, indicating that this may be the base of the fining-upward succession of the TST. LWD gamma-ray values at the base of the pp2(s)–seafloor sequence are moderately high, similar to Hole 1071G (Figs. 2, 5). These values decrease upsection below SS1(s), indicating an increase in grain size. The variations in log value at this depth (~ 45–35 mbsf) are suspect because of hole conditions (Austin et al., 1998); nonetheless, similar variations were observed at Hole 1071G and may be real. As at 1071G, LWD data indicate that there are several meters of coarse-grained sediment immediately beneath the seafloor.

DISCUSSION

We use core-log integration (see *Methods*) to superimpose cores, logs, and paleobathymetry (based on biofacies and lithofacies) directly on a seismic dip line (Fig. 2). The paleobathymetric interpretations are generalized by comparing deep (middle to outer shelf) vs. shallow (inner shelf) biofacies/lithofacies to develop a simple model of the relationship between depositional facies and sequence stratigraphy.

Shallow-water facies indicate that the lowermost portion of the Miocene sequence bounded below by m0.5(s) and above by pp4(s) at Site 1071 (~ 5.4–7.6 Ma) contains shelf-margin or lowstand deposits (*sensu* Posamentier et al., 1988). These deposits are perched on the paleoshelf immediately landward of the clinoform inflection point of the m0.5(s) sequence boundary (Fig. 2) and thus do not constitute classic LST deposits (Posamentier et al., 1988). Rather, this conforms to the shelf-margin systems tract (SMST) model, which predicts that sediments are regressive/progradational in the lower part and increasingly aggradational in the upper part of the SMST (Posamentier et al., 1988). The percent coarse fraction at Site 1071 shows a rapid coarsening-upward (progradational) pattern (~ 254.85–247.30 mbsf) and a thick interval of uniformly (aggradational) coarse material (247.30–228.69 mbsf) (Figs. 2, 5), consistent with SMST deposition. This is supported by previous studies showing that lowstand water depths on Miocene outermost paleoshelves were near 0 m but that the shelf edge was not exposed. Rivers discharged sediments directly to the outermost shelf and upper continental slope at these times, with substantial variability in depocenter location (Fulthorpe and Austin, 1998; Fulthorpe et al., 1999). Extremely shallow water depths combined with varying depositional loci may account for the thick shelf-margin deposits at Site 1071, in contrast to the corresponding section at Site 1072 (Fig. 2).

Deeper-water deposits occur immediately above the SS5(s) surface at both Sites 1071 (~ 6.1 Ma; possibly as old as 6.9 Ma) and 1072 (6.5–7.0 Ma) (Fig. 2). SS5(s) is a transgressive or flooding surface and may be diachronous. At Site 1072, a thick section above SS5(s) (177.04–222.45 mbsf; ~ 5.8–6.3 Ma; Fig. 3B) is a zone of maximum flooding. A truncated thick section of deep-water sediments occurs above SS5(s) at Site 1071 (143.5–171.0 mbsf; ~ 5.4–6.1 Ma), similar to coeval deposits at Site 1072. This relatively thick section of deep-water sediments at both sites reflects a time when accommodation space was high because sediment supply was low and/or global sea level was high; there is no evidence for accelerated tectonic subsidence on the New Jersey margin at this time that could have caused this apparent deepening (e.g., Steckler and Watts, 1978). We favor a eustatic rise because the time between SS5(s) (~ 6.1–7.0 Ma) and the overlying maximum flooding zone (~ 5.4–6.1 and ~ 5.8–6.3 Ma at Sites 1071 and 1072, respectively) correlates with a large glacioeustatic rise inferred from a major $\delta^{18}O$ decrease (Wright, 2001). The $\delta^{18}O$ decrease is too large to be attributed solely to deep-water warming; there must be a eustatic component as well.

An upsection shallowing at Site 1072 below SS4(s) (~ 5.7 Ma) can be traced landward almost to Site 1071 (Fig. 2). Above this, the uppermost portion of this sequence at Site 1072 shows a deepening and indicates that SS4(s) is most likely a flooding surface associated with parasequence deposition. This flooding surface is truncated between Sites 1072 and 1071 (Fig. 2).

The Pleistocene sequence bounded below by pp4(s) and above by pp2(s) (~ 0.78–1.8 Ma) has relatively deep-water deposits in the lower part of the sequence below SS3(s) (~ 1.4 Ma) at both sites (Figs. 5, 6). Facies shoal above this, indicating that SS3(s) is a MFS. Subtle downlap onto SS3(s) (Fig. 2) is consistent with its being a MFS and downlap surface. Sediments overlying SS2(s) at both sites indicate a deepening and identify this as a flooding surface associated with parasequence deposition. SS2(s) is dated at 0.83–0.91 Ma and may correlate to MIS 23 (~ 0.9 Ma), a time of high global sea level. Facies shallow again at the top of the pp4(s)–pp2(s) sequence. Gamma-ray log measurements reach very low values immediately below pp2(s), indicating very sand-rich facies that is associated with very low core recovery. Shelf-margin or lowstand deposits are absent from the pp4(s)–pp2(s) sequence (Fig. 2).

The lower half of the youngest sequence (bounded below by pp2(s)) is dominated by relatively deep-water sediments at both sites. A thin portion of the LST may be preserved at the base of this sequence at Site 1072 (~ 50–62 mbsf; Fig. 5). However, LST sediments are absent from the corresponding section at the shallower Site 1071, despite the similar clay-rich implications of the gamma-ray log data at both sites. Therefore, it is probable that the shallower material at Site 1072 is the base of the fining-upward succession of the TST, with little to no shelf-margin or lowstand deposits preserved in this sequence (Fig. 2). Deep-water deposits extend up to SS1(s), identifying this surface as a MFS. Similarly to trends across SS3(s) in the underlying pp4(s)-pp2(s) sequence, paleodepths shallow across the mid-sequence stratal surface SS1(s) in the upper Pleistocene. SS1(s) (~ 0.1–0.2 Ma) correlates to MIS 5e (0.125 Ma) if the seafloor is Holocene; alternatively, SS1(s) correlates to MIS 7 if the seafloor is MIS 5e (see *Seismic and Age Control*, above).

The Pleistocene sequence stratigraphy sampled by Leg 174A on the New Jersey shelf differs from other studies. Starting at the base of the section, the sequence stratigraphic architecture of the upper Pleistocene Lagniappe delta complex (Mississippi Delta region) consists of highstand, falling-stage, maximum lowstand–early rise, and transgressive deposits (Kolla et al., 2000). The HST is not well developed. The falling-stage and lowstand to early-rise deposits comprise the bulk of the Lagniappe delta complex (Kolla et al., 2000). In contrast, the New Jersey shelf Pleistocene sequences are dominated by transgressive and highstand deposits. The contrast between the sediment-laden Mississippi Delta region and the New Jersey margin emphasizes that sediment supply can be the dominant control on development of systems tracts even during the extremely large (120 m) eustatic variations of the middle–late Pleistocene.

Accordingly, higher-order (Milankovitch-scale; ~ 100 ky, 41 ky, and 23/19 ky) Pleistocene sea-level fluctuations are not well expressed on the sediment-starved, slowly subsiding New Jersey passive margin. Instead, only fragments of these Pleistocene sea-level cycles are preserved, and are concatenated into the longer-term middle–upper Pleistocene pp2(s)–seafloor sequence and the lower Pleistocene pp4(s)–pp2(s) sequence. We propose that changes in mean base level exert the primary control on sedimentation and erosion of these Pleistocene sequences. Changes in mean base level on the New Jersey shelf most likely resulted from major changes in the mean state of glaciation that marked the transition to Northern Hemisphere–dominated glaciation (pp4(s)–pp2(s) sequence) and then to the large eustatic fluctuations of the middle–late Pleistocene (pp2(s)–seafloor sequence) (Fig. 6). We propose that the pp2(s) hiatus (~ 0.46–0.78 Ma) and the pp4(s) hiatus (~ 1.8–5.4 Ma) can be attributed to an erosional response to the lowerings of mean base level that must have occurred at the times of increases in the mean $\delta^{18}O$ values that occurred between 0.9 and 0.6 Ma and 2.5 and 3.4 Ma, respectively (Fig. 6).

SUMMARY AND CONCLUSIONS

The paleodepths of Pleistocene facies tend to be deepest at the bases of sequences and shallow upsection on the outer New Jersey shelf. Little to no Pleistocene shelf-margin or lowstand deposits were found by Leg 174A drilling, indicating that either the shelf was exposed or sediment bypassed the shelf during Pleistocene relative sea-level lowstands. In contrast, shelf-margin or lowstand sediments were deposited on the New Jersey shelf in the Miocene. Thick sections of Miocene deeper-water facies in mid-sequence reflect large available accommodation space, probably the result of a late Miocene eustatic rise. Where deeper-water facies occur in mid- to upper portions of the Miocene and Pleistocene sequences, they correspond to stratal geometries consistent with transgression, maximum flooding, and downlap. Analogous stratal geometries related to flooding surfaces are repeated throughout the section, indicating parasequence deposition on the New Jersey shelf.

The global significance of upper Miocene to Pleistocene New Jersey shelf sequences is unclear, although previous studies have shown that major sequence-bounding unconformities of Oligocene–middle Miocene age on the New Jersey margin resulted from glacioeustatic lowerings (Miller et al., 1998). Nevertheless, the correlation and cause of the m0.5(s)–pp4(s), pp4(s)–pp2(s), and pp2(s)–seafloor sequences have not been firmly established previously, in part because the chronology is uncertain in the intervening upper Miocene and Pleistocene sequences. On the basis of the reinterpretation of the chronology of these surfaces (Fig. 3A, B), we suggest the following correlations: (1) the pp2(s) sequence boundary is associated with a hiatus spanning Bruhnes–Matuyama boundary that includes a time of a change to large, 100 ky–dominated Northern Hemisphere ice sheets (Ruddiman et al., 1986); (2) the pp4(s) sequence boundary correlates with a long hiatus between the Pleistocene and latest Miocene (1.8–5.6 Ma); we propose that a protracted interval of lower sea level associated with Northern Hemisphere ice growth in the Pliocene caused a lowering of mean base level that caused erosion and this long hiatus; (3) the SS5 surface (~ 6–7 Ma) corresponds to a late Miocene eustatic rise; and (4) m0.5(s) is dated as ca. 8 Ma and may correlate with an increase in ice volume and glacioeustatic lowering at this time.

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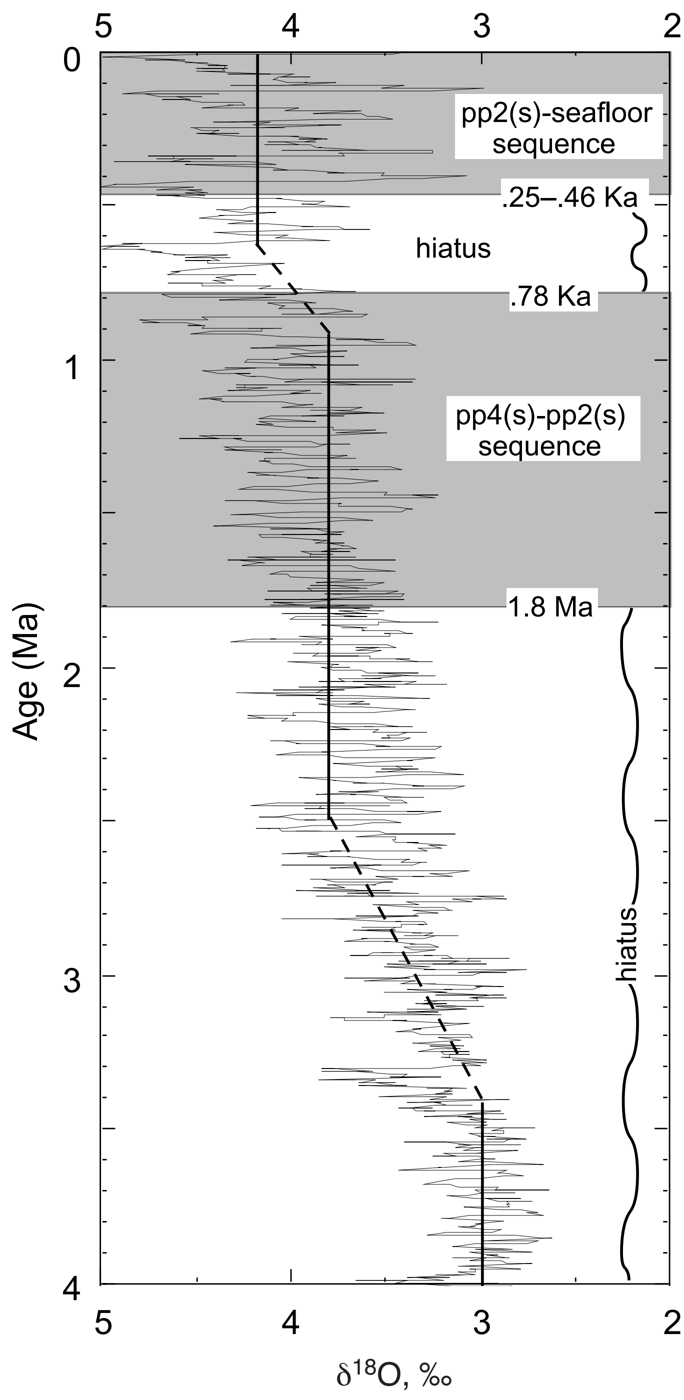

FIG. 6.—Changes in mean $\delta^{18}O$ (Site 846; Shackleton et al., 1995) indicate changes in mean state of glaciation that marked the transition to Northern Hemisphere–dominated glaciation in the mid-Pliocene and then to the large eustatic fluctuations of the middle–late Pleistocene. The pp2(s) hiatus (~ 0.46–0.78 Ma) and the pp4(s) hiatus (~ 1.8–5.4 Ma) could have been an erosional response to the lowerings of mean base level at the times of increases in the mean $\delta^{18}O$ values that occurred between 0.9 and 0.6 Ma and 2.5 and 3.4 Ma, respectively. Shaded areas indicate recovered sediments; white areas indicate hiatuses.

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