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Pleistocene Carbonate Stratigraphy of South Florida: Evidence for High-Frequency Sea-Level Cyclicity

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ABSTRACT

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Pleistocene carbonates of south Florida and islands of the Florida Keys are currently divided into five marine sequences designated, from oldest to youngest, the Q1–Q5 units. The units include a mosaic of freshwater and shallow marine deposits that accumulated on the Florida platform during high sea-level stands. The units are separated by regional-scale subaerial-exposure surfaces that formed during glacioeustatic lowstands. Analyses of cores recovered at Grossman Ridge Rock Reef and Joe Ree Rock Reef in the Florida Everglades reveal additional subaerial-exposure surfaces that are used to delineate subdivisions within units Q1 (Q1a–Q1b), Q2 (Q2a–Q2d), and Q4 (Q4a–Q4b). Units Q1–Q5 preserve evidence of at least 10 separate sea-level highstands, rather than 5 as indicated by previous studies.

Compilation of available uranium-series dates on corals recovered from the Florida Keys indicates that the Q4 unit accreted during sea-level maxima associated with marine oxygen-isotope Stage 9 (Q4a) and isotope Stage 7 (Q4b). The Q5 unit formed during isotope Stage 5. No reliable dates are available for units Q1–Q3. We infer that unit Q3 was formed during the extended sea-level highstand of isotope Stage 11 and that units Q2 and Q1 predate isotope Stage 11.

ADDITIONAL INDEX WORDS: *South Florida chronostratigraphy, South Florida lithostratigraphy, paleodepositional environments, carbonate accumulation, soilstone crusts, sea-level cyclicity, Pleistocene accumulation chronology.*

INTRODUCTION

Pleistocene carbonates of south Florida and the islands of the Florida Keys represent a series of shallow-water deposits that accumulated during interglacial sea-level highstands (Hoffmeister and Multer, 1964, 1968). Depending on the locality and facies, the Pleistocene units have been referred to as the Key Largo Limestone, the Miami Limestone, or the Fort Thompson Formation (see summaries in Cunningham, Mcneill, and Guertin, 1998; Harrison and Coniglio, 1985; Multer *et al.*, 2002; Figure 1). The Key Largo Limestone is a marine limestone containing many fossil corals and is observed on the surface and subsurface of the Florida Keys from Sand Key to Loggerhead Key. The shallow subsurface of south Florida consists of the Miami Limestone (Parker and Cooke, 1944). Previously considered part of the Key Largo Formation (Sanford, 1909; Smith, 1854), the Miami Limestone has been further defined by facies and is a lateral equivalent to the upper, fossil coral reef units of the Key Largo Limestone. Two distinct facies have been recognized in the Miami Limestone, the oolitic facies (found under the city of Miami and in the lower Florida Keys) and the bryozoan facies (observed within the boundaries of Everglades National Park and Florida Bay). The oolitic facies of the Miami Limestone is primarily composed of ooids that have been lithified to form the oolite presently encountered in the region. The bryozoan facies of the Miami Limestone is named after the abundantly observed bryozoan species *Schizoporella floridana* found in high densities within the matrix of the upper surficial limestones of south Florida. The Fort Thompson Formation (Causaras, 1987; Cooke and Mossom, 1929; Parker and Cooke, 1944; Sellards, 1919) is recognized as a lateral equivalent of the lower sequences of the Key Largo Limestone (see Cunningham, Mcneill, and Guertin, 1998, their figure 5) observed in the subsurface of the Florida Keys. The marine limestone is porous, contains mollusks, corals, bryozoans, and benthic foraminifers, and locally includes intermittent pockets of siliciclastics (Causaras, 1987; Missimer, 1984; Warzeski *et al.*, 1996). Freshwater limestones have been observed in the Miami Limestone, as well as, the Fort Thompson Formation. These freshwater limestones are very well cemented and include many freshwater snails that have been identified historically as *Helisoma* sp. and more recently as *Planorbella* sp. (Causaras, 1987; Cunningham *et al.*, 2004; Spear, 1974).

In his detailed study of a series of cores and outcrops south of Lake Okeechobee and along the Florida Keys, Perkins (1977) recognized that the shallow-water Pleistocene deposits of south Florida and the Keys could be divided into five major

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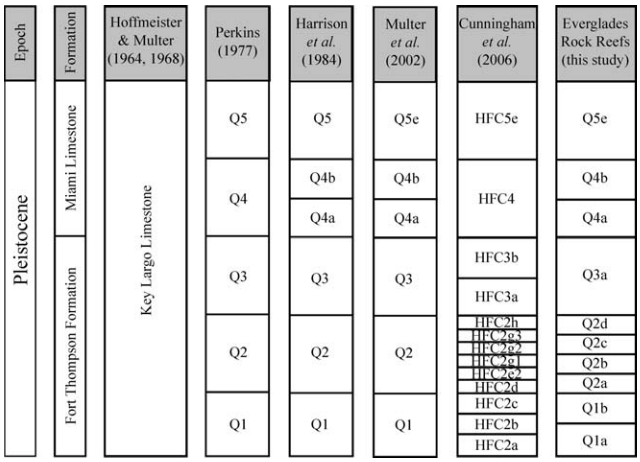

Figure 1. Correlation of previous south Florida stratigraphic terminology of the Fort Thompson Formation and the Miami Limestone (modified from Cunningham *et al.*, 2006).

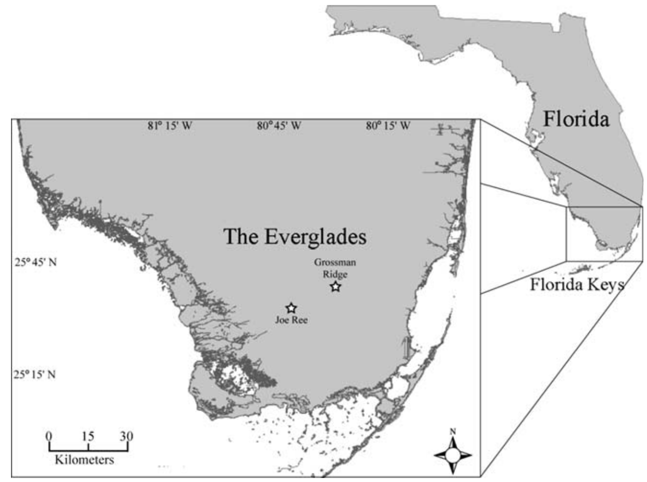

Figure 2. Joe Ree Rock Reef and Grossman Ridge Rock Reef study locations in south Florida.

Pleistocene time-stratigraphic sequences, designated from oldest to youngest as the Q1–Q5 units (Q for Quaternary). The sequences are bounded by discontinuity surfaces identified by features including: (a) vadose sediment, (b) land-plant root structures, (c) laminated crusts, (d) diagenetic soilstones, (e) soils and soil breccias, (f) solution surfaces, (g) bored surfaces, and (h) freshwater limestones (Perkins, 1977). Soilstone crusts have been recognized as particularly valuable indicators of subaerial exposure (Harrison, 1977; Kornicker, 1958; Multer and Hoffmeister, 1968; Perkins, 1977; Robbin, 1981). There is a direct relation between soilstone-crust thickness, porosity, and time (Robbin and Stipp, 1979). Limestone porosity may contribute to crust thickness. A less porous limestone such as the oolitic Miami Limestone retains water from precipitation longer than the more porous reefal Key Largo Limestone, providing more time for pedogenic processes to occur. The boundaries between the stratigraphic units defined by Perkins (1977) represent subaerial-exposure surfaces formed during periods of lower sea levels. Thus, the Pleistocene stratigraphy of south Florida and the Florida Keys is framed in regional units that are linked to sea-level fluctuations associated with glacial–interglacial cycles.

The sequence of Q units defined by Perkins (1977) has been recognized and widely used in subsequent surfical and subsurface stratigraphic and framework studies in south Florida and the Keys (Cunningham *et al.*, 2004, 2006; Halley and Evans, 1983; Harrison and Coniglio, 1985; Harrison, Cooper, and Coniglio, 1984; Ludwig *et al.*, 1996; Muhs *et al.*, 1992; Multer *et al.*, 2002; Shinn, Reese, and Reich, 1994). For example, Harrison, Cooper, and Coniglio (1984) recognized the Q units of Perkins (1977) in their study of the stratigraphy and sedimentology of cores from the islands of Key Largo and Big Pine Key. More recently, Cunningham *et al.* (2006) recognized the Q units while investigating hydrologic characteristics of the limestone beneath Miami-Dade County, Florida.

Uranium-series dates on corals from unit Q5 in the Florida Keys yield dates of 130 to 120 ka (Muhs *et al.*, 2003; Multer *et al.*, 2002), indicating the unit accumulated during the last glacial maximum or substage 5e in the standard oxygen-isotope record (Lisiecki and Raymo, 2005). Ages of the other Q units are not well established. The most recent compilation of available radiometric dates suggested that the entire sequence of Q units was deposited in the last 400,000 years (Multer *et al.*, 2002).

In this study, we report results of our examination of a series of drill cores through linear topographic highs in Pleistocene carbonate sequences in the Florida Everglades. The features are known locally as Grossman Ridge Rock Reef and Joe Ree Rock Reef (Figure 2). Our results allow refinement of the stratigraphic framework established by Perkins (1977). In addition, we summarize and propose a revision of the age assignments of units Q1–Q4 based on published uranium-series dates.

MATERIALS AND METHODS

Five cores were collected in a transect along Grossman Ridge Rock Reef and three along a transect across Joe Ree Rock Reef. Cores were drilled with the U.S. Geological Survey (St. Petersburg, Florida) portable hydraulic drill. This system retrieved a 2 in. diameter rock core and left a 3 in. wide open hole. Depths of penetration and percentages of core recovery for the two transects are available in Table 1.

The cores recovered from the rock-reef transects were transported to the U.S. Geological Survey in St. Petersburg, Florida, for analyses, correlation, and archiving. Lapidary saws were used to slice the predominantly carbonate cores. Cores were slabbed along the long axis to facilitate description. Rock-core description was conducted using a 10× magnification hand lens and a binocular microscope. The carbonate classification of Dunham (1962) was used for describing carbonate lithology and lithofacies. Hickey *et al.* (2004) provides further description of core recovery and curation techniques.

We used micro- and macroscopic analyses to identify key features to determine limestone origin. The occurrence of the

Table 1. *Depth of penetration and core recovery percentages for the two transects.*

	Depth of Penetration		
Core ID	(m)	(ft)	Core Recovery (%)
GR1	13.7	45	50
GR2	14	46	75
GR3	13.4	44	51
GR4	14.3	47	78
GR5	14.6	48	79
JR1	11.3	37	75
JR2	11.3	37	77
JR3	11.3	37	70

freshwater gastropod *Planorbella* sp. characterizes brackish or freshwater limestones (Figures 3A and B). Marine limestones often contain pelecypod shells and shell fragments (Figure 3C) and shallow water marine benthic foraminifers including representatives of the Super Families Miliolaceans, including genera *Quinquelocolina* and *Peneropolis*, and Rotaliaceans, including genera *Ammonia* and *Elphidium* (Figure 3D). Several types of marine benthic foraminifers are present in the burrowed marine limestone in Figure 3D. The burrows contain secondary infilling from the overlying gray, freshwater lime mudstone.

RESULTS

Stratigraphic Units

Generalized lithologic columns for the most complete cores recovered at the Grossman Ridge Rock Reef and Joe Ree Rock Reef transects are shown in Figures 4 and 5. A sequence of lithified carbonate rocks overlying unconsolidated fine-grained quartz sand was recovered from both transects. The unconsolidated quartz sand at the base of the cores represents the Pliocene Tamiami Formation of Ginsburg *et al.* (1989). Distinctive red-stained soil horizons, informally named red soil horizon 1 (soilstone crust rsh1–oldest) through red soil horizon 5 (soilstone crust rsh5–youngest), change in quartz content, skeletal grains, and texture, allowing recognition of the Q units of Perkins (1977) in the carbonate sections.

The major soilstones vary in thickness but are readily identifiable in split core surfaces. Examples of soilstones capping units Q3, Q4, and Q5 are shown in Figures 6A, B, and C. The soilstone at the top of unit Q3 is one of the most prominent discontinuity surfaces in south Florida (Robbin, 1981; Robbin and Stipp, 1979; Shinn, Reese, and Reich, 1994).

Our examination of the sequence of cores at two sites revealed more subtle discontinuity surfaces within the framework of the major soilstone horizons that allow subdivision of units Q1, Q2, and Q4 (Table 2). The less obvious discontinuities represent additional exposure surfaces that are marked by thin soilstones (Figures 7A and B) and horizons of cypress and mangrove roots (Figure 7C).

Q1 Unit (subunits Q1a and Q1b)

Unit Q1 occurs between the unconsolidated quartz sand of the Tamiami Formation and soilstone crust rsh1 (Figures 4 and 5). A quartz-rich sandstone–sandy wackestone with a basal

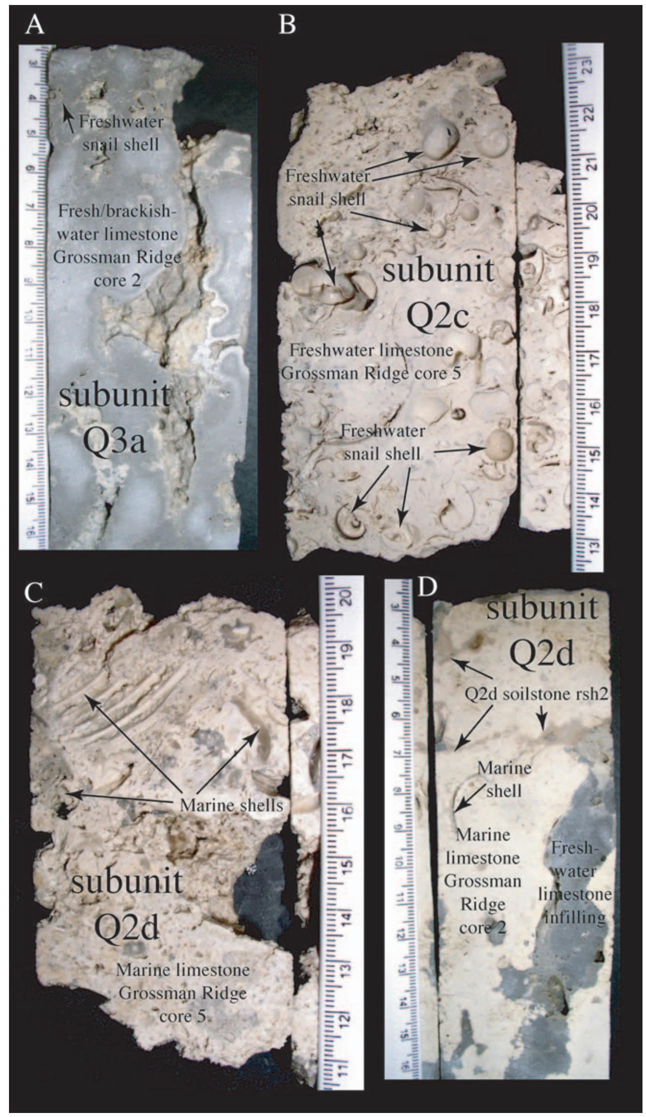

Figure 3. (A) Rock sample is a dense, brackish or freshwater lime mudstone with channel and vuggy porosity collected from Grossman Ridge Rock Reef core 2, subunit Q3a. Interpretation was aided by presence of the gastropod shells of the freshwater snail species *Planorbella*. Scale is in centimeters. (B) Freshwater fossiliferous, light-gray lime wackestone containing *Planorbella* freshwater gastropod shells recovered from subunit Q2c of Grossman Ridge Rock Reef core 5. Scale is in centimeters. (C) Fossiliferous, marine limestone recovered from subunit Q2d along Grossman Ridge Rock Reef core 5. Scale is in centimeters. (D) Recovered core represents a burrowed marine accumulation from Grossman Ridge Rock Reef core 2 with soilstone crust rsh2 present at the 3-, 4-, and 7-cm markers. Later, accumulation of the freshwater lime mudstone secondarily infilled the burrows. Scale is in centimeters.

zone of root molds, root structures, and burrows was recovered above the unconsolidated quartz sand of the Tamiami Formation in all cores. The basal quartz sandstone–wackestone recovered in both transects grades upward into a series of sandy packstone–wackestones. At Grossman Ridge Rock Reef (GR), the quartz-rich sandy packstone–wackestones are capped by soilstone crust rsh1, but at Joe Ree Rock Reef

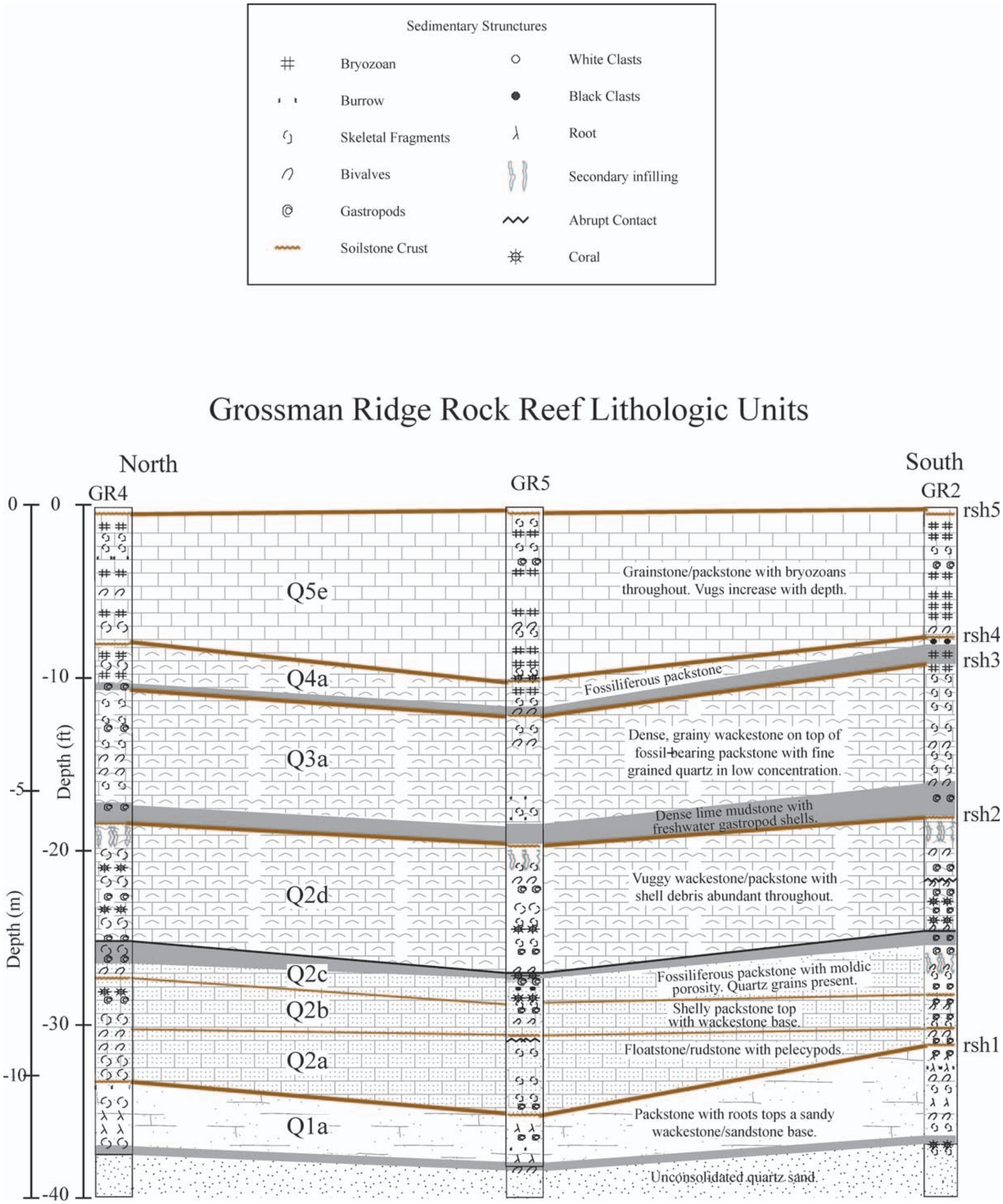

Figure 4. Grossman Ridge Rock Reef lithologic units. Note sharp contact between freshwater (Q2c) and marine (Q2d) sequences. Vertical datum is mean sea level. Gray shaded areas indicate freshwater limestones.

(JRR), skeletal packstones with isolated head corals and common benthic foraminifers are present between the sandy packstone–wackestone sequence and soilstone crust rsh1. The boundary between the sandy packstone–wackestones and skeletal packstones is marked by a caliche (Q1a soilstone, Figure 7B) with root molds (Figure 7C), indicating a subaerial-exposure surface. The lower sequence of quartz-rich sandy packstone–wackestones is assigned to subunit Q1a (Figure 7C). Point-count analysis (Figure 8) of Q1a indicates that over 66% of the thin section is composed of quartz (30.5%) and

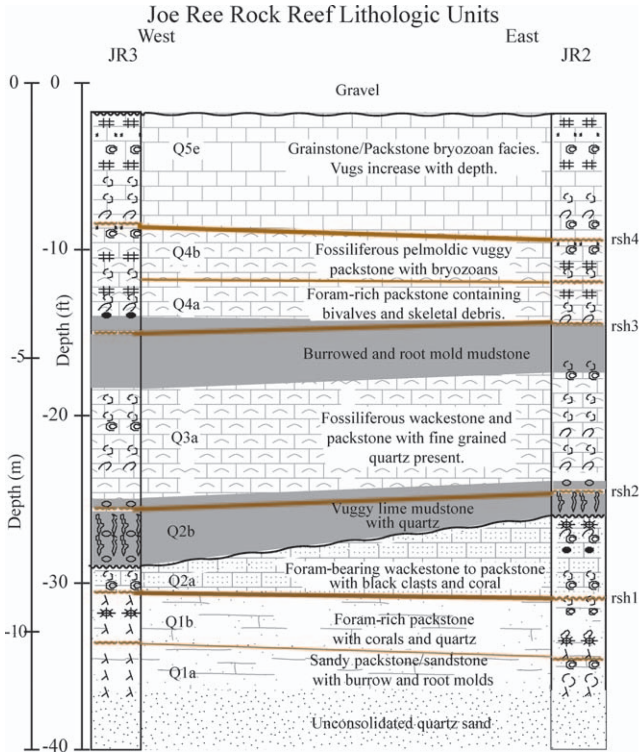

Figure 5. Joe Ree Rock Reef correlated lithologic units. Key same as Figure 4. Vertical datum is mean sea level. Gray shaded areas indicate freshwater limestones.

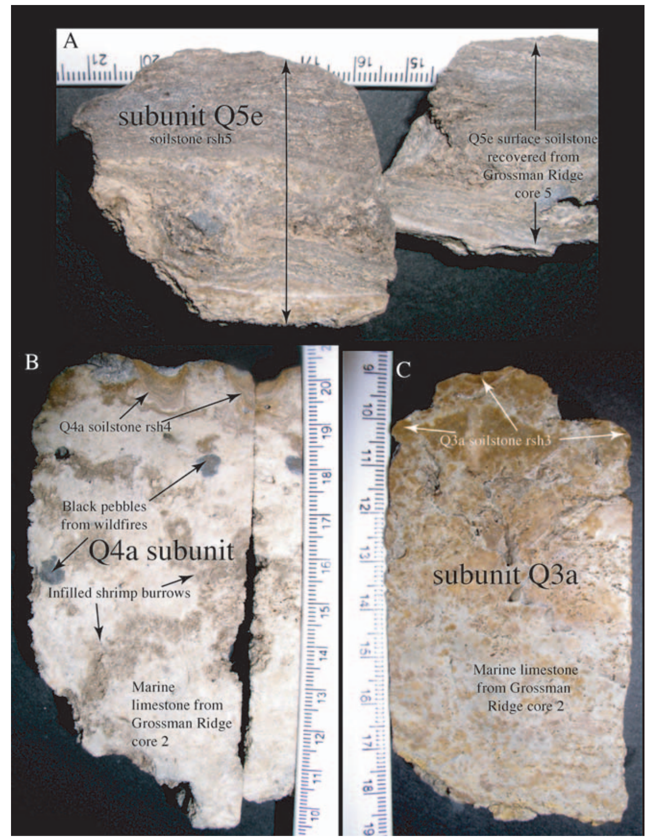

Figure 6. (A) Subaerially formed laminated $CaCO_3$ soilstone crust recovered from the top of Grossman Ridge Rock Reef core 5. Soilstone rsh5 caps subunit Q5e and is commonly exposed throughout south Florida. The soilstone has been sliced and displayed side-by-side. Scale is in centimeters. (B) Capping the highly burrowed Q4a subunit is a persistent soilstone crust recovered from Grossman Ridge Rock Reef core 2. Black pebbles are an effect of wildfires (Shinn and Lidz, 1988). Scale is in centimeters. (C) Continuous soilstone rsh3 on top of subunit Q3a is one of the most recognizable discontinuity surfaces in south Florida. This soilstone was recovered from Grossman Ridge Rock Reef core 2. Scale is in centimeters.

calcite cements (36%). The skeletal packstone found above the caliche at Joe Ree Rock Reef is assigned to subunit Q1b (Figure 5).

Q2 Unit (subunits Q2a and Q2b at JRR, subunits Q2a–Q2d at GR)

Unit Q2 is bounded by soilstone crust rsh1 and soilstone crust rsh2 (Figures 4 and 5). The section recovered at Grossman Ridge Rock Reef reveals that unit Q2 includes a complex sequence of marine and freshwater carbonates, reflecting varying inner-platform depths or elevations that can be separated into at least four subunits defined by exposure surfaces. A floatstone–rudstone with pelecypods (Q2a, Figure 4) overlies soilstone crust rsh1. A laminated soil crust separates Q2a from an overlying shelly wackestone to packstone (Q2b, Figure 7B) with common freshwater gastropods (*Planorbella* sp.). Another laminated soil crust occurs at the top of Q2b (Figure 7A) and separates Q2b from a mollusk-rich packstone with moldic porosity (Figure 4). A light-gray limestone with freshwater gastropods (*Planorbella* sp.) overlies the packstone with moldic porosity. There is an abrupt contact between the light-gray freshwater limestone and an overlying vuggy wackestone–packstone with coarse skeletal fragments and basal rubble layer. We interpret the abrupt contact as evidence for a subaerial-exposure surface. The vuggy wackestone-packstone is capped by soilstone crust rsh2. The mollusk-rich packstone with moldic porosity and the light-gray freshwater limestone are designated Q2c (Figure 3B). The vuggy wackestone–packstone is designated Q2d (Figure 3C). The lithologies and fossil content indicate subunits Q2a–Q2d recovered at Grossman Ridge Rock Reef are shallowing-upward sequences.

Unit Q2 at Joe Ree Rock Reef includes a foraminiferal wackestone to packstone with black clasts and scattered head corals that is overlain by a vuggy lime mudstone with scattered quartz grains (Figure 5). The sharp contact between the wackestone to packstone and the lime mudstone is considered to be evidence for subaerial exposure. Unit Q2 at Joe Ree Rock Reef is truncated. Unit Q2 is a maximum of 2 m thick at Joe Ree Reef, whereas the same unit is up to 5 m thick at Grossman Ridge Rock Reef. Unit Q2 point-count and binocular-microscopic analyses corroborate the designation and the correspondence of subunits Q2a and Q2b in the Joe Ree Rock Reef and Grossman Ridge Rock Reef sections. Quartz concentration of

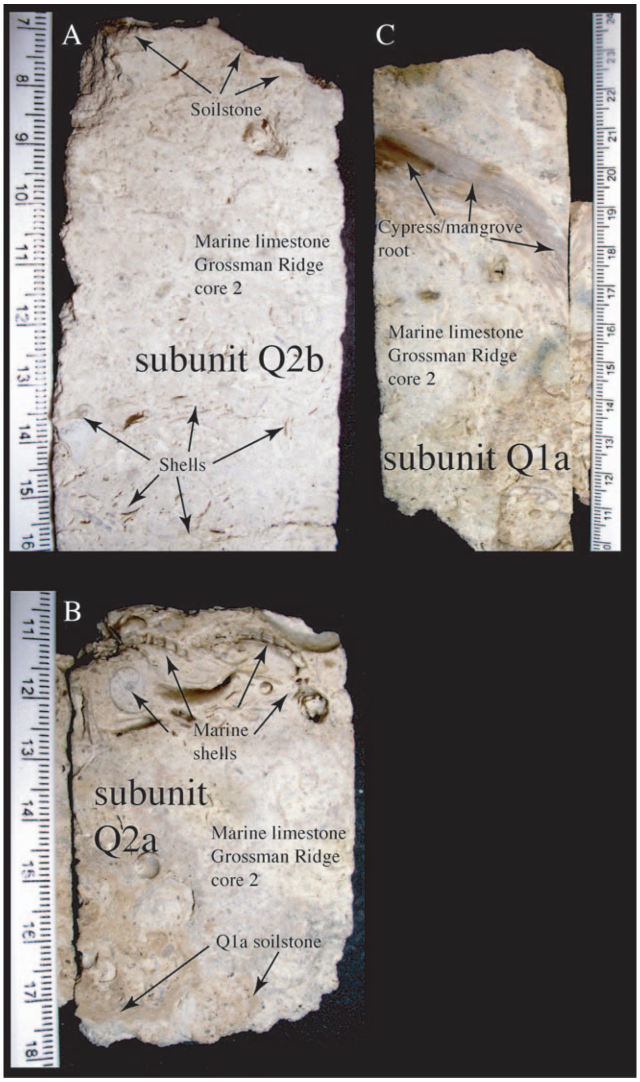

Figure 7. (A) A thin soilstone caps the marine, fossiliferous subunit Q2b recovered from Grossman Ridge Rock Reef core 2. Scale is in centimeters. (B) A thin soilstone located at the base of this fossiliferous, marine limestone was recovered from Grossman Ridge Rock Reef core 2. The soilstone is sandwiched between subunits Q1a from below and Q2a from above. Scale is in centimeters. (C) A cypress or mangrove root identifies the discontinuity surface capping Q1a recovered in Grossman Ridge Rock Reef core 2. Scale is in centimeters.

Q2a declines from 30.5% to 14.5% (quartz continues a decreasing trend upcore) and Q2a calcite cements are 24%. Micrites are the most common constituent in the thin section at 36%, indicating occurrence of diagenetic processes. The Joe Ree Rock Reef sequence confirms that at least two sea-level cycles are present in unit Q2.

Unit Q3 (subunit Q3a)

Subunit Q3a is bounded by soilstone crust rsh2 and soilstone crust rsh3 (Figures 4, 5, and 6C). The base of Q3a is a dense lime mudstone with freshwater *Planorbella* sp. gastropod shells capping the mudstone (Figure 3A). On top of the freshwater lime mudstone is a rubble zone with secondary depositional infilling. The rubble zone grades into a burrowed wackestone with marine *Chione cancellata* shell debris present (Figure 3D). The marine shell debris decreases as the wackestone grades into a packstone throughout the unit. The packstone contains peloids, mollusks, foraminifera, and low concentrations of fine-grained quartz sand. Overlying the packstone in subunit Q3a is a dense, grainy wackestone (Figure 5).

At Grossman Ridge Rock Reef, the wackestone is capped by the laminated subaerial-exposure surface soilstone crust rsh4. The wackestone grades into a burrowed mudstone with quartz-rich root molds at Joe Ree Rock Reef before being capped by soilstone crust rsh4 (Figure 4).

Previous Q3 unit research (Perkins, 1977) indicates the soilstone crust capping the unit (soilstone crust rsh3, Figure 6C) is one of the most prominent subaerial-exposure surfaces throughout south Florida Pleistocene accumulations. Two of five Grossman Ridge Rock Reef cores recovered soilstone crust rsh3, whereas soilstone crust rsh3 was recovered in all Joe Ree Rock Reef cores. Subunit Q3a accumulations comprise the complete unit at both transect sites. Subunit Q3a lime mudstone point-count results indicate that 73.5% is composed of micrite. Recent studies (Cunningham *et al.*, 2004, 2006) have identified a Q3b subunit in north-central Miami-Dade County based on a flooding surface and a subaerial-exposure surface identified in their Q3 unit equivalent.

Table 2. *South Florida Pleistocene nomenclature used in this study compared with the Q units of Perkins (1977) (modified from Cunningham* et al., *2004). A sharp contact separates Q2c and Q2d.*

Series	Litho-stratigraphic Unit		Perkins (1977) Q Units	Q Subunits (This Study)
Pleistocene	Key Largo Limestone	Miami Limestone	Q5	Q5e
			Q4	Q4b
				Q4a
		Fort Thompson Formation	Q3	Q3a
			Q2	Q2d
				Q2c
				Q2b
				Q2a
			Q1	Q1b
				Q1a
Pliocene	Tamiami Formation		Unconsolidated Quartz Sand	

Unit Q4 (subunits Q4a and Q4b at JRR; Q4a at GR)

Unit Q4 is bounded by soilstone crust rsh3 and soilstone crust rsh4 (Figures 4, 5 and 6B). The lower part of Q4 is typically a brecciated freshwater limestone or wackestone with gastropod shells (*Planorbella* sp.). A basal grainstone rubble layer with black carbonate pebbles at the top is found in several cores recovered from Grossman Ridge Rock Reef. The freshwater limestone or wackestones grade upward into marine foraminifera-rich peloidal packstones with bryozoa and ostracods.

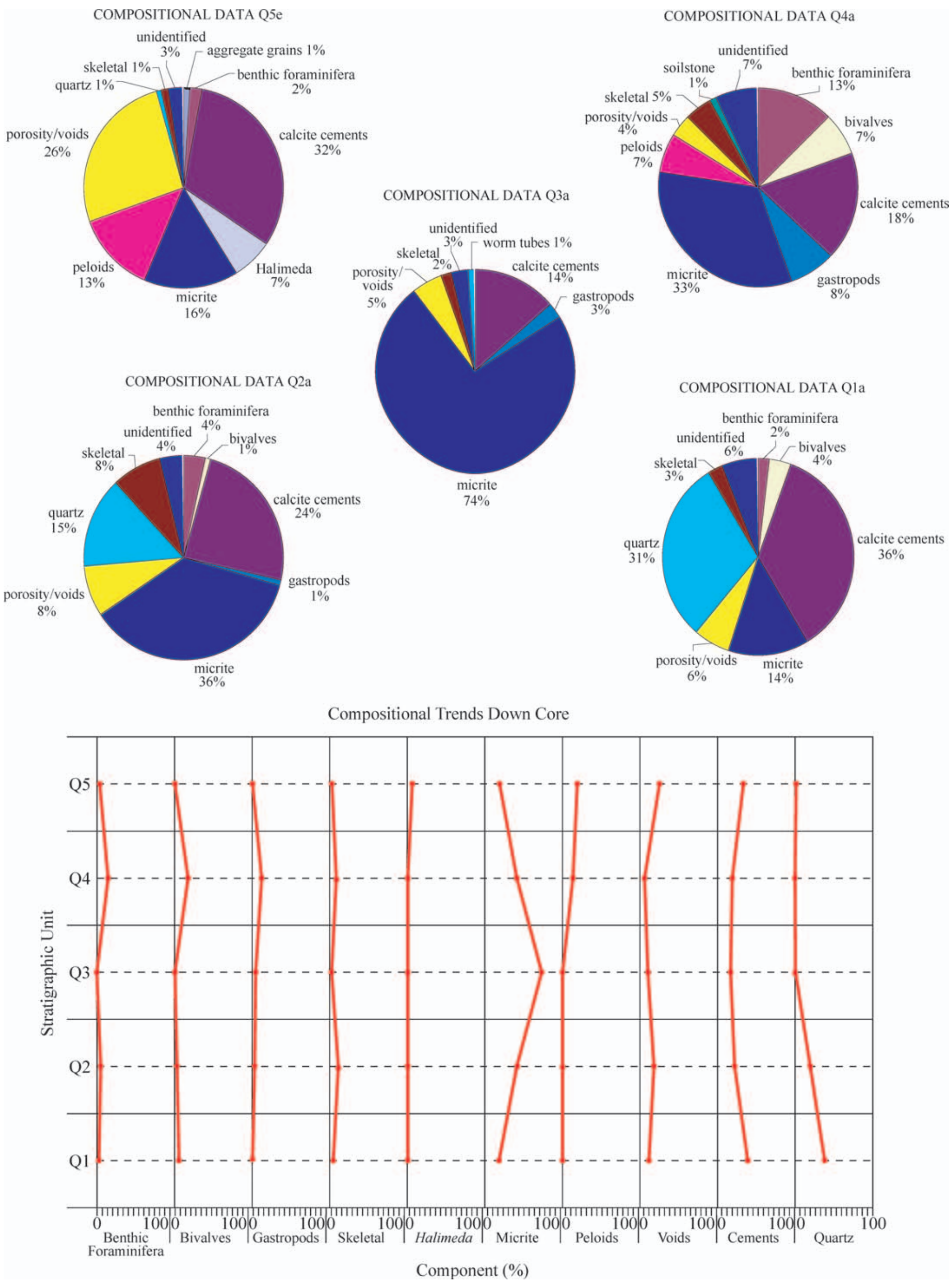

Figure 8. Subunit compositional data from representative thin sections and trends down core identified through quantitative point counting.

At Joe Ree Rock Reef, the foraminifera-rich peloidal packstone is separated by a laminated soilstone crust from an overlying pelmoldic vuggy packstone with bryozoans. The pelmoldic vuggy packstone is in turn capped by soilstone crust rsh4. Another laminated soilstone crust (see Figure 6B) is used to divide unit Q4 at Joe Ree Rock Reef into subunits Q4a and Q4b. At Grossman Ridge Rock Reef, the freshwater limestone or wackestones to marine foraminifera-rich packstone sequence of Q4a is capped by soilstone crust rsh4.

Previous studies of the Pleistocene sequence underlying the Florida Keys have noted that unit Q4 can be separated into two subunits, Q4a and Q4b, based on the presence of quartz sand in

Table 3. *Available radiometric dates for south Florida.*

Unit	Date (ka)	Location	Source	Comments
Q5	130–121	Various		Dates on unit Q5 from several islands in the Florida Keys range between 130 and 121 ka.
Q4b?	230–220	Long Key Quarry	Muhs *et al.*, 2003	235 ka date on coral from spoil pile; best estimate adjusting for calculated high initial $^{234}U/^{238}U$ is 230 to 220 ka. Assignment to subunit Q4b is inferred from location and date.
Q4a	340–300	Point Pleasant core 1	Multer *et al.*, 2002; Muhs *et al.*, 2003	Two dates 370 and 336 ka; best estimate adjusting for calculated high initial $^{234}U/^{238}U$ is 340–300 ka. Reexamination of core shows dated section belongs to subunit Q4a, not unit Q3.
Q4a?	~300	Core R4; Key Largo	Muhs *et al.*, 1992	361 + 120/−61 date; best estimate adjusting for calculated high initial $^{234}U/^{238}U$ is ~300 ka.

the lower part of Q4 that can be abundant enough to be classified as a sandstone (Harrison, Cooper, and Coniglio, 1984). Evidence for an exposure surface at the top of the quartz sandy Q4a in the Keys is present at some localities. For example, a laminated crust separates Q4a and Q4b in core W1 from Big Pine Key, and a soilstone separates Q4a and Q4b in core W9 from Jewfish Creek (Multer *et al.*, 2002, their figure 3). The section from Joe Ree Rock Reef in south Florida confirms that unit Q4 includes deposits of at least two sea-level highstands. Comparing subunits, benthic foraminifera and gastropods are most abundant in Q4a. Point-count analysis indicates 12.5% and 7.5%, respectively. Microscopic lithologic analysis corroborates the placement and identification of the Q4 subunits.

Unit Q5 (subunit Q5e)

Unit Q5 is bounded by soilstone crust rsh4 and soilstone crust rsh5 (Figure 6A). The basal sediments are packstones that have undergone dissolution and/or chemical weathering with bryozoa abundant. Grading upward, the packstone becomes a fossiliferous marine grainstone that is highly bioturbated and burrowed. The subaerial-exposure surface soilstone crust rsh5 is observed in four of five cores at Grossman Ridge Rock Reef but was not recovered in any of the Joe Ree Rock Reef sites. The Q5 accumulations (Q5e) have been well dated (Muhs *et al.*, 1992; Multer *et al.*, 2002), and marine-isotope substage 5e is the interglacial highstand responsible for their deposition. Marine-isotope substage 5e occurred at approximately 125 ka. Post–Stage 5 highstands evidently were not high enough to flood the inner-Florida platform (Lidz, 2006).

Subunit Q5e represents an aggradational cycle in response to a sea-level maximum and available accommodation space on the Florida shelf. Twenty-six percent of the thin-section sample used in Q5e point counting consisted of voids or porosity due to bioturbation. Other constituents more commonly present are calcite cements (31.5%) and peloids (18%). The peloids overall show an increasing trend upcore (Figure 8).

Chronology

Early uranium-series dating (Broecker and Thurber, 1965; Osmond, Carpenter, and Windom, 1965) indicated that the youngest Pleistocene unit of the Florida Keys (later designated the Q5 unit, Perkins, 1977) formed during the peak sea level at ~125 ka of the last interglaciaI marine-isotope substage 5e. Subsequent work by Fruijtier, Elliot, and Schlager, (2000); Muhs *et al.* (1992, 2003); and Multer *et al.* (2002) corroborated the age. Uranium-series ages on corals from unit Q5 from Windley Key, Upper Matecumbe Key, and Key Largo range from 130 to 121 ka after corrections for calculated high initial $^{234}U/^{238}U$ (Muhs *et al.*, 2003). No post-Stage 5e dates have been reported from corals recovered from pits or cores on the exposed Florida Keys. However, several younger dates on submerged corals recovered from the shelf to the east of the Florida Keys are available in the literature (Lidz *et al.*, 1991; Multer *et al.*, 2002; Toscano and Lundberg, 1998) and have been assigned to marine-isotope substages 5c, 5b, and 5a. These post-Q5e interglacial highstands were not high enough to flood the south Florida inner platform (Lidz, 2006). The absence of accumulations on the inner platform is also associated with a southwest tilt of the Florida Platform (Perkins, 1977), making accommodation space available for sediment and reef accumulation offshore but not on the inner platform.

Three additional uranium-series dates from the Florida Keys provide limited but important calibration points for determining the ages of units Q1–Q4 (Table 3). Multer *et al.* (2002) reported dates of ~370 and ~367 ka on two coral samples from the top of a core recovered from Point Pleasant (PPT core 1) near the island of Key Largo. After correction for calculated high initial $^{234}U/^{238}U$, the best estimate for the dates is in the range of 340–300 ka (Muhs *et al.*, 2003), which is consistent with the timing of the maximum sea level in the early part of marine-isotope stage 9 (MIS 9). Multer *et al.* (2002) concluded that the corals were recovered from unit Q3. However we reexamined the top of core PPT and determined that the dated corals were actually recovered from unit Q4a.

Muhs *et al.* (1992) obtained a date of ~300 ka (after correction for calculated high initial $^{234}U/^{238}U$) on a coral from unit Q4 in core R4 on Key Largo. Based on the location close to Point Pleasant and the similarity of the Key Largo unit Q4 coral date to the dates on the Point Pleasant subunit Q4a corals, we infer that the coral from core R4 also belongs to subunit Q4a. Thus the dates from corals in cores PPT and R4 indicate Q4a was deposited during MIS 9.

Muhs *et al.* (2003) reported a date of ~235 ka (corrected for calculated high initial $^{234}U/^{238}U$) from a coral recovered from a spoil pile in a quarry within unit Q4 on Long Key, southwest of Key Largo. The date is consistent with the early part of MIS 7, and we infer that the coral is from unit Q4b.

The most reasonable interpretation of the coral dates from

Table 4. *Comparison of Q units and subunits to marine-isotope stages as interpreted by Multer* et al. *(2002) and Hickey* et al. *(this study). Note six flooding events prior to marine isotope Stage 11.*

Stratigraphic Unit	MIS: Multer *et al.*	MIS: Hickey *et al.*
Q5	5e	5e
Q4	7	b: 7
		a: 9
Q3	9	11
Q2	11	d: Pre 11
		c: Pre 11
		b: Pre 11
		a: Pre 11
Q1	11?	b: Pre 11
		a: Pre 11

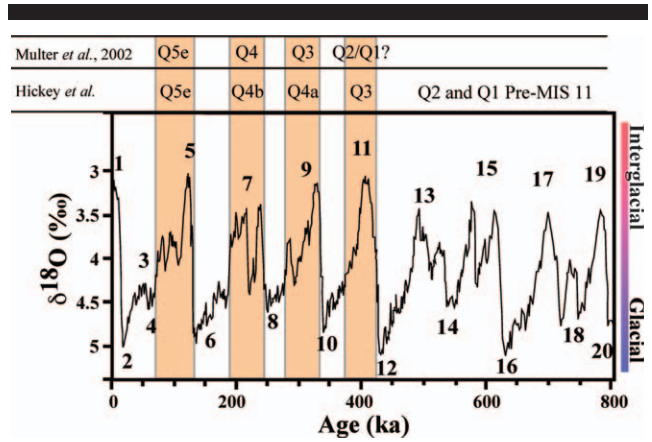

Figure 9. Interpreted correlation of south Florida Pleistocene lithostratigraphy with a benthic $\delta^{18}O$ sea-level record constructed by the correlation of 57 globally distributed benthic $\delta^{18}O$ records (modified from Lisiecki and Raymo, 2005). Odd numbers indicate interglacial isotope stages.

the Key Largo area and Long Key is that subunit Q4a was deposited during the high stand of MIS 9 and that subunit Q4b was deposited during the highstand of MIS 7.

The MIS 9 and MIS 7 dates for unit Q4 indicate that the Q1–Q3 units predate MIS 9. Our preferred interpretation is that Q3 was deposited during MIS 11 and that Q2 and Q1 represent pre-MIS 11 interglacial intervals (Table 4). Studies indicate MIS 11 was the longest and warmest interglacial of the past 500 ka (Droxler, 2003). Climate conditions as warm or warmer than today may have lasted as long as 30 ka during MIS 11, and peak sea level may have been 10 to 20 m above modern sea level (Droxler, 2003; Hearty *et al.*, 1999; Howard, 1997; Poore and Dowsett, 2001). Thus, it is possible that part of the Q2 unit could also have been deposited during MIS 11. However, the multiple exposure surfaces in units Q2 and Q1 make it unlikely that Q1, Q2, and Q3 were all deposited during MIS 11. Comparison of our age assignments of units Q1–Q5 with the assignments of Multer *et al.* (2002) is shown in Table 4 and Figure 9.

SUMMARY AND CONCLUSIONS

Lithologic and geophysical analyses of cores from two south Florida sites reveal the presence of previously unrecognized subaerial-exposure surfaces in the Q1, Q2, and Q4 units of Perkins (1977). Unit Q2 contains at least three such surfaces, and units Q1 and Q4 each contain at least one. Units Q1–Q5 preserve evidence of at least 10 separate sea level high stands, not 5 as indicated by previous studies.

Unit Q5 accumulated during the maximum sea level of the last interglacial interval (MIS 5e) when sea level was about 6.7 m above modern sea level. Radiometric dates on unit Q5 from various locations throughout the Florida Keys range between 130 and 121 ka.

The two subunits within unit Q4 were probably formed by two different sea-level maxima. Interpreting the uranium-series date available for subunit Q4b from the Long Key Quarry (Muhs *et al.*, 2003), after adjusting for high initial $^{234}U/^{238}U$, is 230–220 ka, which is consistent with MIS 7 time. A uranium-series date of 361 (+120/−61) ka on a coral from subunit Q4a, core R4 from Key Largo (Muhs *et al.*, 1992), indicates the unit probably accumulated during MIS 9. The best estimate after adjusting for the calculated high initial $^{234}U/^{238}U$ is approximately 300 ka. Two other uranium-series dates of 370 and 336 ka from subunit Q4a, recovered from Pleasant Point on Key Largo (Muhs *et al.*, 2003; Multer *et al.* 2002), are 340 and 300 after adjusting for calculated high initial $^{234}U/^{238}U$. Reexamination of the Pleasant Point core shows the dated section belongs to subunit Q4a, not the Q3 unit.

Without having any data, we must infer the accumulation history of the older units (Q3–Q1). The Q3 unit is correlated with the highstand during MIS 11 when sea level was as much as 20 m above modern sea level. Sequence Q3 lithology reflects this deepening submergence of the south Florida inner platform. Units Q2 and Q1, containing multiple subaerial-exposure surfaces, represent pre-MIS 11 interglacial intervals.

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