CHRONOLOGIC MODEL AND TRANSGRESSIVE-REGRESSIVE SIGNATURES IN THE LATE NEOGENE SILICICLASTIC FOUNDATION (LONG KEY FORMATION) OF THE FLORIDA KEYS

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ABSTRACT: Recent drilling of continuous cores in southernmost Florida has documented a thick unit of upper Neogene siliciclastics subjacent to surficial shallow-water Quaternary carbonates exposed on islands of the Florida Keys. The siliciclastics comprise the Long Key Formation and were identified in two cores collected from the middle and upper Florida Keys. A chronologic model based on new planktic foraminiferal biochronology and strontium-isotope chronology suggests the timing of siliciclastic deposition and provides a basis for regional correlation. The chronologic model, supplemented by vertical trends in quartz grain size, pattern of planktic menardiiform coiling direction, and paleoenvironmental interpretations of benthic foraminiferal assemblages, shows that the Long Key Formation contains three intervals (I-III) of varying thickness, grain-size composition, and paleo-water depth. Interval I is uppermost Miocene. The quartz grains in Interval I fine upward from basal very coarse sand to fine and very fine sand. Benthic foraminifera indicate an upward shift from an outer-shelf to inner-shelf depositional environment. Interval II, deposited during the late early to early late Pliocene, contains reworked upper Miocene siliciclastics and faunas. In the upper Keys, quartz grains in Interval II range from very coarse sand that fines upward to very fine sand and then coarsens to very coarse and medium sand. *In situ* benthic faunas indicate an upward shift from outer-shelf to inner-shelf deposition. In the middle Keys, Interval II is different, with the quartz grains ranging primarily from medium to very fine sand. *In situ* benthic taxa indicate deposition on an inner shelf. In both the middle and upper Keys, the upper Pliocene siliciclastics of Interval III contain quartz grains ranging from very coarse to very fine sands that were deposited on an inner shelf.

 A sequence boundary between Interval I and Interval II is suggested by: an abrupt shift in the strontium-isotope chemostratigraphy; coarsening in quartz grain size above the boundary; an abrupt landward shift in depositional facies in the upper Keys core; and a distinct variation in the predominant coiling direction of the menardiiform planktic foraminifera, from fluctuating dextral-sinistral to dextral in the upper Keys core. Successive siliciclastic infilling, likely associated with eustatic sea-level change and current redeposition, formed a foundation for subsequent carbonate deposition. Deep-sea biostratigraphic techniques, integrated with ages derived from strontium-isotope chemostratigraphy, can be successfully applied to coastal-margin sequences, even though a depauperate suite of faunal markers is common.

INTRODUCTION

The late Neogene stratigraphy of southernmost Florida is complicated because of vertical and lateral mixing of carbonate and siliciclastic sediments. The existence of siliciclastic sands in the subsurface of the Florida Keys has been known since the early 1900s (e.g., Vaughan 1910; Matson and Sanford 1913). However, the areal distribution of the sands was only recently documented (Warzeski et al. 1996; Cunningham et al. 1998). These reports describe a thick (~ 150 m) siliciclastic package (Cunningham et al. 1998) extending a distance of some 160 km between the middle and upper Florida Keys and sandwiched between shallow-marine carbonates (Warzeski et al. 1996).

The University of Miami's Rosenstiel School of Marine and Atmospheric Science and the Florida Geological Survey developed the South Florida Drilling Project (SFDP) to examine the complex temporal and spatial mixing of Tertiary carbonates and siliciclastics in south Florida. The Florida Geological Survey drilled four core borings (Fig. 1), providing nearly complete lithologic records previously not available in the region. A fifth core was drilled at Lake Surprise (Fig. 1) by the Florida Department of Transportation. One of the objectives of the SFDP was to develop a high-resolution chronostratigraphy for each core using a combination of dating techniques (biostratigraphy, strontium-isotope chemostratigraphy, and magnetostratigraphy). This paper presents results of the planktic foraminiferal biostratigraphy and strontium-isotope chemostratigraphy from the siliciclastics in two of the holes, drilled on Fiesta Key (Long Key Core) in the middle Keys and on north Key Largo (Carysfort Marina Core) in the upper Keys (Table 1; Fig. 1). The siliciclastics comprise the newly defined Long Key Formation (Cunningham et al. 1998). The entire Long Key Formation was penetrated in both cores. Limestones of the Arcadia Formation were not recovered during drilling of the Carysfort Marina Core (Fig. 2). However, a black phosphatic crust that marks the top of the Arcadia Formation throughout south Florida was recovered at the north Key Largo drill site, signifying that the entire siliciclastic unit there was penetrated.

GEOLOGIC SETTING

Continuous cores drilled in the Florida Keys reflect the complex stratigraphy contained in the shallow subsurface. Extensively studied outcrops of Quaternary shallow-water carbonates are underlain by a thick unit of marine siliciclastic sediments (Ginsburg et al. 1989), which overlie middle Miocene carbonates of the Arcadia Formation (Gomberg 1976; Cunningham et al.
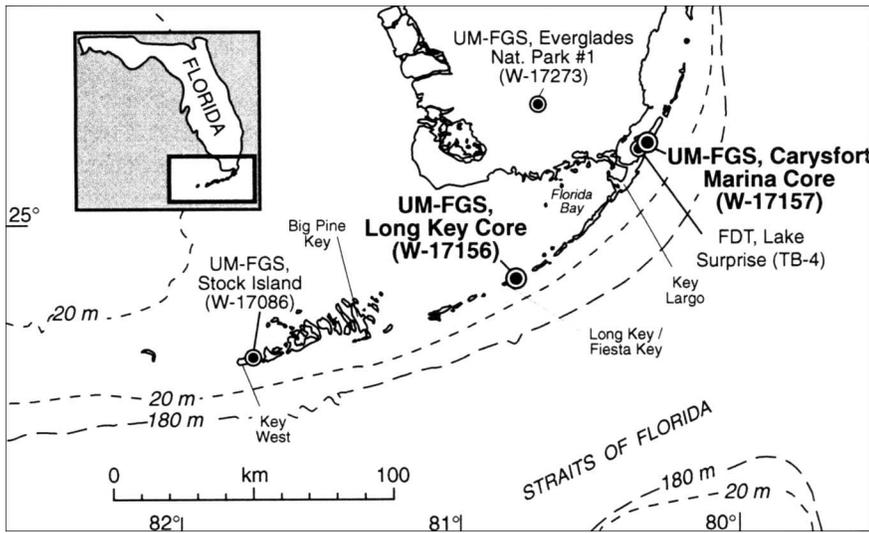
FIG. 1. Index map showing locations of core holes from the South Florida Drilling Project. This study analyzed Long Key and Carysfort Marina Cores. FGS = Florida Geological Survey; UM = University of Miami; FDT = Florida Department of Transportation.

1998). The succession of basal carbonates-siliciclastics-surficial carbonates signifies that at some time in the past, carbonate deposition on the southernmost Florida platform was punctuated by a widespread siliciclastic-dominated depositional setting. The siliciclastics provided a substrate suitable for the establishment of the Quaternary reef tract (Warzeski et al. 1996).

The siliciclastic source is believed to lie approximately 1000 km to the north in the Appalachian Mountains (Scott 1988). During the late Cretaceous to late Paleogene, the Gulf Trough separated the Florida platform from the southeast part of modern North America. The trough extended through north Florida and southeast Georgia (Chen 1965) and acted as a seaway for marine currents flowing between the Gulf of Mexico and the Atlantic Ocean. Siliciclastic sediments eroded from the Appalachians were restricted to the north side of the trough. The seaway provided sufficient isolation of the Florida platform to allow accumulation of pure carbonates south of the trough. A paleo-Florida Current that developed in the early Paleocene to early Eocene(?) flowed through the modern southern Straits of Florida, weakening the current flow through the Gulf Trough (Denny et al. 1994). In addition, from the late Paleocene to early Eocene(?), the Gulf Trough began infilling with sediments from uplift and erosion of the Appalachian Mountains (Riggs 1979). By the late Eocene, complete closure of the Gulf Trough diverted all current flow from the Gulf of Mexico through the Straits of Florida (Chen 1965).

With the Gulf Trough closed, the seaway no longer acted as a dynamic barrier to southward transport of siliciclastics. The siliciclastics first began mixing with peninsular carbonates in the

Oligocene (Sharpe 1980; Brewster-Wingard et al. 1997). There has been and continues to be much debate as to how the coarse siliciclastic sediments were transported so far south from their Appalachian source. Alt (1974) and Kane (1984) proposed that the siliciclastics in central Florida were introduced by longshore transport. Bishop (1956), Pirkle et al. (1964), and Puri and Vernon (1964) suggested that extensive distribution of the siliciclastics throughout the peninsula was due to a large prograding delta or river flowing southward along the peninsular axis with deposition occurring in a nearshore, marine to brackish environment (Peck et al. 1979). Winker and Howard (1977) questioned why a major river, presumably originating in Georgia, would avoid the most direct routes to the sea such as those followed by the Altamaha and Apalachicola Rivers today and proceed for a few hundred kilometers down the approximate center of an active structural arch. Ginsburg et al. (1989) suggested that a combination of longshore and fluvial transport was responsible for carrying the siliciclastics to the southern end of the peninsula, with redistribution by currents and waves into a giant, arcuate, spit-like feature

	LONG KEY CORE	CARYSFORT MARINA CORE
Location	Fiesta Key, Fla.	Key Largo, Fla.
Latitude	24°50′08″ N	25°15′00″ N
Longitude	80°47′40″ W	80°18′55″ W
Township/Range	SW ¼ Sec. 26	NW ¼ Sec. 1
	T64S R35E	T60S R40E
Total core depth	427.3 m (1401.5 ft)	139 m (456 ft)
Total core recovery	62.2%	53.9%
Top siliciclastics	48.2 m (158 ft)	43.0 m (141 ft)
Base siliciclastics	191.9 m (629.6 ft)	139 m (456 ft)
Siliciclastic recovery	46.9%	52.2%

TABLE 1. Location and recovery data pertaining to the cores used in this investigation.

FIG. 2. Cross section showing the relative thickness of the Long Key Formation within and between cores collected at Fiesta Key and Carysfort Marina (Fig. 1).

2

		Candeina nitida	Catapsydrax dissimilis	Dentoglobigerina altispira altispira	Dentoglobigerina altispira globosa	Globigerina ampliapertura	Globigerina ciperoensis angulioofficinalis	Globigerina helicina	Globigerina praebulloides leroyi	Globigerina pseudoampliapertura	Globigerina venezuelana	Globigerinoides altiaperturus	Globigerinoides bisphericus	Globigerinoides conglobatus	Globigerinoides elongatus	Globigerinoides extremus	Globigerinoides obliquus obliquus	Globigerinoides ruber	Globigerinoides trilobus immaturus	Globigerinoides trilobus sacculifer	Globigerinoides trilobus trilobus	Globoquadrina dehiscens	Globorotalia crassaformis	Globorotalia margaritae	Globorotalia menardii cultrata	Globorotalia menardii menardii	Globorotalia merotumida	Globorotalia miocenica	Globorotalia multicamerata	Globorotalia obesa	Globorotalia plesiotumida	Globorotalia pseudomiocenica	Globorotalia truncatulinoides	Globorotalia tumida	Hastigerina aequilateralis	Hastigerina pelagica	Neogloboquadrina acostaensis	Neogloboquadrina dutertrei	Neogloboquadrina humerosa	Neogloboquadrina mayeri	Orbulina suturalis	Orbulina universa	Pulleniatina obliquiloculata	Pulleniatina primalis	Sphaeroidinella dehiscens	Sphaeroidinellopsis multiloba	Sphaeroidinellopsis seminulina
48.8 m	C													X	X	X		X	X	X	X															X		X						X			
49.1 m	C	X									X			X	X	X	X	X	X		X	X								X					X					X	X			X	X		
51.5 m	R													X				X	X	X															X												
68.6 m	C			X							X		X			X		X			X					X	X			X			X			X		X			X						
70.1 m	C				X						X					X		X	X		X			X	X			X							X				X		X						
71.6 m	C				X						X					X		X	X		X				X			X						X	X	X		X									
73.2 m	C									X	X		X	X		X		X			X				X			X						X										X			
73.8 m	C			X	X						X					X	X	X			X			X															X								
82.0 m	C								X					X	X		X		X			X				X				X										X				X			
84.7 m	C			X	X				X					X	X	X		X		X	X			X													X			X	X		X			
87.5 m	R			X							X	X	X				X				X																	X			X						
88.4 m	C										X			X	X	X		X		X	X						X									X			X		X			X			X
102.1 m	C			X			X				X			X	X	X	X	X	X		X			X													X			X		X					X
103.0 m	C										X			X	X		X	X			X		X		X					X		X				X			X	X	X					X
104.5 m	C						X				X		X			X		X			X			X								X			X			X			X					X
105.2 m	C		X							X		X		X	X		X	X			X				X	X	X					X	X			X					X					X
105.6 m	C										X			X	X	X		X			X			X	X										X					X						
106.8 m	C			X						X	X		X	X	X	X	X	X	X	X	X		X	X	X		X	X		X		X			X	X	X	X		X			X		X	X
107.0 m	R										X			X				X			X											X			X					X							
116.1 m	R	X									X						X				X			X					X							X					X						
116.4 m	R										X			X	X	X		X			X															X											
116.9 m	R										X	X		X		X				X															X					X						
117.3 m	R										X	X		X	X	X		X			X		X			X									X		X			X						
118.9 m	C										X							X			X														X											
120.4 m	C				X						X				X	X	X			X	X														X					X						
121.7 m	R										X				X	X	X	X	X	X	X														X											
125.0 m	C			X						X								X		X		X						X									X			X					X		
128.0 m	C			X							X				X	X	X	X	X																	X					X						X
128.9 m	C							X			X	X	X		X	X	X			X	X									X																	
130.0 m	C			X		X					X							X	X	X																				X	X						
131.1 m	R										X										X																										
134.5 m	C			X							X				X		X		X	X	X							X									X			X						X
136.6 m	C			X	X						X				X		X		X	X								X												X		X					X
140.2 m	C											X	X	X	X		X	X	X	X											X			X	X	X			X				X
143.0 m	A		X	X						X		X	X		X		X	X	X			X											X		X		X				X	X	X	X
145.1 m	R			X							X								X																	X										
146.3 m	C			X	X					X		X			X	X			X	X																X				X						
150.0 m	C			X		X		X	X		X	X			X	X		X				X							X						X		X								
152.4 m	R			X														X																												
165.2 m	R																X																														
191.9 m	R									X	X						X	X			X	X											X			X									X		

"A" indicates >45 specimens per sample. "C" represents an average of 45 to 15 specimens per sample. "R" indicates <15 specimens in a sample. Taxonomy according to Berggren et al. (1995b).

TABLE 2. Planktic foraminifera listed alphabetically and their distribution with depth in the Long Key Core.

that served as a foundation for the Quaternary sediments of the Keys. Through examination of cores and well cuttings, Warzeski et al. (1996) proposed that a pathway of maximum paleocurrents and a coincident trend of coarse-grained siliciclastics existed through the central section of the peninsula. Sea-level fluctuations and strong currents that swept through the region redistributed the siliciclastics to the south and east. Cunningham et al. (1998) revised the siliciclastic corridor (Fig. 3) by more precise mapping of the net thickness of the coarse-grained fraction of the siliciclastics.

The siliciclastic sediments in north and central Florida were described by Scott (1988) and defined as the Peace River Formation of the Hawthorn Group. In southernmost Florida, the siliciclastics were redefined as the Long Key Formation (Cunningham et al. 1998), a quartz sandstone with less than 50% carbonate grains and minor components of feldspar, mica, and phosphorite.

METHODS

Biostratigraphic data from the Long Key and Carysfort Marina Cores are combined with ages derived from strontium-isotope chemostratigraphy and lithologic data to define depositional age and timing of events and sequences and to help identify and evaluate eustatic signals in the Long Key Formation. These methods have been applied in other locations, such as on the New Jersey coastal plain (Miller et al. 1996; Pekar and Miller 1996), where the techniques have proven effective in validating and refining parts of the proposed Haq et al. (1987) global sea-level curve.

All ages reported in this manuscript are based on the time scale of Berggren et al. (1995b). All biostratigraphic datums were taken from the publications of Berggren et al. (1995a), Berggren et al. (1995b), and Chaisson and Pearson (1997). Ages discussed herein from previous studies have been converted to the Berggren et al. (1995b) time scale to allow temporal comparisons.

Biostratigraphy

Microfossil data have proven very useful in determining

3

FIG. 3. Structure contour map of the top of the Arcadia Formation, which underlies upper Miocene-Pliocene siliciclastic sediments of the Long Key Formation in southernmost Florida. To the north, the siliciclastics of the Peace River Formation and Long Key Formation overlie the Arcadia Formation. Dashed gray line reflects the probable transport pathway of coarse quartz sand. Modified from Cunningham et al. (1998).

the age (Blow 1969; Berggren et al. 1985; Bolli and Saunders 1985; Berggren et al. 1995a; Berggren et al. 1995b) and environments of deposition (Phleger 1951; Bandy 1954; Parker 1954) for marine lithologic units. Planktic and benthic foraminifera examined from the Long Key Formation constrain timing of sediment deposition and paleo-water depth, respectively.

Planktic Foraminifera. - Data on planktic foraminifera are used in constructing a biochronology from two continuous cores, collected from Fiesta Key and north Key Largo (Table 1, Fig. 2) in the Florida Keys. The upper and lower contacts of the Long Key Formation in each core are easily recognized and defined by abrupt juxtaposition of Long Key Formation siliciclastics with overlying and underlying carbonate rocks. The siliciclastics are uncemented to slightly cohesive. Biostratigraphic sampling was first carried out at approximately 1.5 m intervals. Where intervals did not yield adequate planktic taxa or other reliable age control, a finer-scale sampling interval (~ 0.3 to 0.5 m) was used.

Eighty-two samples from the Long Key Core and 54 samples from the Carysfort Marina Core were analyzed for planktic foraminifera. The samples were disaggregated in a mixture of distilled water and sodium hexametaphosphate and wet-sieved through 250-, 150-, and 63-μm sieves. The samples were dried and examined under a binocular microscope. The planktic foraminifera were picked from the > 250-μm size fraction. Foraminifera collected from the > 150-μm size fraction were typically poorly preserved, reflecting calcite overgrowth and corrosion, and

only a small number could be used. The 150-63 μm size fraction was not examined because of the difficulty of working with the smaller, poorly preserved grains and the lack of significant age-marker species. Low-latitude Cenozoic planktic foraminiferal species were identified following the criteria of Bolli (1957) and Bolli and Saunders (1985). Tables 2 and 3 show the distribution of planktic taxa identified for each microfossil sample.

Following age data and taxonomies of Berggren et al. (1995a), Berggren et al. (1995b), and Chaisson and Pearson (1997), ages were assigned to first- and last-appearance datums (FAD, LAD) for 16 species (Table 4). To determine range in age for individual samples, the youngest FAD and the oldest LAD of identifiable taxa were used. After establishing first (FO) and last occurrences, plots of age versus depth were constructed (Figs. 4, 5). Useful age-diagnostic biohorizons are listed in Table 5. Forty-one samples (out of 82) examined from the Long Key Core and 46 samples (out of 54) from the Carysfort Marina Core contained planktic foraminifera (Tables 4, 5).

Benthic Foraminifera. - A general sampling survey for benthic foraminifera in the Long Key Formation was completed for the two cores. The > 250-μm and > 150-μm size fractions of 10 samples from the Long Key Core and 14 samples from the Carysfort Marina Core were examined (Tables 6, 7). These particular samples were chosen because of the abundance of benthic foraminifera. Identification at the genus level was aided by reference to Bock et al. (1971), Poag (1981), and Jones (1994). For paleoenvironmental interpretations, the inner shelf is here

4

Depth	Abund.	Candeina nitida	Catapsydrax dissimilis	Dentoglobigerina altispira altispira	Dentoglobigerina altispira globosa	Globigerina ampliapertura	Globigerina ciperoensis anguliofficinalis	Globigerina praebulloides leroyi	Globigerina praebulloides praebulloides	Globigerina pseudoampliapertura	Globigerina venezuelana	Globigerinoides altiaperaturus	Globigerinoides bisphericus	Globigerinoides conglobatus	Globigerinoides elongatus	Globigerinoides extremus	Globigerinoides obliquus obliquus	Globigerinoides ruber	Globigerinoides trilobus immaturus	Globigerinoides trilobus sacculifer	Globigerinoides trilobus trilobus	Globoquadrina dehiscens	Globorotalia crassaformis	Globorotalia margaritae	Globorotalia menardii cultrata	Globorotalia menardii menardii	Globorotalia merotumida	Globorotalia multicamerata	Globorotalia obesa	Globorotalia plesiotumida	Globorotalia pseudomiocenica	Globorotalia tumida	Hastigerina pelagica	Neogloboquadrina acostaensis	Neogloboquadrina dutertrei	Neogloboquadrina humerosa	Neogloboquadrina mayeri	Orbulina suturalis	Orbulina universa	Sphaeroidinella dehiscens	Sphaeroidinellopsis multiloba	Sphaeroidinellopsis seminulina
57.5 m	C									X					X						X												X		X	X				X		
59.7 m	C						X		X						X	X	X		X		X					X									X		X					
61.0 m	C		X				X		X					X	X	X	X	X	X	X	X	X			X	X	X								X	X	X			X		
62.5 m	C				X		X	X						X	X	X	X	X	X	X	X	X				X			X					X	X	X						X
65.5 m	C		X				X		X					X		X	X	X	X	X	X	X			X		X	X			X				X				X			
67.7 m	C							X		X				X				X		X	X	X			X										X		X	X				
68.6 m	C		X		X									X	X		X		X	X	X				X										X				X			
73.3 m	R			X							X										X																X					
74.4 m	C			X	X	X						X	X		X		X		X	X	X			X				X	X	X	X	X	X	X	X	X	X			X		
77.9 m	A			X	X		X					X			X	X	X	X	X	X	X				X		X				X	X	X	X	X	X				X		
80.5 m	C			X	X							X			X	X		X		X	X	X		X		X		X		X					X	X			X			
83.9 m	A			X	X	X						X			X			X		X	X														X	X			X			
85.4 m	A		X	X	X		X	X				X	X		X	X		X	X	X	X	X	X			X	X	X		X					X	X	X	X	X			X
86.6 m	C		X			X	X	X		X			X		X	X		X	X	X	X				X	X		X	X					X	X	X		X			
89.9 m	C		X			X	X	X					X		X	X		X	X	X	X				X	X		X					X	X	X			X			
93.3 m	C			X	X	X						X			X		X	X	X	X	X				X	X		X					X	X	X			X			
95.7 m	C			X	X		X					X			X	X	X	X	X	X	X	X			X	X						X		X	X	X			X		
97.5 m	A				X							X			X	X	X	X	X	X	X				X			X	X	X			X	X	X			X			
99.4 m	C		X									X			X	X				X	X				X	X			X					X	X			X			
99.7 m	C	X	X						X			X			X	X	X	X		X	X	X	X	X		X	X				X	X	X	X	X			X	X		X
100.2 m	C	X	X							X		X	X		X	X	X	X		X	X				X	X	X				X	X	X	X	X			X	X		X
102.1 m	C	X	X									X			X	X	X			X	X				X	X							X				X				
103.1 m	C						X					X			X			X			X				X									X				X			X
103.6 m	C		X		X			X	X			X			X	X	X	X		X	X	X	X	X	X	X		X						X				X			
106.7 m	C		X		X							X			X		X	X	X		X	X	X	X		X			X				X	X			X				
108.2 m	C			X				X				X			X	X		X			X				X	X	X	X					X					X			
108.5 m	R											X			X		X			X					X								X					X			X
109.7 m	R			X								X			X		X								X								X				X			X
111.3 m	A			X	X							X	X		X	X	X	X	X	X	X	X			X	X	X			X			X	X	X	X			X		X	
111.9 m	R	X										X				X		X		X					X								X				X			X		X
112.5 m	C											X							X						X	X							X				X			X		
113.4 m	C				X		X	X				X	X		X	X		X	X		X				X	X	X			X			X				X	X	X	X		
115.5 m	C			X	X		X					X	X		X				X						X	X								X				X				X
117.3 m	C			X	X		X			X		X			X			X	X	X					X	X	X						X				X			X	X	
118.9 m	A	X		X				X	X	X	X	X	X		X			X		X	X				X	X	X	X		X		X		X		X	X		X	X	X	X
120.4 m	A		X								X				X	X	X	X	X		X	X			X	X	X		X		X			X			X			X	X	X
122.2 m	C		X									X			X		X	X		X					X								X					X			X	X
125.3 m	C		X						X			X		X	X		X	X		X	X				X	X		X					X		X		X	X	X	X	X	X
125.9 m	A		X						X			X			X		X	X	X		X	X			X				X	X			X		X	X	X	X	X	X		X
128.3 m	A		X		X		X		X			X			X		X	X	X		X	X			X			X	X		X	X	X		X	X		X				X
131.4 m	C		X									X		X	X	X		X		X	X	X			X				X				X		X			X	X	X		X
134.1 m	C		X								X			X	X	X		X	X	X	X				X			X					X				X	X	X	X		X
135.3 m	C								X			X	X		X	X	X		X	X		X			X				X	X			X		X	X	X		X		X	X
137.2 m	C		X	X			X		X			X	X	X		X	X		X	X		X			X	X		X			X				X		X	X				X
137.8 m	C		X				X					X				X		X	X	X		X	X		X	X				X				X	X	X	X					X
138.5 m	C		X	X					X			X			X		X	X	X		X	X			X	X	X				X						X			X	X	X

"A" indicates >45 specimens per sample. "C" represents an average of 45 to 15 specimens per sample. "R" indicates <15 specimens in a sample. Taxonomy according to Berggren at al. (1995b).

TABLE 3. Planktic foraminifera listed alphabetically and their distribution with depth in the Carysfort Marina Core.

defined as extending from mean sea level to a depth of 100 m. The outer shelf extends from 100 to 200 m of water depth (Murray 1991). Murray (1991) grouped individual associations and species into these broad depth categories (Table 8) because benthic species have well-defined local depth distributions that vary from one area to another.

Strontium-Isotope Chemostratigraphy

Both shell material (pelecypods) and planktic foraminifera that were unaltered and preserved their original mineralogy were collected for strontium-isotope analysis from nine samples of the Long Key Formation (Table 9). Three of the samples were from the Long Key Core, and six were from the Carysfort Marina Core. The shell material was cleaned in distilled water in an ultrasonic cleaner and allowed to dry. If a shell was free of cement and matrix, it was then ground with mortar and pestle. Otherwise, a microdrill was used to obtain unaltered parts of the shell. X-ray diffraction analyses showed the mineralogy of the pelecypods to be low-magnesium calcite. X-ray diffraction was not performed on the bulk planktic foraminiferal samples because of the limited number of specimens collected.

The raw $^{87}Sr/^{86}Sr$ data were normalized to published values of SRM-987 appropriate to the lab where the samples were analyzed (Table 9). Ages and 95% confidence intervals were

Datum event	Magnetic polarity	Age (Ma)
LAD *Globigerinoides extremus*	C2n (top Olduvai Subchron)	1.77 (a)*
FAD *Globorotalia truncatulinoides*	C2r.1r (just below Olduvai Subchron)	2.0 (a)
LAD *Globorotalia miocenica*	C2r.2r (below Reunion Subchron)	2.3 (a)
LAD *Dentoglobigerina altispira*	C2An.1r (Kaena Subchron)	3.09 (a)
LAD *Globorotalia multicamerata*	C2An.1r (Kaena Subchron)	3.09 (a)
LAD *Sphaeroidinellopsis seminulina*	C2An.2n (just below Kaena Subchron)	3.12 (a)
FAD *Globorotalia miocenica*	C2An.3n (Mammoth Subchron)	3.55 (a)
LAD *Globorotalia margaritae*	C2An/C2Ar (Gauss/Gilbert boundary)	3.58 (a)
FAD *Globorotalia crassaformis*	C3n.2n (Nunivak Subchron)	4.5 (a)
LAD *Globorotalia tumida*	C3r (early Gilbert Chron reversed)	5.6 (a,b)
FAD *Globigerinoides conglobatus*	C3An.2n	6.2 (c)
FAD *Globorotalia margaritae*	Mid-C3An.2n	6.4 (a)
FAD *Candeina nitida*	C4r.1r	8.1 (b)
FAD *Globigerinoides extremus*	C4r.2r	8.3 (b)
FAD *Globorotalia plesiotumida*	C4r.2r	8.3 (b)
FAD *Neogloboquadrina humerosa*	C4r.2r	8.5 (b)

* References: (a) Berggren et al. (1995a); (b) Berggren et al. (1995b); (c) Chaisson and Pearson (1997).

TABLE 4. Planktic-foraminifera age datums used for the biochronology.

determined graphically from the curve of Farrell et al. (1995). The curve extends from 0 to 6.5 Ma.

Lithostratigraphy

Detailed description of lithology and unconformities and less abrupt contacts were completed on the Long Key Formation siliciclastics with hand lens and binocular microscope. Core descriptions for the siliciclastic sections in the Long Key and Carysfort Marina Cores are presented in McNeill et al. (1996) and

Cunningham et al. (1998). Variations in quartz grain size (Figs. 4, 5) and X-ray diffraction data from both cores are also reported in McNeill et al. (1996).

The grain-size scale used is the Udden-Wentworth scale. Very coarse sand refers to quartz grains 2 to 1 mm in diameter. Coarse sand is 1 to 0.5 mm in diameter. Medium sand ranges from 0.5 to 0.25 mm, and fine sand ranges from 0.25 to 0.125 mm. Very fine sand is 0.125 to 0.0625 mm, and all grains smaller than 0.0625 mm are categorized as clay-silt (mud).

RESULTS

Many of the same planktic and benthic foraminiferal species were found in both cores. A chronologic model derived from combining biostratigraphic and strontium-isotope data indicates that siliciclastic deposition began in the latest Miocene and was followed by two separate depositional episodes during the Pliocene. The planktic foraminiferal zonation of Berggren et al. (1995b) could not be assigned to the Long Key Formation because of the absence of many key marker species. For age diagnosis, we have relied on several well-established foraminiferal first and last occurrences and on dates derived from strontium-isotope chemostratigraphy.
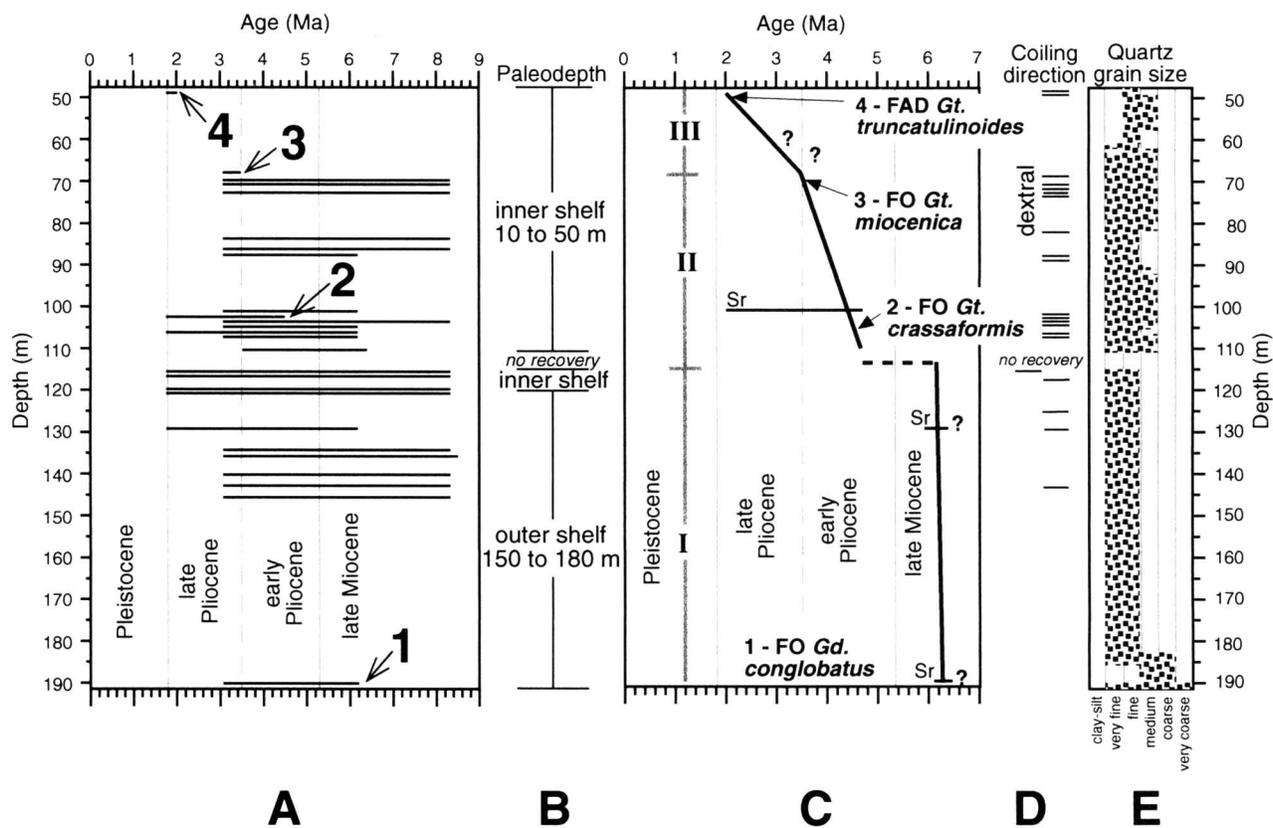
FIG. 4. Compilation of foraminiferal and strontium-isotope data collected from the Long Key Formation with quartz grain-size variations in the Long Key Core. A) Plot of age versus depth, showing horizontal bars that represent the best constrained age defined by the planktic-foraminifera age datums. Key datum markers are noted by numbered 1- 4. B) Paleodepth interpretations from benthic foraminifera. C) The plot of age versus depth includes planktic-foraminifera and strontium-isotope data and is an interpretation for the timing of siliciclastic deposition, with the Roman numerals representing three intervals of deposition. The bold solid line is the best-fit integration of both data sets. D) Coiling directions for menardiiforms are plotted at depth. Tick marks on the left indicate sinistral coiling, and tick marks on the right indicate a dextral coiling. Horizontal line shows where a sample had both coiling directions present. E) Grain-size plots, showing the size distribution of the quartz grains.
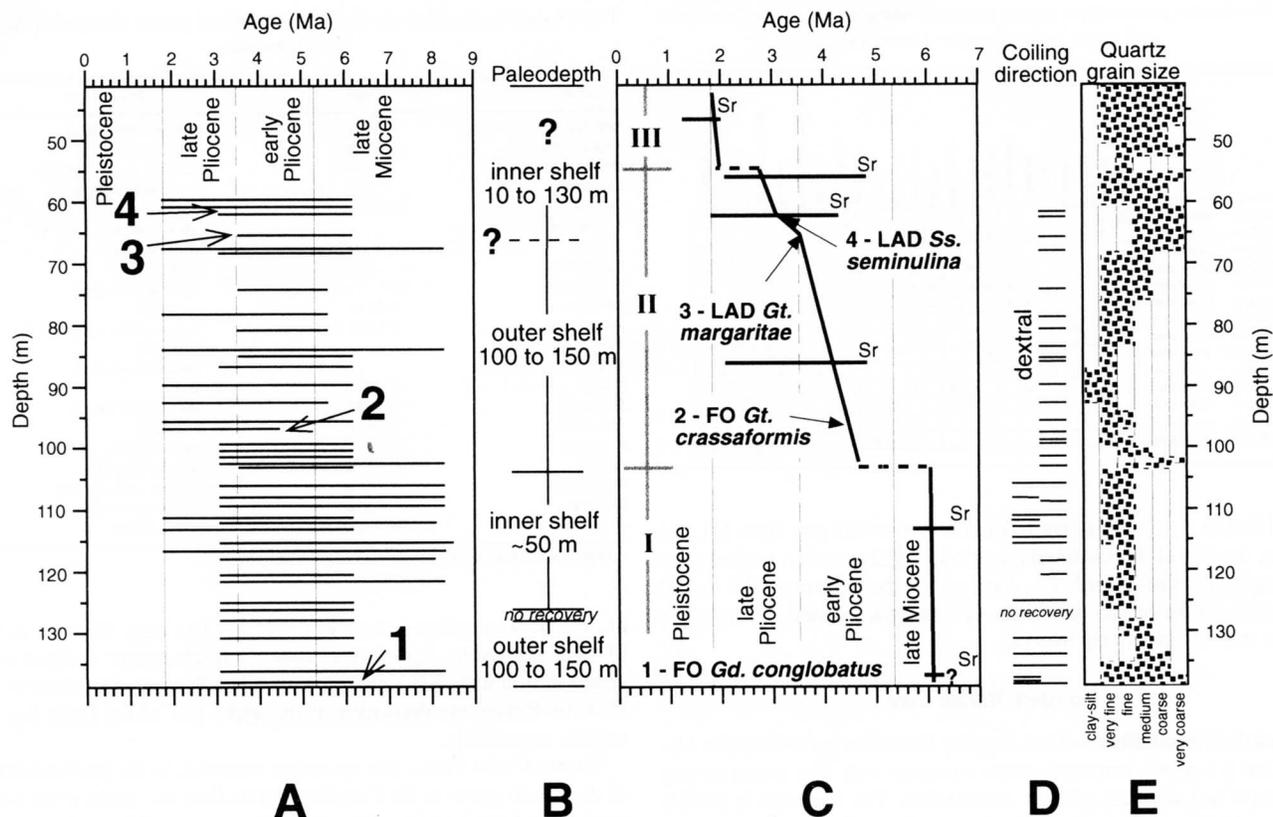
FIG. 5. Compilation of foraminiferal and strontium-isotope data with quartz grain-size variations in the Carysfort Marina Core. See Figure 4 caption for description.

The application of open-ocean foraminiferal biostratigraphy to shallow-water siliciclastic sediments warrants a cautionary note regarding the reliability of biohorizons as representative of absolute age. We realize that establishing age relations based on an often impoverished faunal data set can be tenuous. Some common limitations expected in this setting may include: reworking of older fauna, hiatuses of considerable duration, delayed first occurrence or occurrences at a single level in the core, and the absence of key marker species due to environmental controls. Age constraints proposed for these shallow-water siliciclastics should be viewed with these limitations in mind.

Long Key Core

Planktic Foraminifera. - Forty-six planktic foraminiferal species were identified in the siliciclastics of the Long Key Core (Table 2). Foraminiferal abundance varied in samples from barren to as many as 24 identifiable species (Table 2, Fig. 6A).

Taxa from a sample collected at the base of the siliciclastics (191.9 m) constrains the age between 6.2 and 3.12 Ma. Samples collected from the overlying 25 m (191.0 to 166.0 m) are barren of planktic specimens (Fig. 6A). The interval between 165.2 and 116.1 m contains a minor number of taxa, few of which are useful as age markers. At 103.0 m, the FO of *Globorotalia crassaformis* defines an age no older than 4.5 Ma. The FO of *Globorotalia miocenica* (FAD 3.55 Ma) occurs at 68.6 m (Fig. 4). However, because these species are found only once, i.e., at single levels in the core, it is unlikely that their occurrences represent true FADs. We can say only that the ages of their respective core levels are younger than those of their FADs. The interval from 67.7 to 50.3 m is nearly barren and the few specimens found are not age diagnostic. The age at the top of the siliciclastic unit (48.8 m) is constrained to the latest Pliocene by the overlap of *Globorotalia truncatulinoides* (FAD 2.0 Ma) and *Globigerinoides extremus*

Core Name	Datum	Age	Depth
LONG KEY CORE	FAD *Gt. truncatulinoides*	2.0 Ma	48.8 m
	FAD *Gt. miocenica*	3.55 Ma	68.6 m
	FAD *Gt. crassaformis*	4.5 Ma	103.0 m
	FO *Gd. conglobatus*	6.2 Ma	191.9 m
CARYSFORT MARINA CORE	LAD *Ss. seminulina*	3.12 Ma	62.5 m
	LAD *Gt. margaritae*	3.58 Ma	85.4 m
	FAD *Gt. crassaformis*	4.5 Ma	97.5 m
	FO *Gd. conglobatus*	6.2 Ma	138.5 m

First occurrence of *Gd. conglobatus* at the base of unit may not represent its FAD; therefore, base of unit may be younger than 6.2 Ma. Ages for each foraminiferal datum are referenced in Table 4.

TABLE 5. Biohorizons defined by age-diagnostic planktic forminifera for each core.

Depth	Environment	Ammonia	Amphistegina	Bulimina	Cancris	Cassidulina	Cibicides	Cibicidoides	Dentalina	Ehrenbergina	Elphidium	Fursenkoina	Guttulina	Hanzawaia	Lagena	Lenticulina	Nodosaria	Nonion	Nonionella	Planorbulina	Planulina	Plectofrondicularia	Rosalina	Textularia	Trifarina	Uvigerina
49.1 m	inner shelf	X	X				X				X		X	X					X			X		X		
88.4 m	inner shelf		X	X			X		X		X		X			X	X				X	X				
105.2 m	inner shelf		X				X						X			X					X	X				
106.8 m	inner shelf			X			X		X		X				X			X	X							
116.1 m	inner shelf	X		X	X			X		X						X		X	X				X		X	
116.9 m	inner shelf	X		X		X	X					X		X			X		X							
117.3 m	inner shelf	X			X		X		X	X			X					X	X				X	X	X	X
120.4 m	outer shelf			X	X			X			X	X		X	X		X						X			
128.0 m	outer shelf			X			X		X			X	X		X		X	X						X		
191.9 m	outer shelf						X	X	X						X	X	X			X						

TABLE 6. Benthic foraminiferal genera listed alphabetically and their distribution with depth in the Long Key Core.

7

TABLE 7. Benthic foraminiferal genera listed alphabetically and their distribution with depth in the Carysfort Marina Core.

Depth	Environment	Amphistegina	Brizalina	Bulimina	Cancris	Cassidulina	Cibicides	Cibicidoides	Dentalina	Guttulina	Hanzawaia	Lagena	Lenticulina	Nodosaria	Nonion	Nonionella	Planorbulina	Planulina	Plectofrondicularia	Rosalina	Siphonogenerina	Textularia	Trifarina	Uvigerina
57.5 m	inner shelf	X													X	X		X						
67.7 m	outer shelf		X	X		X		X							X	X		X		X				
77.9 m	outer shelf														X	X		X						X
97.5 m	outer shelf					X					X	X	X			X		X						X
99.7 m	outer shelf			X			X	X	X	X		X	X			X		X	X			X		
100.2 m	outer shelf			X			X	X		X		X	X			X		X				X		
103.1 m	outer shelf								X	X						X		X						
103.6 m	outer shelf			X				X					X		X	X		X				X		
108.5 m	inner shelf				X											X								
111.9 m	inner shelf			X		X		X		X					X		X	X	X			X		
113.4 m	inner shelf			X			X			X		X	X		X			X						
120.4 m	inner shelf	X		X	X			X	X	X			X	X	X	X	X	X				X		
137.2 m	outer shelf		X	X						X			X	X	X	X		X						X
138.5 m	outer shelf			X						X			X	X	X	X		X				X		X

(LAD 1.77 Ma). The overlap of these two biohorizons suggests that deposition of the Long Key Formation ended between 2.0 and 1.77 Ma at Long Key.

A preference for dextral or sinistral coiling has been documented (e.g., Bolli 1950, 1970; Bolli and Premoli Silva 1973; Bolli and Saunders 1985) for some menardiiform Caribbean taxa (e.g., *Globorotalia merotumida*, *Globorotalia plesiotumida*, *Globorotalia pseudomiocenica*, *Globorotalia miocenica*, *Globorotalia multicamerata*, *Globorotalia menardii cultrata*, and *Globorotalia menardii menardii*). Frequent coiling changes are common for the Caribbean area of the Atlantic region, such those noted by Robinson (1969) from Jamaica. The coiling direction of the menardiiforms identified in the Florida cores served as an additional useful biostratigraphic parameter. The pattern for a preferred coiling direction throughout accumulation of the Long Key Formation in the Long Key Core is shown in Table 10 and Figure 4. Of the 21 samples amenable to analysis of coiling direction, 20 contained dextral forms and only one yielded sinistral forms.

Benthic Foraminifera. - Ten samples were examined in the Long Key Core for benthic foraminifera (Table 6). Benthic genera from the base of the Long Key Formation (191.1 m to 120.4 m) comprised an outer-shelf assemblage, suggesting deposition in ~150 to 180 m of water depth (Table 6). From 117.3 m to the top of the formation (48.2 m), an inner-shelf assemblage was recognized, which is consistent with deposition in water depths of 10 to 50 m.

Strontium-Isotope Data. - Utilizing the ages from the curve of Farrell et al. (1995), a strontium-isotope chemostratigraphy is shown for the Long Key Formation in the Long Key Core (Table 9; Fig. 4). Siliciclastic sediments were transported into the region and deposited on the upper surface of the Arcadia Formation at ~6 Ma, or possibly earlier judging by age constraints derived from strontium-isotope chemostratigraphy. Within dating resolution, there was a steady late Miocene influx of siliciclastics between the base of the formation (191.9 m) and 128.9 m. The interval from 128.9 to 102.1 m recorded a shift in age from latest Miocene-earliest Pliocene to early late Pliocene. The biostratigraphy developed for the upper part of the Long Key Formation supported early late Pliocene deposition. Because of a lack of datable material from 62.4 to 48.2 m, the age of the uppermost

Genus	Depth	Environment
Ammonia	0–50 m	lagoons—inner shelf
Amphistegina	0–130 m	coral reefs, lagoons
Brizalina		marginal marine—bathyal
Bulimina		inner shelf—bathyal
Cancris	50–150 m	shelf
Cassidulina		shelf—bathyal
Cibicides	0–>2,000 m	shelf—bathyal
Cibicidoides		shelf—bathyal
Ehrenbergina		outer shelf—bathyal
Elphidium	0–50 m	inner shelf
Fursenkoina	0–1,200 m	lagoons, shelf, upper bathyal
Hanzawaia		inner shelf
Lenticulina		outer shelf—bathyal
Nonion	0–180 m	shelf
Nonionella	10–1,000 m	shelf—upper bathyal
Planorbulina	0–50 m	inner shelf
Planulina		shelf—bathyal
Rosalina	0–100 m	lagoons, inner shelf
Textularina	0–500 m	lagoons, shelf—bathyal
Trifarina	0–400 m	shelf—upper bathyal
Uvigerina	100–>4,500 m	shelf—bathyal

Depth and environment information according to Murray (1991).

TABLE 8. Ecological data for benthic foraminiferal genera identified in the Long Key Formation.

Long Key Formation could not be determined using strontium-isotope chemostratigraphy.

Quartz Grain Size. - The diameter of siliciclastic grains varies throughout the Long Key Formation (Fig. 4). A thin (8.7 m) interval (191.9 m to 183.2 m) of very coarse- to medium-grained sand lies at the base of the formation in the Long Key Core. This basal unit is overlain by 67.4 m (183.2 to 115.8 m) of fine- and very fine-grained quartz sand. The interval from 115.8 to 111.2 m was not recovered. Above this gap, from 111.2 to 61.3 m, the size of the siliciclastic grains is slightly coarser, ranging from medium to very fine grained. The upper part of the formation (61.3 to 48.2 m) consists predominantly of medium- and fine-grained sand, again slightly coarser than the underlying interval.

Carysfort Marina Core

Planktic Foraminifera. - The Long Key Formation in the Carysfort Marina Core is a poorly cemented quartz sandstone with very coarse to very fine grains and abundant planktic foraminifera. The formation is notably calcareous in its mineralogic content in some intervals. Forty-one planktic species were identified (Table 3), with abundance ranging from barren to as many as 22 taxa present in any one sample (Table 3, Fig. 6B). The

Depth (m)	Description	$^{87}Sr/^{86}Sr$*	Age (Ma)
LONG KEY CORE			
102.1	bulk planktic foraminifera	0.70906	2.15–4.83
128.9	bulk planktic foraminifera	0.70897	5.96–?
191.9	bulk planktic foraminifera	0.70896	6.15–?
CARYSFORT MARINA CORE			
45.8	pelecypod	0.70901	1.26–2.08
55.6	pelecypod	0.70906	2.15–4.83
62.5	bulk planktic foraminifera	0.70907	1.87–4.40
86.2	bulk planktic foraminifera	0.709044#	1.95–4.58
113.2	bulk planktic foraminifera	0.70898	5.78–6.58
137.8	bulk planktic foraminifera	0.70897	5.96–?

* Normalized to $^{86}Sr/^{88}Sr = 0.1194$ and relative to $^{87}Sr/^{86}Sr$ of SRM-987 = 0.710244. Estimated 2σ error of analysis is ± 0.00002.

Carysfort Marina Core sample 86.2 m measured at Cambridge University. Normalized to $^{86}Sr/^{88}Sr = 0.1194$ and relative to $^{87}Sr/^{86}Sr$ of SRM-987 = 0.710230. Estimated 2σ error of analysis is ± 0.00002.

TABLE 9. Strontium-isotope composition and corresponding ages for samples from the Long Key Formation.

8
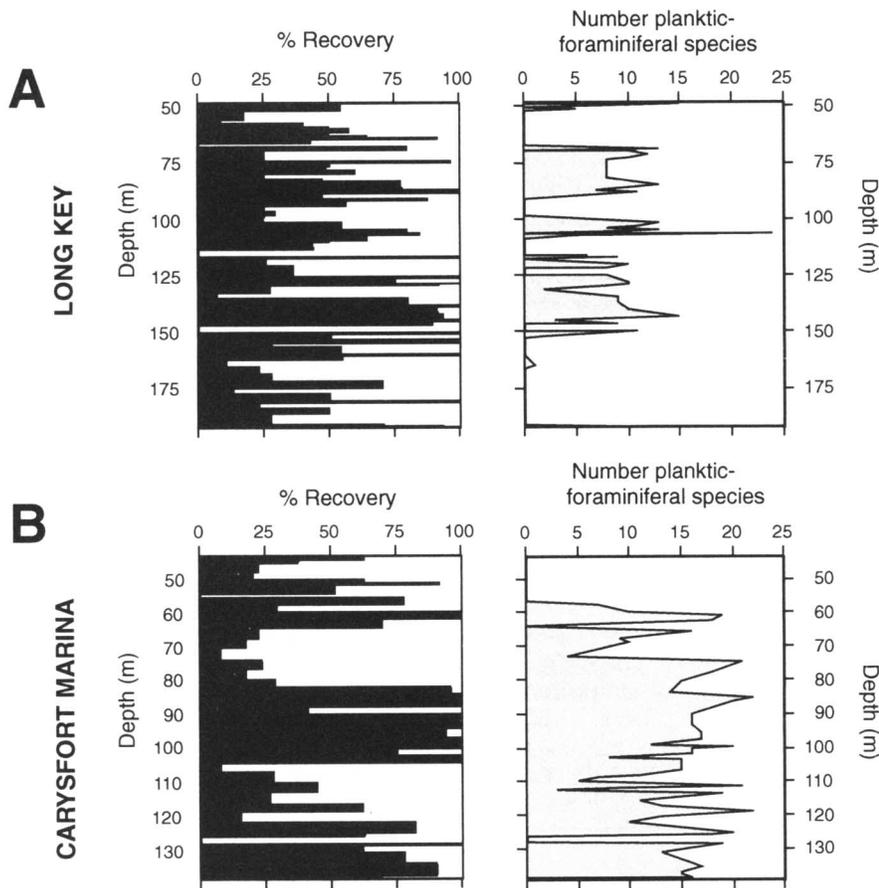
FIG. 6. Percent core recovery and number of planktic foraminiferal species identified versus depth for the Long Key Formation in the A) Long Key and B) Carysfort Marina Cores.

base of the siliciclastic unit contains poorly preserved (corroded) unidentifiable species. From the base of the core (139 m) to approximately 100 m, the age (< 6.2 Ma) is constrained by the first occurrence of *Globigerinoides conglobatus* (FAD 6.2 Ma) and LAD of *Sphaeroidinellopsis seminulina* (3.12 Ma). At 97.5 m, the age assigned is 4.5 Ma or younger on the basis of the sole occurrence of *Globorotalia crassaformis*. These ages (6.2 to 4.5 Ma) correlate with those of the lower part of the Long Key Formation at Long Key. Above a core depth of 97.5 m, identifiable species with well-constrained, diagnostic FADs were lacking. In the Carysfort Marina Core, unlike the Long Key Core, no planktic taxa are present in the upper part of the Long Key Formation to constrain its youngest age (i.e., none present at a core depth of less than 57.5 m; Fig. 6B). The patterns of menardiiform coiling direction throughout the formation are shown in Figure 5. Of the 35 samples examined, menardiiforms in the lower 17 (138.5 to 106.7 m) showed fluctuating or mixed coiling directions, whereas taxa in overlying samples (103.6 to 61.0 m) showed consistent dextral coiling.

Benthic Foraminifera. - Fourteen samples collected from throughout the Long Key Formation in the Carysfort Marina Core were examined for benthic foraminifera. The base of the formation contained an outer-shelf assemblage, suggesting deposition in 100 to 150 m of water. The assemblage present from 120.4 to 111.9 m was consistent with deposition on an inner shelf in water approximately 50 m deep. Taxa examined from 103.6 to 59.7 m suggested a slightly deeper environment, on an outer shelf in depths of 100 to 150 m. Benthic foraminifera from a single sample at 57.5 m suggested an inner- to outer-shelf environment

(10 to 130 m water depth), assuming that the assemblage did not include redeposited shallow-water taxa.

Strontium-Isotope Data. - A strontium-isotope chemostratigraphy was constructed for most of the Long Key Formation in the Carysfort Marina Core (Fig. 5). Ages obtained from the curve of Farrell et al. (1995) showed siliciclastic deposition beginning at ~6 Ma or earlier (Table 9). At a depth of 86.2 m, a strontium-isotope age suggests late early Pliocene to latest Pliocene deposition. Ages derived from strontium-isotope analyses at 55.6 m and 45.8 m indicated a shift from mid-late Pliocene deposition to latest Pliocene-Pleistocene deposition of the upper part of the Long Key Formation, respectively.

Quartz Grain Size. - The upsection variations in the predominant size of siliciclastic grains in the Carysfort Marina Core are similar to the vertical trend in the Long Key Core (Fig. 5). A thin segment (0.6 m) of very coarse-grained sand occurs at the base of the formation (139.0 to 138.4 m). The overlying interval (138.4 to 103.9 m) becomes significantly finer grained and is dominated by grains of fine to very fine sand size. An overlying interval (103.9 to 102.8 m) of very coarse- and coarse-grained sand caps the underlying finer-grained interval. This coarse-grained interval is overlain by a section (102.8 to 84.1 m) of fining-upward grain size and contains an interval of coarse silt between 92.7 and 87.5 m. From 84.1 to 61.3 m, grain size coarsens upward, reaching a very coarse sand from 68.6 to 61.3 m. From 61.3 m to the top of the formation (43.0 m), a poorly sorted quartz sand ranges from very coarse to very fine.

9

Depth (m)	Coiling Direction	Interval (Long Key)	Depth (m)	Coiling Direction	Interval (Carysfort)
		LONG KEY CORE			CARYSFORT MARINA CORE
48.8	dextral		61.0	dextral	
49.1	dextral	Interval III	62.5	dextral	
68.6	dextral		65.5	dextral	
70.1	dextral		67.7	dextral	
71.6	dextral		74.4	dextral	
73.2	dextral		77.9	dextral	
73.8	dextral		80.5	dextral	
82.0	dextral		83.9	dextral	
87.5	dextral		85.4	dextral	
88.4	dextral	Interval II	86.6	dextral	Interval II
102.1	dextral		89.9	dextral	
103.0	dextral		93.3	dextral	
103.8	dextral		95.7	dextral	
104.5	dextral		97.5	dextral	
106.8	dextral		99.4	dextral	
107.0	dextral		99.7	dextral	
116.1	sinistral		102.1	dextral	
117.3	dextral		103.6	dextral	
125.0	dextral		106.7	both	
128.9	dextral	Interval I	108.2	sinistral	
143.0	dextral		108.5	dextral	
			111.3	both	
			111.9	sinistral	
			112.5	sinistral	
			113.4	both	
			115.5	both	
			118.9	dextral	Interval I
			120.4	dextral	
			125.3	both	
			131.4	both	
			134.1	both	
			135.3	both	
			137.2	sinistral	
			137.8	sinistral	
			138.5	both	

FIG. 10. Coiling-direction data of the menardiiform planktic foraminifera in the Long Key and Carysfort Marina Cores.

DISCUSSION

Timing and Nature of Siliciclastic Deposition

A chronologic model, which is the best fit of combined results of biostratigraphy and strontium-isotope chemostratigraphy, constrains the age of the siliciclastics from the latest Miocene to latest Pliocene in both the Long Key and Carysfort Marina Cores. Three depositional intervals with varying thicknesses are proposed for the Long Key Formation (Figs. 4, 5): a basal uppermost Miocene interval (Interval I), a later lower Pliocene to mid-Pliocene (near the early-late Pliocene transition) interval (Interval II), and an uppermost Pliocene interval (Interval III). We realize that the lack of biostratigraphic marker species may bias the definition of the proposed depositional intervals. However, corresponding dates derived from strontium-isotope chemostratigraphy support the proposed biostratigraphic-lithostratigraphic intervals.

The lowermost siliciclastic sample collected in each core contains *Globigerinoides conglobatus* (FAD 6.2 Ma) and *Sphaeroidinellopsis seminulina* (LAD 3.12 Ma). Because there are no samples below these core levels to show the absence of *Globigerinoides conglobatus*, its presence at these levels does not represent its true FAD and thus indicates that the basal siliciclastics are younger than 6.2 Ma. In the Long Key Core (191.9 m), the strontium-isotope chemostratigraphy indicates a minimum age of 6.13 Ma. The maximum age is greater than 6.5 Ma, the limit of the Farrell et al. (1995) curve. The lowermost strontium-isotope sample from the Carysfort Marina Core (137.8 m) also indicates a minimum latest Miocene age of 5.94 Ma. A sample from 128.9

m in the Long Key Core has a minimum strontium-isotope age of 5.94 Ma, and a sample from 113.2 m in the Carysfort Marina Core records a strontium-isotope age of 5.75 to 6.58 Ma.

A proposed sequence boundary marks the Interval I-II transition in both cores, with the siliciclastics in each interval marked by the FOs and LADs of age-diagnostic planktic foraminifera and different ages derived from the strontium-isotope chemostratigraphy (Tables 5, 9, Figs. 4, 5). The proposed sequence boundary lies between 111.2 and 115.8 m in the Long Key Core and at 103.9 m in the Carysfort Marina Core. By definition, the most pronounced attributes of a sequence boundary in siliciclastic sediments are seismic truncation, a basinward shift in facies, and subaerial exposure (Van Wagoner et al. 1990). In shallow-marine settings, the facies shift is often associated with an abrupt grain-size increase (Emery and Myers 1996). In the Florida Keys, the siliciclastics of the Long Key Formation contain evidence for a sequence boundary at the Miocene/Pliocene boundary (Interval I-Interval II boundary), although subaerial exposure was not recognized. As will be shown, both the Long Key and Carysfort Marina Cores reflect a temporal hiatus on the basis of biostratigraphic parameters, strontium-isotope chemostratigraphy, a major increase in quartz grain size, and an abrupt deepening of the depositional facies upward, across the sequence boundary (Figs. 4, 5). The interval that would contain this sequence boundary in the Long Key Core was not recovered by coring (Fig. 7), yet the physical characteristics above and below the interval of no recovery provide evidence that a boundary exists.

The benthic foraminifera in the Long Key Formation indicate variations in paleoenvironment and inferred water depth during siliciclastic deposition (Fig. 7). The base of the Long Key Formation in both cores contains benthic genera characteristic of an outer-shelf environment. In Interval I of both cores, the faunas indicate a transition from an outer-shelf to inner-shelf environment, below the level at which the FO of *Globorotalia crassaformis* (FAD 4.5 Ma) occurs and at a level where a change in coiling pattern of the menardiiform species occurs. Above the interval of no recovery (111.2 to 115.8 m) in the Long Key Core (Fig. 4), an inner-shelf benthic assemblage is consistently present through the rest of the siliciclastic section, up to 48.2 m. Benthic faunas in the Carysfort Marina Core (Fig. 5), in contrast, indicate an upward shift to a deeper outer-shelf environment above the sequence boundary. Outer-shelf depositional characteristics persist until the appearance of shallow-water genera at 57.5 m. An outer-shelf to inner-shelf assignment in both cores for Interval II is probably more realistic than the inner-shelf assignment presently allocated to the Long Key Core. The basal inner-shelf part of Interval II probably contains allochthonous shallow-water components introduced by reworking of sediments from other parts of the peninsula. Preservation of the inner-shelf fauna from this interval is poor (reflecting much abrasion) compared to that of the outer-shelf fauna. However, the upward shift from inner-shelf to outer-shelf deposition in the Carysfort Marina Core does correlate with an upward shift in the menardiiform coiling pattern and with a change in the quartz-grain size from fine- to very fine-grained to an isolated interval of very coarse- and coarse-grained sand. The Long Key Core does not have an equivalent coarse-grained unit prior to the FO of *Globorotalia crassaformis*, although a coarse unit may have been present in

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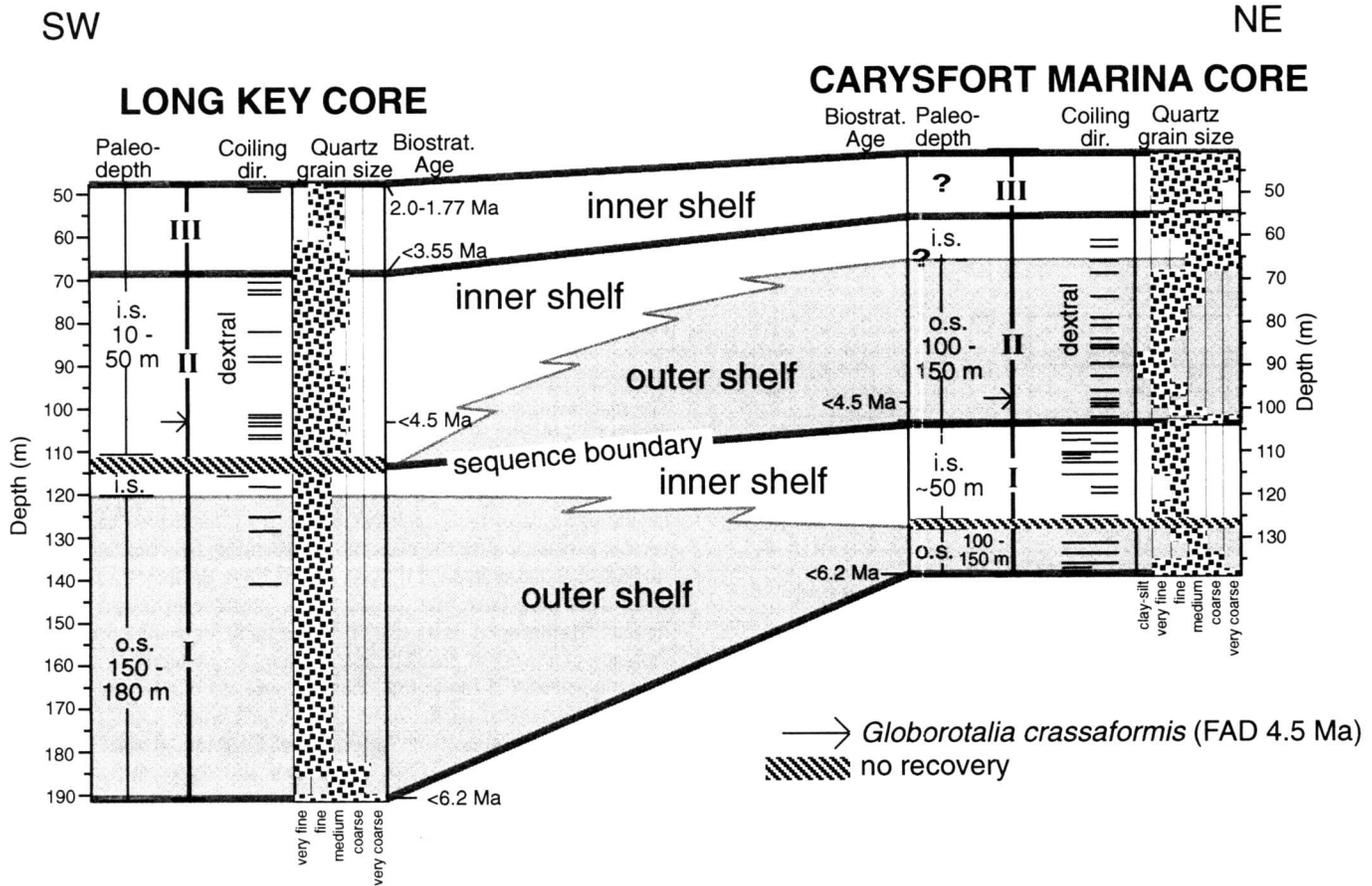
FIG. 7. Correlation of the Long Key Formation plotted to scale between the Long Key and Carysfort Marina Cores. For each core the inferred depositional environment, locations of Intervals I, II, and III, coiling direction of the menardiiform planktic foraminifera, and the distribution of quartz grain size with depth are presented.

the 4.6-m-thick unrecovered section. On the other hand, the Long Key Core does contain an abrupt upward increase in grain size across the core gap, which may indicate presence of a sequence boundary in the unrecovered part of the core (Fig. 7).

The difference in depth to the base of the siliciclastics between the two cores (191.9 m in Long Key, 139.0 m in Carysfort Marina) is consistent with greater accommodation space in the middle Keys relative to that available in the upper Keys during deposition of Interval I. Today, depth to Pleistocene bedrock is still several meters greater at Long Key than in the upper Keys (Lidz and Shinn 1991). The lower Pliocene sediments (Interval II) at Long Key (above the FO of *Globorotalia crassaformis*) possibly remained in the inner-shelf range, whereas at Carysfort Marina an outer-shelf benthic assemblage indicates deeper water. A persistent inner-shelf depth at Long Key may also reflect a higher rate of sedimentation relative to that in the Carysfort Marina Core. A differential rate of infilling between the two core sites is consistent with mapping of the siliciclastics by Cunningham et al. (1998), which suggests that the Long Key Core may be positioned within a trend of coarse-grained siliciclastics. However, the shallow-water conditions recorded during Interval II at Long Key most likely reflect the incorporation of reworked shallow benthic taxa from farther north on the Florida platform, thereby biasing the paleodepth data. The abraded condition and poorer preservation of the inner-shelf fauna versus those of the outer-shelf fauna support this hypothesis. Furthermore,

Intervals II and III at both core sites contain reworked planktic foraminifera of Oligocene and early Miocene age that are heavily corroded and recrystallized. In the Carysfort Marina Core, the interpreted transition from outer to inner shelf is probably accurate on the basis of the differences in test preservation and ability to distinguish reworked from *in situ* benthic fauna.

The data on menardiiform coiling direction from our study are used as an additional diagnostic biostratigraphic parameter, especially in the Carysfort Marina Core. In the upper Miocene Interval I at Carysfort Marina, a fluctuating coiling direction is consistent with the random directions expected for the late Miocene (Fig. 8; Bolli and Saunders 1985). From 103.6 m to the uppermost recovered planktic foraminifera at 61.0 m (Intervals II and III), the menardiiform species show dextral coiling in an outer-shelf interval. The dextral direction is consistent with a Pliocene age. Coiling data in the Long Key Core are not as definitive as in the Carysfort Marina Core because of fewer samples. Only one yielded sinistral specimens (Table 10). In accordance with the summary published by Bolli and Saunders (1985) (Fig. 8), the coiling-direction data suggest that the upper 62.4 m of siliciclastics (and the planktic foraminifera) in the Long Key Core are Pliocene deposits. Because this interval also contains the corroded and recrystallized Oligocene planktic species *Globigerina ciperoensis anguliofficinalis*, *Catapsydrax dissimilis*, and *Globigerina praebulloides leroyi*, which last occurred in the early Miocene, the sinistrally coiled menardiiforms present at 116.1 m

Planktic Foraminiferal Zones	Age (Ma)	Menardiiform Coiling Direction
Pleist. — Pt1	1.77	sinistral
PL6	2.30	
PL5	3.09	
PL4	3.12	dextral
PL3	3.58	
PL2	4.18	
PL1	5.60	
M14	6.00	fluctuating
M13	10.9	
M12	11.4	
M11	11.8	sinistral
M10	11.9	
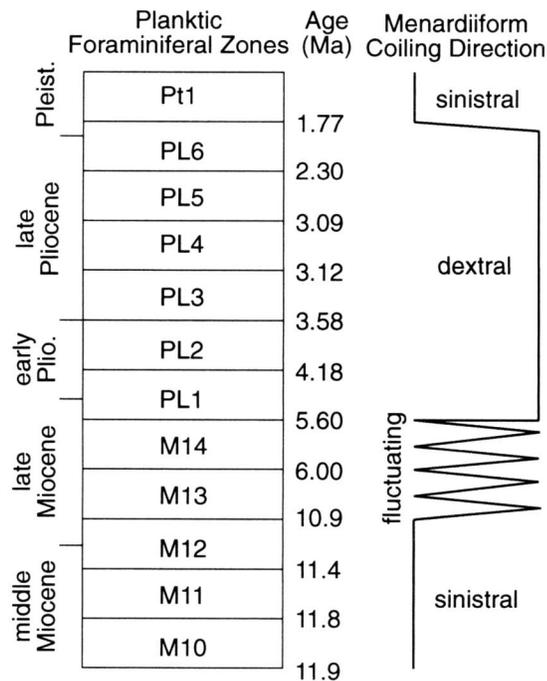
FIG. 8. (Sub)tropical planktic-foraminifera zones defined by Berggren et al. (1995b). The timing of changes in coiling direction were taken from Bolli and Saunders (1985) and updated to the Berggren et al. (1995b) time scale.

may also be reworked.

Regional and Global Events

The timing of late Neogene siliciclastic deposition coincides with a series of regional geologic events. Our chronologic model indicates that siliciclastic Interval I was deposited in south Florida during the latest Miocene and is coincident with a late Miocene intensification of the Florida Current-Gulf Stream system (Mullins et al. 1980; Eberli et al. 1997). Deposition of Interval I near the Miocene-Pliocene transition is also correlative with an accumulation of winnowed foraminiferal ooze on the Blake Plateau that occurs below and above a disconformity that spans the Miocene-Pliocene boundary (Kaneps 1979). Deposition of the Blake Plateau ooze was interrupted by a period of nondeposition or erosion, represented by the disconformity. The nondeposition or erosion is attributed to the late Miocene glacial maximum on Antarctica that occurred prior to the FAD of *Globorotalia crassaformis* at 4.5 Ma (Shackleton and Kennett 1974). In south Florida, the first occurrence of *Globorotalia crassaformis* is not until siliciclastic Interval II (late early Pliocene). We thus can correlate the timing of the arrival of siliciclastics in south Florida to the interval of winnowed foraminiferal ooze on the Blake Plateau that spans the Miocene-Pliocene disconformity (Kaneps 1979). More recent evidence for current intensification comes from Ocean Drilling Program (ODP) Leg 166, where proposed contour-current activity is observed in a borehole located in the Santaren Channel just east of the Great Bahama Bank (Eberli et al. 1997). The ODP Shipboard Party has assigned a preliminary age of ~6.6 to 4.9 Ma to this interval. This period of current intensification may be linked to eustatic lowstands or to a shift of currents across the Bahama platform during the subsequent transgression. Evidence for a latest Miocene-earliest Pliocene lowstand was also found in the Bahamas Drilling Project borehole UNDA, where a 61.9-m-thick interval of upper Messinian reef complex capped by a subaerial exposure horizon was recovered (McNeill et al. in press).

The timing of siliciclastic deposition in south Florida is tentatively correlated with highstand-to-lowstand transitions during supercycle TB3 of Haq et al. (1988) (Fig. 9). Siliciclastic Interval I is tentatively correlated to bracket the TB3.3-TB3.4 boundary, with possible development of a depositional hiatus during the TB3.4 cycle across the Miocene-Pliocene boundary. The latest Miocene-early Pliocene global highstand (cycle TB3.4) has been interpreted in south Florida as a marine transgression that occurred at approximately 4.9 to 4.3 Ma. (Willard et al. 1993). A subaerial-exposure disconformity overlain by a deep-shelf facies representing cycle TB3.4 has also been identified on the western Great Bahama Bank and dated at ~4.2 to 5.3 Ma (McNeill et al. in press). The early Pliocene transgression appears to have flooded the Florida platform and may have mobilized the coarser siliciclastic sediments located to the north. The subsequent regression then transported the sediments southward (Fig. 2). Similarly, siliciclastic Interval II was first deposited near the TB3.4-TB3.5 transition and likely ended during TB3.6 cycle. The base of Interval III at ~2.0 Ma (or younger) began to accumulate during TB3.8 near the end of the Pliocene. A major late Pliocene lowstand, resulting from nearly final restriction of flow across the Isthmus of Panama (Coates et al. 1992) and the onset of Northern Hemisphere glaciation (Shackleton et al. 1984; Burton et al. 1997), likely influenced termination of siliciclastic deposition in the Florida Keys region near the Pliocene-Pleistocene transition. Again, we stress that correlations to the Haq et al. (1988) eustatic curve are tentative; age resolution of the siliciclastics and uncertainty in the age resolution of the eustatic curve preclude specific correlation to parts of the proposed eustatic cycle (i.e., transgression, highstand, lowstand).

The changes in siliciclastic grain size may also be a reflection of regional oceanographic events. For example, sediments in the Yucatan Channel between western Cuba and the Yucatan Peninsula show evidence of winnowing by deep currents that have flowed since at least the early Pliocene, with intermediate-depth and surface currents supplying fine sediments to the Straits of Florida (Brunner 1986). In the Florida Straits, the sand-size fraction increased slightly throughout the late Pliocene and Quaternary (Brunner 1979), and the intervals containing the highest proportions of sand-size material were believed to have been winnowed by bottom-current activity during late Pliocene and Pleistocene glacial events (Brunner 1984). The variations in grain size in the Yucatan Channel and Florida Straits correlate with a similar quartz grain-size record in the Long Key Formation. Siliciclastic Interval III contains few fines, and there is an associated increase in the percentage of very coarse- to medium-grained sand as well as a marked reduction in the medium- and fine-grained components.

The thick foundation of siliciclastic sediments deposited in south Florida during the late Miocene to late Pliocene served as the template for subsequent Quaternary carbonate deposition. Siliciclastic deposition was likely related to a structural low at
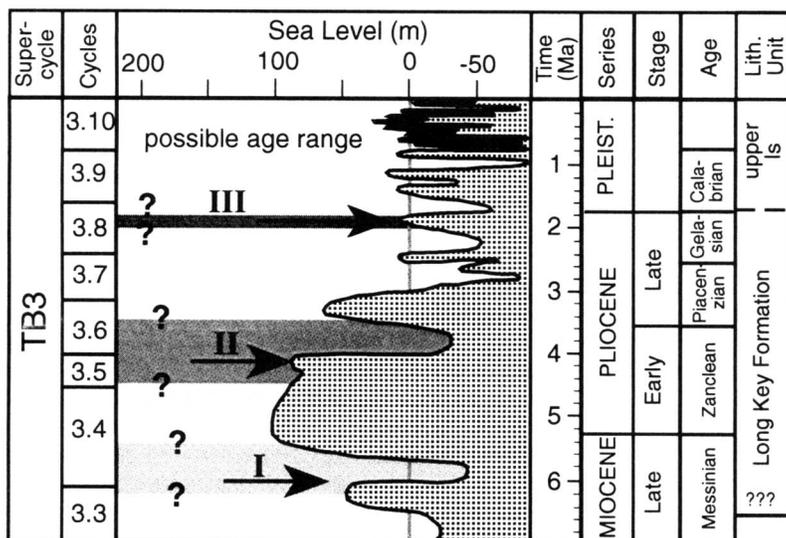
FIG. 9. Comparison of the estimated age ranges of intervals of siliciclastic deposition of the Long Key Formation of the Long Key Core to the eustatic curve of Haq et al. (1988), adjusted to the Berggren et al. (1995b) time scale. Low resolution in ages of the lithologic units and the eustatic curve precludes an accurate correlation between intervals of siliciclastic deposition and changes in sea level. High-frequency fluctuations in late Pleistocene make that part of the curve appear black.

the top of the Arcadia Formation (Fig. 3) that existed from west of Lake Okeechobee to the Florida Keys. Siliciclastics, were transported southward and filled an interpreted shallow-marine basin at the south end of the peninsula. As the siliciclastics prograded to the east and southeast (Cunningham et al. 1998), they were likely subjected to current reworking and winnowing. The location and pattern of the Pleistocene oolitic (Miami Limestone) and reefal limestones (Key Largo Limestone) and the modern reef tract were in large part determined by the geometry of the siliciclastic debris, in addition to fluctuating sea level. The Quaternary limestones above the Long Key Formation range from 18 to 61 m in thickness (Ginsburg et al. 1989) and were deposited during several Pleistocene highstands (Perkins 1977).

CONCLUSIONS

An investigation integrating results of biostratigraphy, strontium-isotope chemostratigraphy, and grain-size analyses of the siliciclastic Long Key Formation, recovered in two boreholes drilled in the middle and upper Florida Keys, shows that the sands accumulated from as early as the latest Miocene to late Pliocene in outer- to inner-shelf environments. On the basis of planktic foraminiferal and strontium-isotope data, we propose that deposition was discontinuous and that the siliciclastics represent three episodes of accumulation. As presently interpreted, core Intervals I and III are correlative between the boreholes with respect to paleo-water depth of accumulation. Depositional environments in Interval II are disparate between the holes because of the likely inclusion of reworked benthic taxa in the middle Keys. Evidence for discrete uppermost Miocene (Interval I) and lower Pliocene (Interval II) depositional units consists of concomitant changes in grain-size fraction and in planktic menardiiform coiling directions at the Interval I-II contact. Evidence for a possible discrete uppermost Pliocene unit (Interval III) is defined only by a general change in grain size. Whereas the sands in the upper Keys Carysfort Marina Core clearly indicate two transgressive/regressive cycles based on benthic taxa, those in the middle Keys Long Key Core appear to indicate a single cycle. The conflicting paleodepth data from Interval II can be interpreted in two ways. The first invokes a higher rate of siliciclastic sedimentation at Long Key than at Carysfort Marina. Interval II in the Long

Key Core contains coarser quartz grains and is located closer to the proposed source of siliciclastic influx to the Keys. Rapid infilling of the middle Keys area would allow for the presence of inner-shelf benthic taxa. An alternative and more favorable explanation for the disparate environments between the two cores suggests that during Interval II in the middle Keys, the indicators for paleo-water depth may have been biased by the presence of reworked benthic foraminifera imported on an early Pliocene influx of shallow-water debris. Presence of reworked planktic taxa in Long Key Interval II support the influx hypothesis. If this is true, then this unit at Long Key may actually have been deposited on the outer shelf, which would correlate with the depositional environment for Interval II at Carysfort Marina. The siliciclastics in the Long Key Core would then also represent two complete transgressive/regressive cycles.

A thicker upper Miocene section to the south than to the north suggests greater accommodation space to the south during the Messinian-Gelasian transition. Sea-level fluctuations and strong regional currents served as the primary controls for eroding, transporting, and winnowing the siliciclastics, believed to have originated from a source area in the Appalachian Mountains.

ACKNOWLEDGMENTS

ments, which significantly improved the manuscript.

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