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Key Largo Limestone Revisited: Pleistocene Shelf-edge Facies, Florida Keys, USA

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In memoriam J. Edward Hoffmeister (1899-1991)

KEYWORDS: KEY LARGO LIMESTONE – CARBONATES CORALS REEF U-SERIES DATING DIAGENESIS – FLORIDA – PLEISTOCENE

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SUMMARY

New dates and analysis of 12 deep and 57 shallow cores allow a more detailed interpretation of the Pleistocene shelf edge of the Florida Platform as found in various facies of the Key Largo Limestone beneath the Florida Keys. In this study a three-phase evolution of the Quaternary units (Q1-Q5) of the Key Largo is presented with new subdivision of the Q5. (1) In the first phase, the Q1 and Q2 (perhaps deposited during oxygen-isotope

stage 11) deep-water quartz-rich environment evolved into a shallow carbonate phase. (2) Subsequently, a Q3 (presumably corresponding to oxygen-isotope stage 9) flourishing reef and productive high-platform sediment phase developed. (3) Finally, a Q4 and Q5 (corresponding to oxygen-isotope stages 7 and 5) stabilization phase occurred with reefs and leeward productive lagoons, followed by lower sea levels presenting a sequence of younger (isotope substages 5c, 5a) shelf-margin wedges, sediment veneers and outlier reefs. The Key Largo Limestone provides an accessible model of a carbonate shelf edge with fluctuating water depth, bordering a deep seaward basin for a period of at least 300 ka. During this time, at least four onlaps/offlaps, often separated by periods of karst development with associated diagenetic alterations, took place. The story presented by this limestone not only allows a better understanding of the history of south Florida but also aids in the interpretation of similar persistent shelf-edge sites bordering deep basins in other areas.

1 INTRODUCTION

Successive superimposed shelf-edge facies of the Pleistocene Key Largo Limestone offer a 225-mile-long (360 km) opportunity to study transgressive/regressive dynamic sedimentation along the very edge of a tropical continental shelf where shallow waters meet the deep sea (Fig. 1). As found elsewhere along the eastern U.S. continental margins (Riggs and Belknap 1988), the Pleistocene record in south Florida is characterized by (1) rapid glacio-eustatic sea-level fluctuations, causing shifts in marine and non-marine environments over the whole southern Florida platform, and (2) strong changes in climatic zones which affected oceanographic conditions, biological zonations and weathering processes including soil formation and karst development during successive emergences.

The Florida Keys area is also the site where North American shallow-water marine carbonate studies were first initi-

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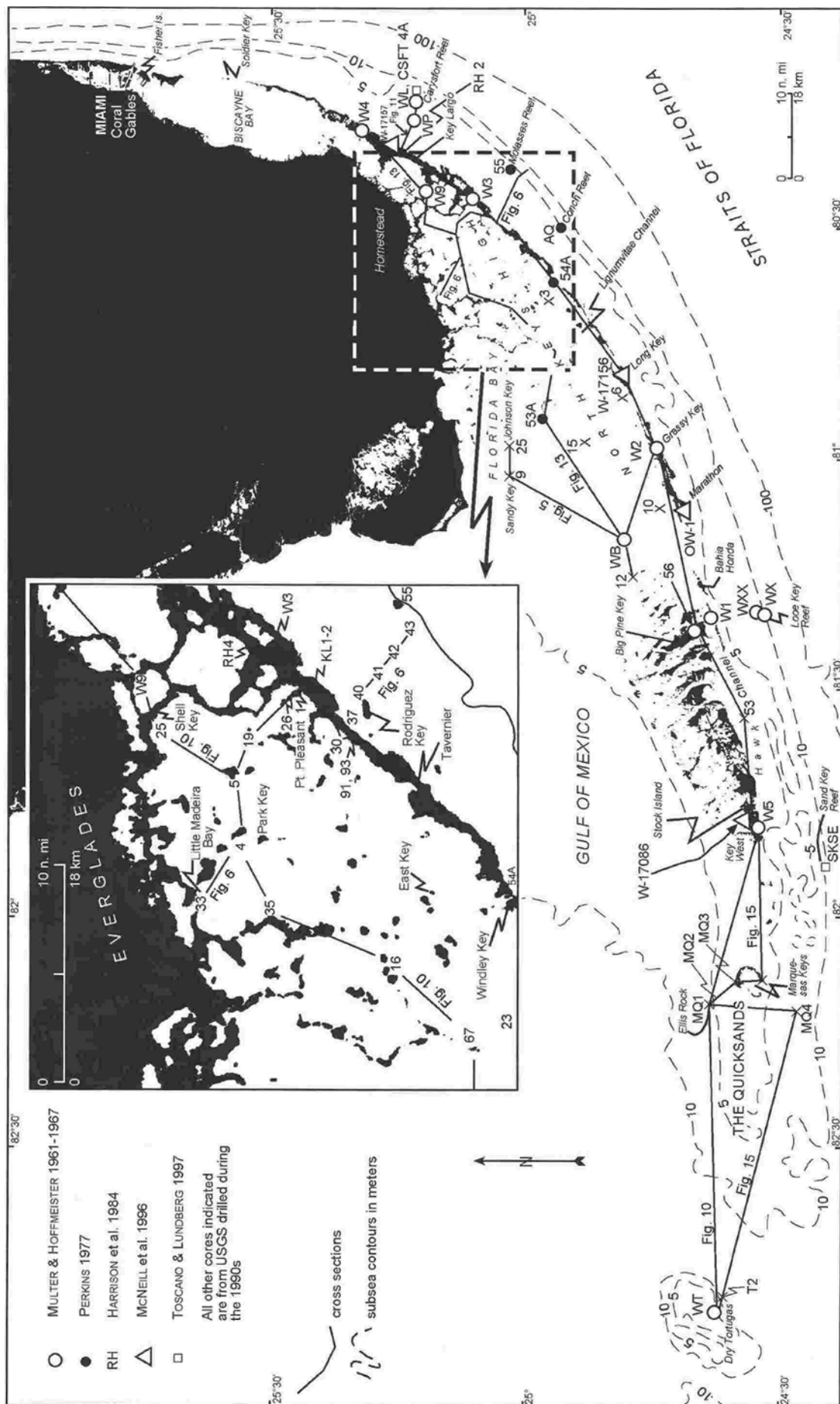


Fig. 1. Index map of Florida Keys (Key Largo to Dry Tortugas), showing locations of cores and reefs noted in this study.

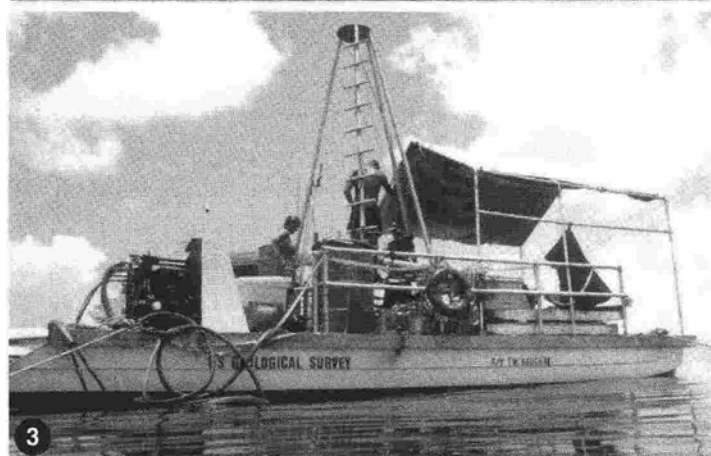
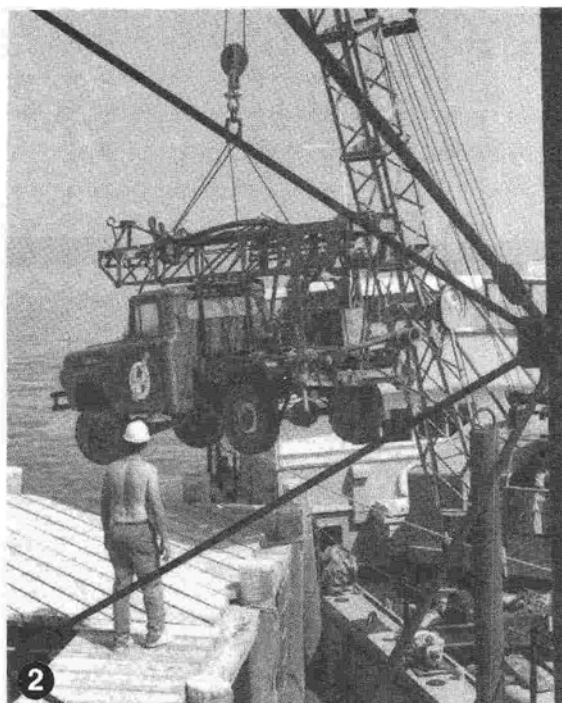
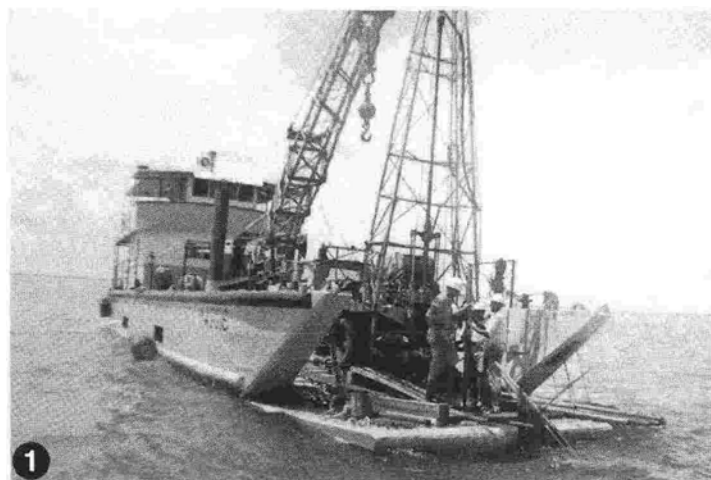


Plate 40 Key Largo Limestone, Florida: A Pleistocene shelf-edge facies. Coring procedures.

Fig. 1. A rotary truck-mounted rig that was used in the 1960s for all deep cores drilled on land was loaded onto a boat for drilling deep offshore cores WP, WB, WX and WXX. The boat

was stabilized by dropping two vertical steel pole studs as well as setting bow and stern anchors. Coring was done through a hole in the lowered bow door.

Fig. 2. For the WL core, a smaller drill rig was hoisted with a crane onto the Carysfort Lighthouse docking platform in May 1967. Dock is reported as no longer existing.

Fig. 3. Shallow cores were drilled by divers using SCUBA with a submerged tripod or from a USGS custom-designed shallow draft drill barge "R/V T. W. Vaughan".

ated by T.W. Vaughan at his Dry Tortugas laboratory in the early 1900s. Subsequently the Keys became a classic field area for Holocene and Pleistocene carbonate studies. However, what Coniglio and Harrison (1983b, p. 135) noted is still true today: "...Holocene sediments of the area have received considerable attention, (whereas) detailed studies of the Pleistocene sediments are few in number."

The underlying Pleistocene bedrock package, not as readily accessible as the Holocene, has especially been neglected although it contains key information. It provides a better understanding of the evolution of the peninsula of south Florida including its long periods of embayments alternating with periods of karstification, and it reveals important freshwater and marine diagenetic processes controlling porosity/permeability that serve as models for other ancient carbonates. In addition, it provides data on bedrock hydrology (Halley et al. 1997) and tidal flux beneath the present Florida Keys (Shinn et al. 1994; Reich et al. 2001) that serve as aids in resolving today's local environmental challenges (Lidz 1997, 2000). In this paper we expand the

present knowledge of the Key Largo Limestone with aid of new radiometric, lithologic and paleontologic data from 12 deep and 57 shallow cores. When combined with recently published drilling information from other sources, these new data provide the opportunity for a better understanding of Pleistocene shelf-edge carbonate facies.

2 GEOLOGIC SETTING

The Florida Keys today represent a tiny arcuate emergent rim of an often formerly submerged Pleistocene platform defined by the 100-m isobath. This thick carbonate platform of upper Mesozoic and Cenozoic sediments rests on a Paleozoic basement (Barnett 1975; Missimer 1984). Its local as well as regional geologic setting is well described and illustrated by Enos (1977). Thick siliciclastic foundations strongly influenced subsequent Quaternary carbonates at the southern edge of the platform as first noted by Ginsburg et al. (1989). The arcuate trends of southeastern Florida may be related to possible fault scarps or depth

contours established by the regional southern bulging of the Peninsular Arch (Ginsburg 1987). During the Pleistocene, the island chain of the Florida Keys, as a shelf-edge rim, was periodically separated from the mainland some 100 miles (162 km) to the north by a shallow marine embayment.

3 PREVIOUS STUDIES

The name Key Largo Limestone was first applied by Sanford (1909, p. 214) to "the elevated reef that forms the backbone of the main chain of the Florida Keys from Soldier Key to Bahia Honda." Previous investigators (Whiting 1838; Conrad 1843; Touney 1851; L. Agassiz 1851) noted the existence and discussed the origin of a coral reef rock in the Florida Keys. More comprehensive studies were made by A. Agassiz (1883, 1895, 1896) who extended his observations to Dry Tortugas. Working out of the Carnegie Institution Marine Biological Laboratory in the Dry Tortugas, Vaughan (1910, 1914, 1919) proposed a geologic history for the Florida Keys including Pleistocene bedrock and presented results of his paleoecological research on coral reefs (see Ginsburg 1995). For stratigraphic relations of the Key Largo Limestone see Cooke and Mossum (1929), Parker and Cooke (1944), and Perkins (1977). Studies of the limestone multiplied with the opening of R.N. Ginsburg's Shell Development Research Laboratory in Coral Gables, succeeded later by the University of Miami's T. Wayland Vaughan Laboratory of Comparative Sedimentology and a U.S. Geological Survey (USGS) laboratory at Fisher Island. Subse-

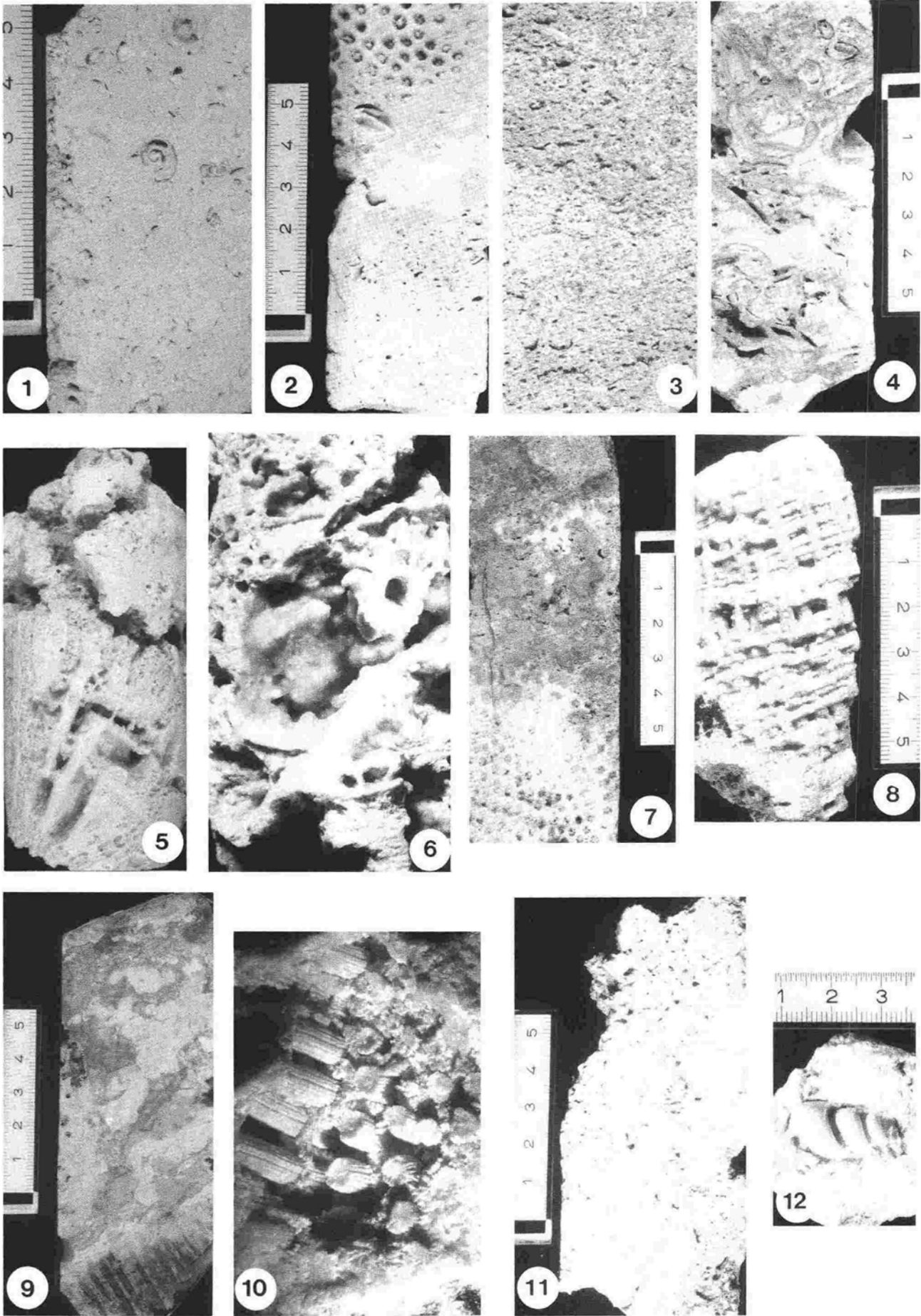
quently a significant amount of research was done by various independent investigators working on the Key Largo Limestone (see Appendix for a list by subject).

4 METHODS

Documentation for this paper is based predominantly on unpublished data from a series of deep and shallow cores drilled into the Key Largo Limestone (Plate 40). Megascopic analysis of core pieces and microscopic analysis of more than 200 thin sections were made of 12 deep (to 200 ft/60 m) cores (Figs. 2 and 3) drilled by the senior author in the 1960s and 57 shallow (to 45 ft/13.5 m) cores drilled by the USGS in the 1990s (Fig. 1). Selected samples were studied under SEM. The deep cores penetrated about 1,510 ft/453 m of Key Largo Limestone in total (Figs. 2, 3). Recovery ranged from 20-100%, averaging about 35%. Only thickness and generalized lithology of five of these cores and the reporting of *Acropora palmata* at Looe Key (Hoffmeister and Multer 1968) as well as an abstract noting three Key Largo Limestone facies (Multer and Hoffmeister 1968b) have been published. The USGS provided 57 shallow cores taken in the 1990s from the Florida Bay, lower Keys and Marquesas/Dry Tortugas areas. Graphic logs of six of these cores are published (Shinn et al. 1994). Whenever possible in the present study, an attempt was made to integrate published core data with the new results. Such data include four cores from Perkins (1977), two cores from Harrison et al. (1984), three cores from McNeill et al. (1996) and

Plate 41 Key Largo Limestone, Florida: A Pleistocene shelf-edge facies. Typical facies of the Key Largo Limestone (all depths are below core tops).

- Fig. 1. Mollusk-foram wackestone with moderate moldic porosity, core W5 (Key West, Fig. 3), depth 189 ft (57.3 m), unit Q1. Scale in cm.
- Fig. 2. Mollusk wackestone to packstone, moldic porosity, boring bivalve at base of recrystallized *Montastrea* coral, core W5 (Key West, Fig. 3), depth 150 ft (45.5 m), unit Q2. Scale in cm.
- Fig. 3. Quartzose molluskan grainstone with moldic porosity, rock displays rare angular bedding, core W3 (Winston Waterway, Key Largo, Fig. 3), depth 47 ft (14.2 m), unit Q2. Width of photo is 5 cm.
- Fig. 4. Quartzose molluskan packstone with chaotic bedding, moldic porosity, spar is coating open vugs, fragment of soilstone at base of sample, core 9 (Sandy Key #2, well #9, Florida Bay, Fig. 5), depth 32 ft (9.7 m), unit Q2. Scale in cm.
- Fig. 5. Diagenetically altered coral and quartzose mollusk packstone displaying intense dissolution and spar coating, core 16 (Bob Allen Key-A, Fig. 13), depth 14 ft (4.2 m), unit Q3. Width of photo is 5 cm.
- Fig. 6. Bioturbated mollusk packstone-grainstone with solution voids coated with thick layers of drusy calcite, core WB (Florida Bay, Fig. 2), depth 79 ft (23.9 m), unit Q3. Width of photo is 6 cm.
- Fig. 7. *Montastrea* coral overlain by grainstone with fragments of coral (*Porites*?) and unidentified (plant?) tubes, core 6 (Old Dan Bank, northwest off Long Key, Florida Bay), depth 10 ft (3.0 m), unit Q4b. Scale in cm.
- Fig. 8. *Montastrea* coral displaying dissolution and recrystallization, vugs coated with chalky wackestone, core W9 (Jewfish Creek, Fig. 3), depth 20 ft (6.0 m), unit Q4b. Scale in cm.
- Fig. 9. Vuggy coral (*Porites* and *Montastrea*) boundstone with brownish skeletal wackestone infill, core W9 (Jewfish Creek), depth 10 ft (3.0 m), unit Q4b. Scale in cm.
- Fig. 10. Cast of a *Montastrea* coral, core W5 (Key West, Fig. 3) depth 37 ft (11.2 m), unit Q4. Width of picture is 7.5 cm.
- Fig. 11. *Montastrea* coral encrusted by crustose coralline algae, core WT (Dry Tortugas, Fig. 2), depth 56 ft (17.0 m), Q unit unidentified. Scale in cm.
- Fig. 12. Mold of gastropod in foram-peloid-molluskan packstone facies, core 5 (Key West, Fig. 3), depth 130 ft (39.4 m), unit Q3. Scale in cm.



Cunningham et al. (1998) from the lower to upper Keys, and limited use of information from unpublished theses by Coniglio (1981), Fuhr (1988), and Textoris (1988) from the middle and upper Keys. Outlier reef cores (described by Lidz et al. 1991, 1997b; Ludwig et al. 1996; Toscano and Lundberg 1997) were also helpful.

More than 150 x-ray diffractometry analyses for identifying unaltered, aragonitic corals were performed. Radiometric dates (Table 1) of aragonitic coral samples were determined using thermal ionization mass spectrometry (TIMS) (Chen et al. 1991; Edwards et al. 1986; Ludwig et al. 1992). Some coral samples were analyzed using multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS). Surface textures of quartz grains from 30 samples, mainly taken near subaerial horizons, were investigated under SEM. Thirty to 40 grains per sample were inspected, and the most common features were noted.

Split samples of all deep cores will be stored at the core depository of the Florida Geological Survey, Tallahassee, and the Geologisch-Paläontologisches Institut of the Johann Wolfgang Goethe-Universität, Frankfurt am Main, Germany. Shallow cores are held by the U.S. Geological Survey at St. Petersburg, Florida.

5 RESULTS

Examination of deep and shallow cores taken along the shelf edge demonstrates high variability in lithofacies due to the transgressive and regressive nature of the Pleistocene seas over the Florida Platform (Fig. 4, Pls. 41, 42). Following the stratigraphic nomenclature based on recognition of paleo-earst criteria established by Perkins (1977), the present authors have identified rocks belonging to each of his five Quaternary units, which he named Q1 (oldest) to Q5 (young-

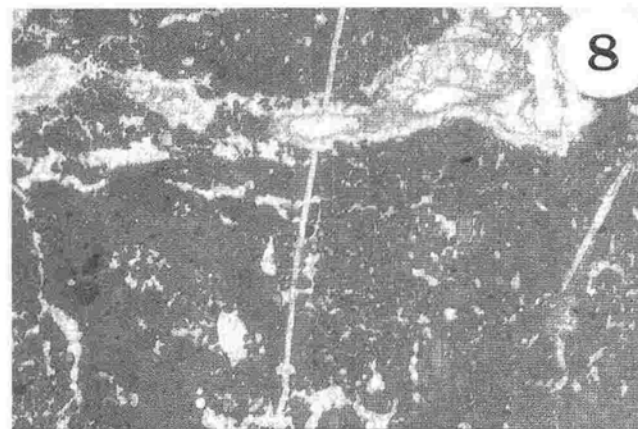
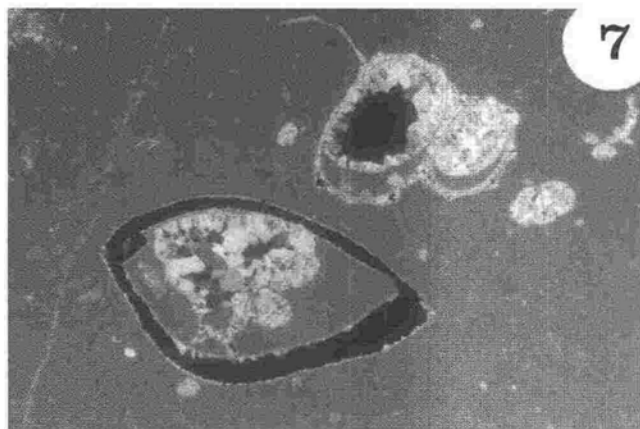
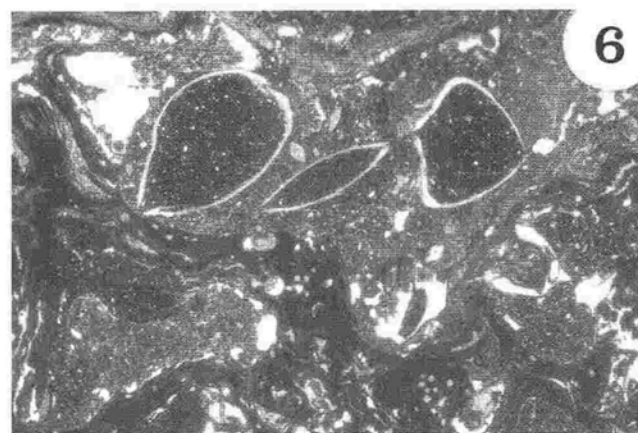
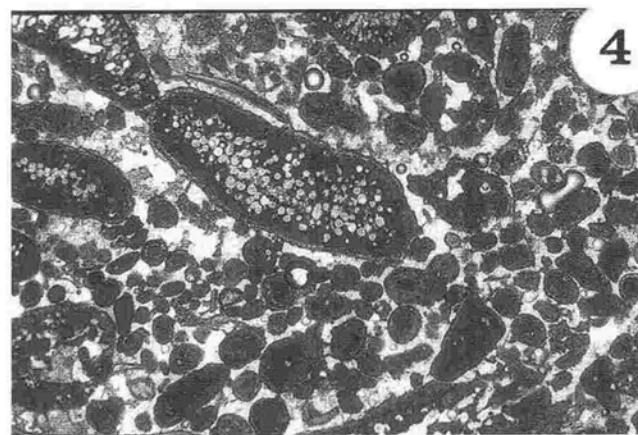
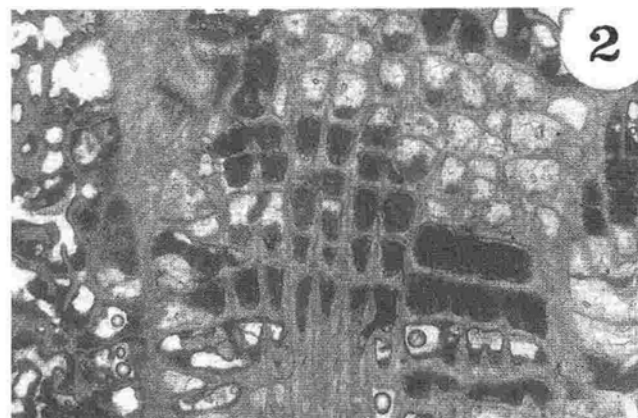
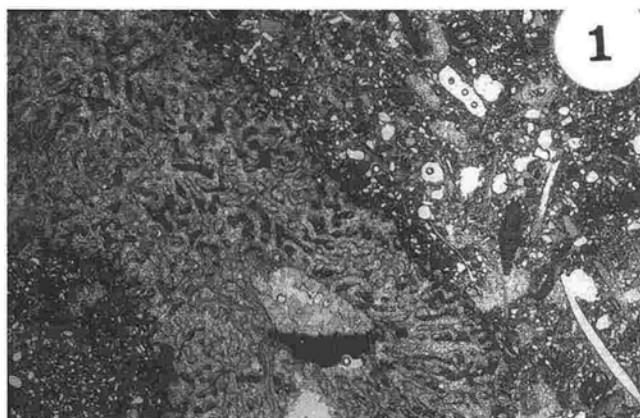
est), and have divided the Q5 into Q5e and post-Q5e for discussion purposes in this study. However, since subaerial features used to identify Q units have been found to be very discontinuous and sometimes even repetitive within what appears to be a single Q package of sediments, lateral correlations must remain tentative. The present study has found several overall major trends with regard to composition and texture in the Key Largo Limestone along its arcuate path from north Key Largo to Key West (Fig. 1). Generally speaking, abundant quartz is largely restricted to units Q1, Q2, and Q4a (subdivision of Q4 from Harrison et al. 1984) whereas units Q3, Q4b (Harrison et al. 1984), Q5 and younger Pleistocene units are carbonate. Corals and coral boundstones are most abundant in unit Q3. Fragments of the codiacean alga *Halimeda* are only abundant in unit Q5. Oolitic grainstones in the Florida Keys are confined to the southwestern area of unit Q5.

5.1 Lithology of unit Q1

The lowermost unit of the Key Largo Limestone is characterized by an abundance of quartz grains. Mollusk fragments and benthic foraminifera occur frequently. Quartz grainstones, mixed quartz-mollusk grainstones, and mollusk-quartz wackestones are the common lithology. Quartz grains are mostly subangular to subrounded (Pl. 43/1). The upper parts of this unit were recovered in only four cores. However, taking into account additional core data from Perkins (1977) and McNeill et al. (1996), it appears that quartz is more abundant in the upper Keys than in the lower Keys. In the latter area, the abundance of skeletal grains such as bivalve and gastropod mollusks, miliolid and peneroplid forams, and rare branched corals is greater. In core W2 from the middle Keys area, however, branched coralline red algae occur. Fecal pellets are found in cores W3 and W5.

Plate 42 Key Largo Limestone, Florida: A Pleistocene shelf-edge facies. Microfacies of the Key Largo Limestone (all depths are below core tops).

- Fig. 1. Grainstone with coral (with geopetals), mollusk, forams, echinoids, quartz, moldic porosity, core W4 (North Key Largo, Fig. 3), depth 100-105 ft (30.3-31.8 m), unit Q3. Width of picture 15 mm.
- Fig. 2. Recrystallized *Montastrea* coral, partial infill of skeletal framework with fine sediment and calcite spar, note geopetal, core 13 (Boundary Marker, Florida Bay, Fig. 12), depth 5 ft (1.5 m), unit Q4. Width of picture 7 mm.
- Fig. 3. Quartz-rich molluscan packstone with fragments of peneroplid foraminifera, moldic porosity, voids partially filled with blocky calcite, micrite envelopes preserved, note bored shell, echinoid fragment shows syntaxial cement, core WB (Florida Bay, Fig. 2), depth 146 ft (44.2 m), unit Q2. Width of picture 15 mm.
- Fig. 4. Grainstone with ooids, peloids, *Halimeda*, mollusks, forams and rare quartz grains, meniscus cement, core 10 (John Sawyer Bank, 3 miles (4.8 km) north of Marathon, Florida Bay, Fig. 1), top of core, unit Q4. Width of picture 6.5 mm.
- Fig. 5. Mollusk-foraminifera packstone with two generations of fine-grained quartzose-skeletal mud infill, core W5 (Key West, Fig. 3), depth 182 ft. (55.2 m), unit Q1? Width of picture 12 mm.
- Fig. 6. Packstone to wackestone with coralline algae, mollusks, foraminifera, core W2 (Grassy Key, Fig. 3), depth 60 ft (18.2 m), unit Q3. Width of picture 15 mm.
- Fig. 7. Mollusk wackestone with recrystallized shells and moldic porosity, molds geopetal and partially filled by sparry calcite, core 4 (Lake Key, Fig. 13), depth 6 ft (1.8 m), unit Q4. Width of picture 7 mm.
- Fig. 8. Peloidal packstone that was subaerially exposed, note subsequent quartz grain infill and possible vertical shrinkage crack, core WB (Florida Bay), depth 30 ft (9.1 m), top of W4b. Width of picture 14 mm.



5.2 Lithology of unit Q2

Lithologies in unit Q2 are very much the same as in unit Q1, with fewer quartz grains. Grainstones and packstones with variable amounts of bivalve and gastropod mollusks, foraminifera (with peneropliids and miliolids), and quartz are abundant. As in unit Q1, quartz appears to be more abundant in the upper Keys (W9 in Fig. 3; Sandy Key and Johnson Key in Fig. 5) than in the lower Keys area. Quartz grains are mostly subangular (Pl. 43/3, 6). The upper Q2 grainstones under the central part of the island of Key Largo (W3) display bedding that dips up to 45 degrees at 43-ft (12.9-m) depth below sea level. Red coralline algae are significantly more abundant in this unit than in Q1. Corals (*Montastrea annularis*, *Porites* sp., and *Acropora cervicornis*) occur both in the northern (cores W3, W9, WP) and in the southern (core W5) parts of the study area.

5.3 Lithology of unit Q3

Unit Q3 is characterized by the frequent occurrence of thick sequences of coral boundstone particularly in cores under the present emergent Florida Keys. The massive coral *Montastrea annularis* is most abundant. Other common corals include species of *Porites*, *Siderastrea*, *Diploria*, *Acropora cervicornis*, and rare *Acropora palmata* (core WB). Fragments of red coralline algae are also very common constituents. Wackestones and packstones with fragments of bivalve and gastropod mollusks as well as foraminifera (peneropliids and miliolids) are especially abundant under Florida Bay and northern Keys areas (Fig. 6). *Halimeda* fragments are rare. Quartz is found in abundance only in parts of core W4 with grains mostly subangular. In cores W3 and W9, coral boundstone intervals are reduced in thickness.

5.4 Lithology of unit Q4

The abundance of coral, coral boundstone, and red coralline algae decreases in unit Q4 as compared to Q3. Corals are abundant in cores W2 and W4 in the middle and northern study area and in core W5 in the south. *Montastrea* and *Porites* are the most common genera. Packstones and grainstones with mollusks, foraminifera (with peneropliids and miliolids), and fecal pellets are abundant beneath Florida Bay. Quartz grains are found in cores W1 and W3 and less frequently in W9, WB and W2 (Pl. 43/5). They are predominantly subangular. *Halimeda* fragments are present in low numbers; however, there is an increase in abundance compared to unit Q3.

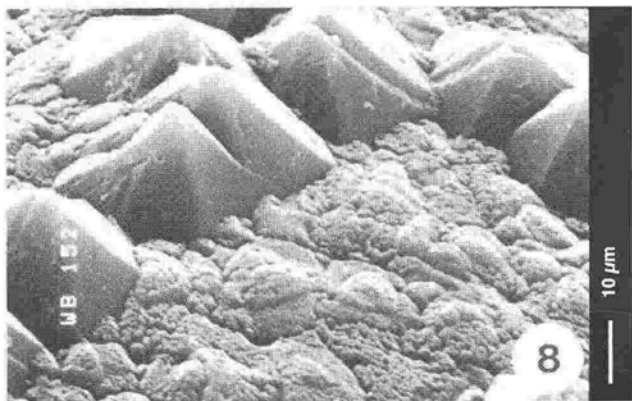
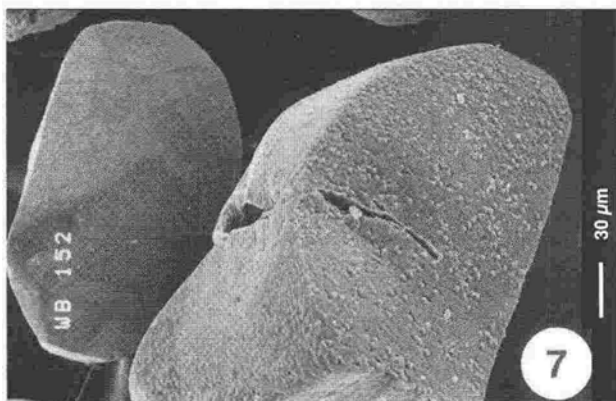
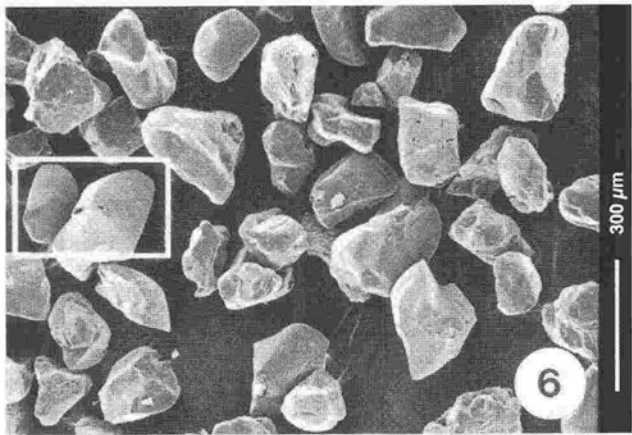
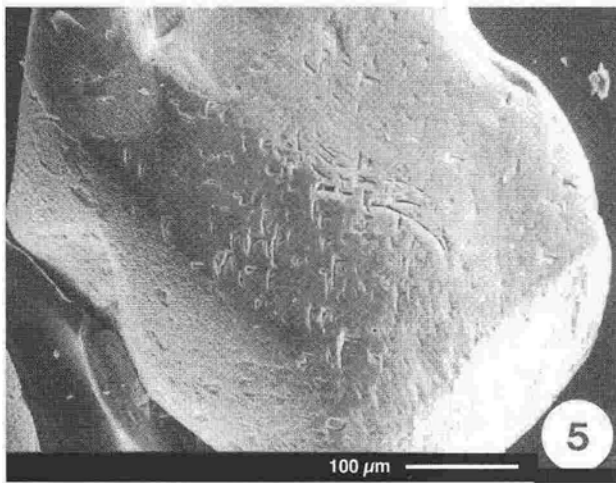
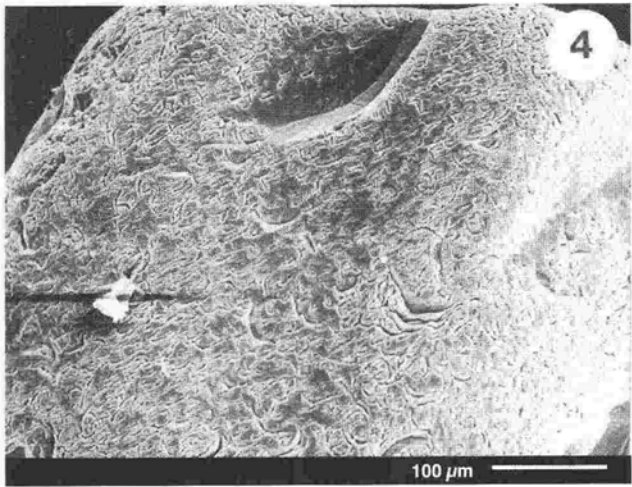
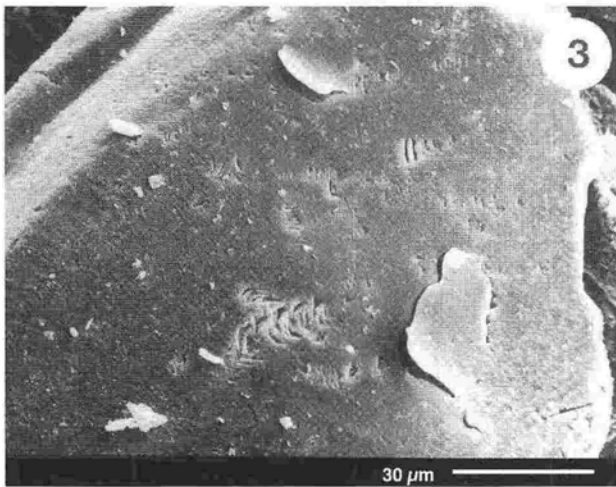
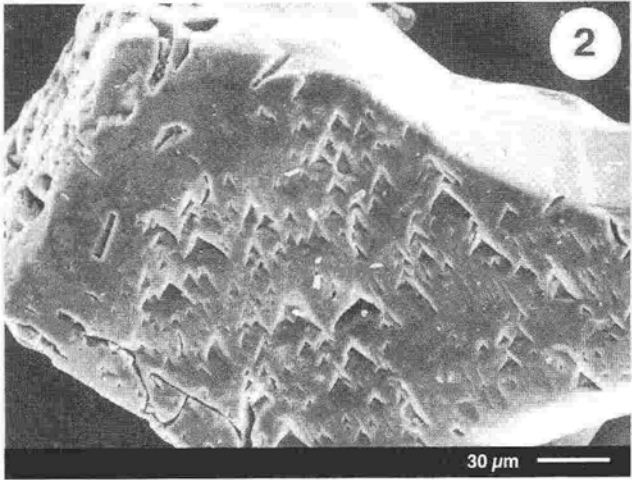
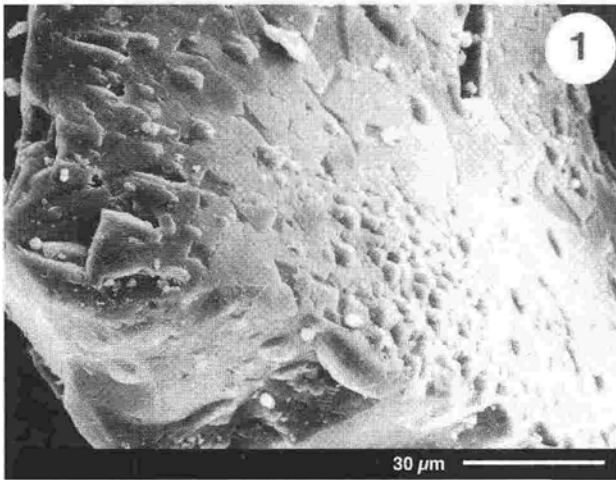
At the base of the Q4 unit is a quartzose packstone/ grainstone (first named Q4a by Harrison et al. 1984) containing mollusks, foraminifera, rare *Porites* coral, and common pellets. Moldic porosity and open vugs are common. Fine to medium, round to subrounded quartz grains (Pl. 43/5) increase toward the base with some quartz sandstone layers up to 2 cm thick (Pl. 44/3) occurring on top of an underlying subaerial crust zone. Q4a quartzose grainstones in the northeastern corner of Florida Bay (Shell Key core A-1 #21) and under the southern part of the island of Key Largo (core W3) display 45-degree inclined bedding. In places under Key Largo this layer of quartz sand is also cross-bedded.

5.5 Lithology of unit Q5e

Q5 rocks are exposed along the Florida Keys and are therefore the most extensively studied unit of the Key Largo Limestone. These exposed rocks in the present study are designated Q5e as a lithologic unit whose age corresponds to oxygen-isotope stage 5e (Table 1). Papers by Stanley (1966)

Plate 43 Key Largo Limestone, Florida: A Pleistocene shelf-edge facies. SEM of quartz grains in the Key Largo Limestone (all depths are below core top).

- Fig. 1. Rounded quartz grain showing subsequent platy and pyramidal crystal overgrowth, core W2 (Grassy Key, Fig. 3), depth 156-165 ft (47.3-50.0 m), unit Q1?
- Fig. 2. Subangular quartz grain displaying oriented Vs, core W1 (Big Pine Key, Fig. 3), depth 55 ft (16.7 m), boundary between units Q3 and Q4.
- Fig. 3. Subrounded quartz grain with centipede-type solution marks and defoliation/scaling. Such features may be diagenetically derived by in-place weathering and dissolution in the regolith environment (Manker and Ponder 1978). Krinsley and Doornkamp (1973) also report similar features. Core W2 (Grassy Key, Fig. 3), depth 143-144 ft (43.3-43.6 m), unit Q2.
- Fig. 4. Rounded quartz grain showing straight and curved solution pits, core WB (Florida Bay, Fig. 2), depth 137.5 ft (41.7 m), boundary between units Q2 and Q3.
- Fig. 5. Rounded quartz grain displaying oriented pits. Features such as these are described by Margolis and Krinsley (1974) as commonly found in marine sand environments, core W2 (Grassy Key, Fig. 3), depth 17 ft (5.1 m), base of unit Q4.
- Fig. 6. Typical subangular to subrounded quartz grains found in the lower parts of the Key Largo Limestone, core WB (Florida Bay, Fig. 2), depth 152 ft (46.1 m), unit Q2.
- Fig. 7. Enlargement of grain (Fig. 6 inset) showing secondary pyramidal overgrowth.
- Fig. 8. Enlarged detail of two phases of quartz overgrowth (individual pyramids and irregular) found on grain in foreground of Fig. 7.



and Hoffmeister and Multer (1968) are largely based on investigations of this unit. Coral and coral boundstone occur but less frequently than in unit Q3. Common corals in the Q5e are *Montastrea annularis*, *Porites* sp., *Diploria* sp. and *Acropora cervicornis*. Red coralline algae are abundant as are packstones and grainstones of mollusk, foraminifera, and fecal pellets. The abundance of *Halimeda* is noteworthy as compared to the lesser amounts in Q4 and Q3 and its paucity in units Q2 and Q1. According to Stanley (1966), *Halimeda* makes up 17% of the exposed Key Largo rock volume he measured on the island of Key Largo. In the lower Keys (core W5), oolitic grainstone dominates. Quartz grains are found only in the northern study area at the base of core W4 (Fig. 3). Questionable fragments of bryozoa occur in core W4.

5.6 Lithology of post-Q5e units

The youngest Pleistocene units of the Key Largo Limestone found using TIMS dating (Table 1) in this investigation are designated post-Q5e. Dates from these rocks correspond to the oxygen-isotope substages 5c and 5a (Table 1). These rocks were found under the shelf edge (Fig. 7) at Conch Reef (core AQ), at Looe Key (core WX), under Carysfort Light (core WL) and at the shelf edge near Molasses Reef (core KL5 #43). Other post-Q5e rocks may also be

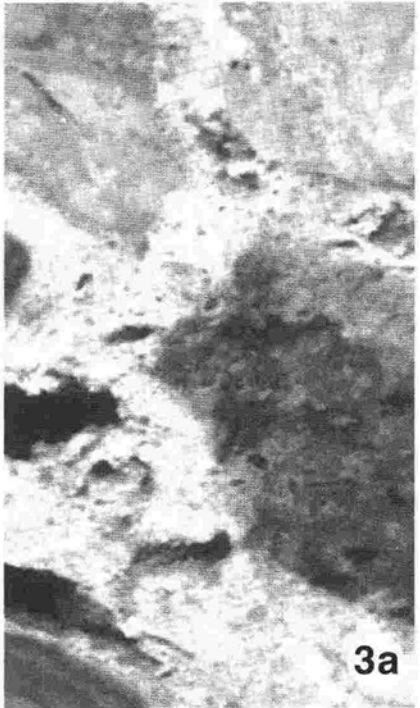
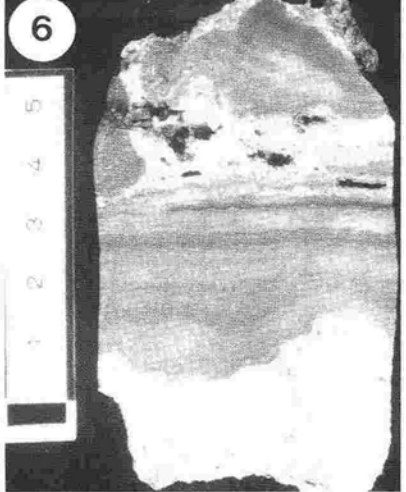
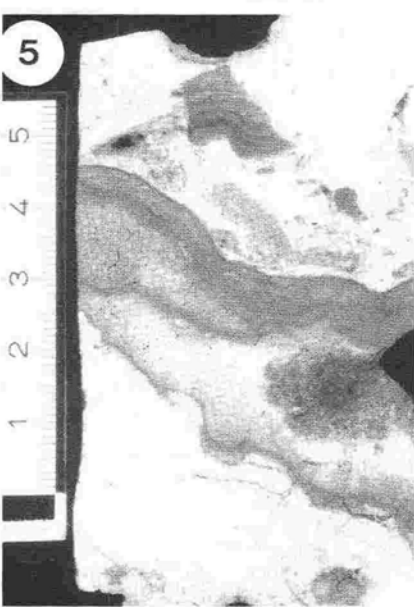
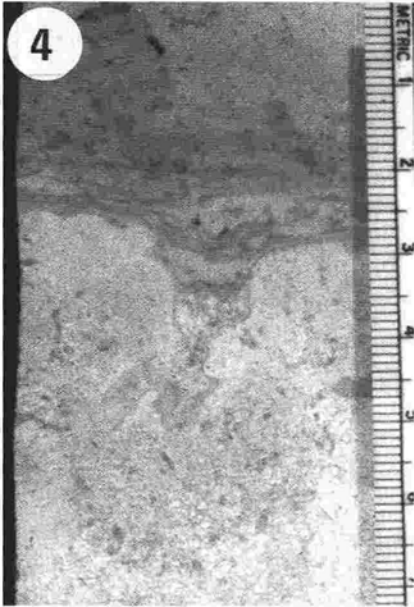
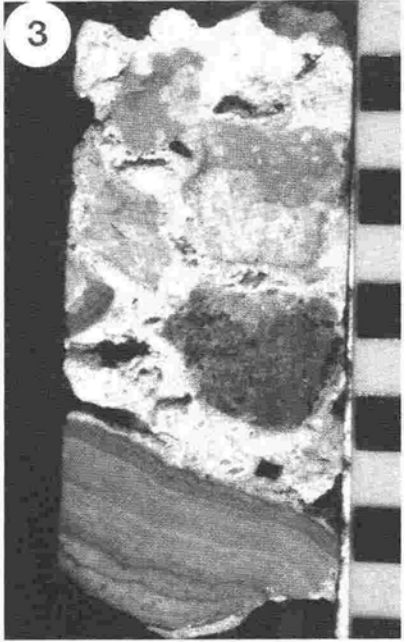
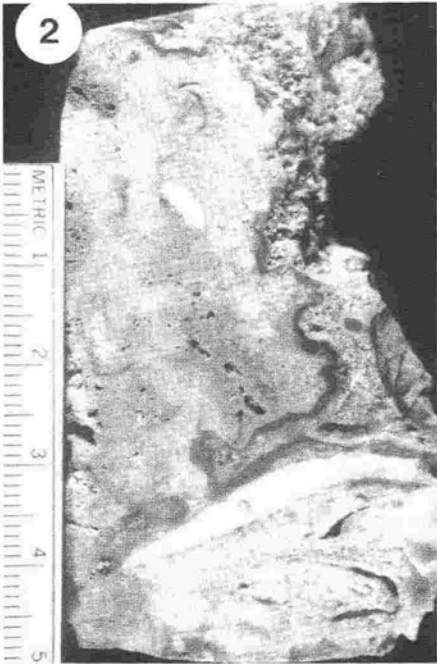
present in core WT (Dry Tortugas), as well as in core WP (Basin Hill Shoals) in the mid-shelf area of the northern Keys (Fig. 1). These post-Q5e rocks are composed of coral boundstone (commonly *Montastrea annularis*, *Porites* sp. with less common *Acropora palmata*) and coralline grainstones with mollusks, *Halimeda*, coralline algae, forams, and peloids. In the mid-shelf below the Basin Hill Shoals area (core WP), this unit is characterized by *Montastrea*, mollusk-foram-peloidal packstones, and rare thin quartz layers at its base.

5.7 Diagenesis of Q units

After shallow-water deposition and lithification, each of the Q units of the Key Largo Limestone was subject in turn to subaerial exposure. Diagenetic features are predominantly indicative of the meteoric environment. An important feature throughout the Key Largo Limestone is interparticle and intraparticle porosity (Pl. 42). Intraparticle, moldic porosity is very common. Parts of grains and entire grains are dissolved, leaving voids that exhibit the shape of the former constituent particle. In numerous cases, micrite envelopes are the only evidence of former grains. Many constituent particles of high-magnesium calcite and aragonite that are not dissolved have been neomorphosed to low-magnesium calcite. Diagenetic alteration can be found in various stages

Plate 44 Key Largo Limestone, Florida: A Pleistocene shelf-edge facies. Boundaries between Q units in the Key Largo Limestone (all depths are below core top).

- Fig. 1. A dark brown laminated subaerial crust and vein-filling microcrystalline rind defining the contact between a Q3 packstone with mollusks, forams, peloids and moldic porosity and overlying Q4a rubble of grainstone containing mollusks, forams, peloids, quartz, and rounded reworked encrusted fragments of rock from below crust, core 3 (Cotton Key, Florida Bay, Fig. 1), depth 11 ft (3.3 m), boundary between Q3 and Q4a.
- Fig. 2., 2a Example of subaerial diagenesis including (1) encrusted solution cavity filled with soilstone displaying moldic porosity, (2) sheltering by pelecypod shell from further meteoric alteration, core 10 (John Sawyer Bank, Florida Bay, Fig. 1), depth 4 ft (1.2 m), boundary between Q3 and Q4. Fig. 2a: Detail.
- Fig. 3., 3a Thick subaerial laminated crust at top of Q3 with rare rhizoids and quartz grains underlying base of a Q4a quartz grainstone rubble that is made up of various fragments of coral, crust, and a variety of packstone pebbles containing red coralline algae, mollusks, peloids and forams, core 30 (Bayside Well Cluster # 2, Florida Bay, Fig. 6), depth 19 ft (5.8 m). Fig. 3a: Detail.
- Fig. 4. Subaerial contacts between Q2 and Q1? seen here (and also found between Q5 and Q4 elsewhere) are well known to be thin, discontinuous and subtle with the lithology above and below the contact very similar in nature. Here a thin brown crust with rhizoids coats and fills fractures at the top of a tan quartz-rich packstone with mollusks and rare forams. Above the crust is a similar darker brown packstone containing only an increase in mollusk debris, core 9 (Sandy Key #2, Fig. 5), depth 43 ft (13.0 m).
- Fig. 5. Molluskan-foram-peloid packstone overlain by laminated crust containing thick interbeds of peloidal packstone and random quartz overlain by a pebbly grainstone rubble with fragments of skeletal wackestone and grainstone, laminated pebbles and rare mud infilling, core 23 (Lignumvitae Channel, Florida Bay, Fig. 1), depth 10.5 ft (3.2 m), boundary between Q4b? and Q4a?
- Fig. 6. Molluskan-peloidal-foram packstone overlain by thick laminated crust which in turn is overlain by foram peloidal grainstone rubble with few quartz grains and displaying a large laminated pebble, black soilstone pebble with "floating" mollusks, forams and quartz grains, core 23 (Lignumvitae Channel, Florida Bay, Fig. 1), depth 15 ft (4.5 m), boundary between Q4a? and Q3?
- Fig. 7. Thin discontinuous laminated crust coats deeply weathered surfaces, various solution cavities and fractures to depths of 1 ft (0.3 m). This skeletal (mollusks, forams) quartzose packstone contains common open voids partially filled with quartz, unidentified tubes and skeletal debris. Core 4 (Lake Key, Florida Bay, see inset of Fig. 1). Depth 10 ft (3 m), top of Q3 ?



ranging from entire grains such as mollusk shells or coral fragments of blocky calcite to grains that are only partly neomorphosed. In all Q units, however, coral and mollusk fragments were detected that still show at least partial primary mineralogy. It is noteworthy that these aragonitic particles are most abundant in the shelf-edge cores WL, WX, WXX, WT, and also in WP offshore from the present mainland. Moldic porosity in these cores is also less than in the rest of the cores, suggesting that the lower elevation at the shelf margin had less exposure to meteoric waters and therefore less diagenetic alteration. An analysis of spatial trends in diagenetic features is shown in Figure 8.

5.8 Chronology

Twenty-five radiometric dates were obtained via TIMS and MC-ICP-MS analyses of coral samples containing greater than 95% aragonite (Table 1). Eleven are Pleistocene (370.2 to 77.8 ka) with the remaining 14 being Holocene (9.3 to 2.3 ka). Half-lives used to determine the ages were ^{234}U and ^{230}Th of 245,250 years and 75,690 years, respectively (Cheng et al. 2000). Activity ratios were calculated from the atomic ratios by normalizing to a secular equilibrium standard, assuming the above half-lives. Criteria sought for reliable U-series ages were (1) U concentrations similar to those found in living specimens of the same genus, (2) little or no evidence of recrystallization to calcite, (3) little or no "inherited" ^{230}Th (indicated by high $^{230}\text{Th}/^{232}\text{Th}$ ratios and small amounts of ^{232}Th), and (4) calculated initial $^{234}\text{U}/^{238}\text{U}$ ratio in agreement within analytical uncertainty to a modern seawater activity ratio of about 1.148 (Chen et al. 1986). Most U-series studies indicate that calculated $^{234}\text{U}/^{238}\text{U}$ initials from 1.145 to 1.159 are indications of reliable ages (Stirling

et al. 1998). Higher than modern calculated initial $^{234}\text{U}/^{238}\text{U}$ values bias corals to older apparent ages (Gallup et al. 1994).

Perkins (1977, p. 139), in naming the Pleistocene rocks of south Florida Q1 through Q5, stressed that these units are time-stratigraphic and are delineated by discontinuity surfaces. Subsequent studies (Cronin et al. 1981; Szabo 1985; Muhs et al. 1992; Gallup et al. 1994; Kindler and Hearty 1996; Ludwig et al. 1996; Toscano and Lundberg 1997; Sterling et al. 1998; Petit et al. 1999; Fruijtier et al. 2000) have helped establish a chronological scale (see Fig. 9) useful for the Key Largo Limestone. For example, the 120- to 130-ka rocks that Perkins (1977) discussed as Q5 at Windley Key Quarry are correlative with isotope substage 5e. Evidence for two separate sea-level peaks during 5e time has been suggested (Muhs et al. 1992; Fruijtier et al. 2000). Various ultimate deglaciation peaks including at 135 ka are discussed by Henderson and Slowey (2000). Stage 5 also contains two younger sea level low stands (substages 5c and 5a) which are estimated by Cronin et al. (1981) to have existed at 105 and 82 ka, respectively. The present paper (Fig. 7) notes a number of new and published isotope substage 5a dates and one possible 5c date from various cores.

Dates on the Key Largo Limestone in the Florida Keys have been very limited in both geographic and vertical distribution. Until more age data establish the extent of various substages, the present authors have found it more workable to use the terms Q5e and post-Q5e for rocks that appear to belong in oxygen-isotope stage 5 (see Figs. 7, 9 and Table 1). Dated cores of rocks designated post-Q5e in this paper usually lack the evidence of good unconformable surfaces and wide distribution, a situation that future research will hopefully rectify with more precise strati-

Plate 45 Key Largo Limestone, Florida: A Pleistocene shelf-edge facies. Examples of boundaries between Q units in the Key Largo Limestone (all depths are below core top).

Fig. 1. Thin laminated crust often coats solution cavities shown here filled with skeletal and peloidal pebbles and capped with thick laminated crust, core W2 (Grassy Key, Fig. 3), depth 18 ft (5.5 m), boundary between Q3 and Q4.

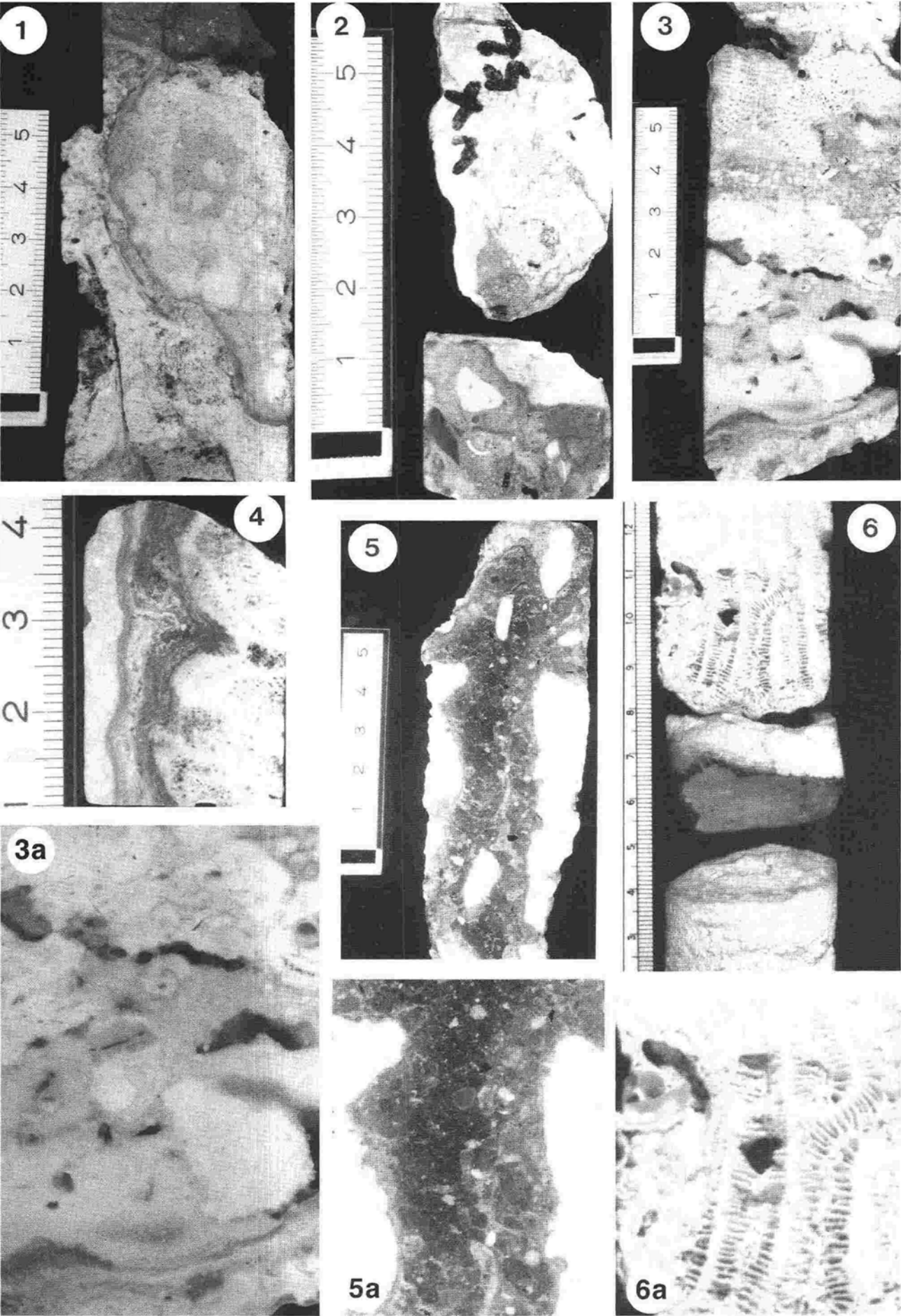
Fig. 2. Various thicknesses of dark brown to gray soilstone (diagenetic mudstones) locally containing "floating" shells as well as brown and black pebbles can be found at the top surface of Q units, core WX (Looe Key, Fig. 2), depth 52 ft (15.8 m), top of post-Q5e.

Fig. 3., 3a At the boundary between Q3 and Q4a, quartz sandstone with pebbles of packstone can be found overlying laminated crust; above the quartz layer are found skeletal packstone and coral, core 93 (Bayside Cluster D, Florida Bay, Fig. 6), depth 40 ft (12.1 m). Fig. 3a: Detail.

Fig. 4. Coral with vertical cavities can be coated with thick laminated crust containing black pebbles, core W2 (Grassy Key, Fig. 3), depth 1 ft. (0.3 m), top of Q5.

Fig. 5., 5a Vertical cavity in a mollusk-foram wackestone is filled with dark gray soilstone and black pebbles, core WP (Basin Hill Shoals, Fig. 2), depth 35 ft (10.6 m), top of post-Q5e. Fig. 5a: Detail.

Fig. 6., 6a A thin microcrystalline rind (sometimes all that is present at contacts) is illustrated by three consecutive core pieces in descending order displaying (1) *Diploria* coral, (2) encrusted grainstone composed of mollusks, forams, *Halimeda* and peloids with thin (1-2 mm) black and dark brown microcrystalline rind coating surfaces and voids; cavities in fossils near crust show vadose whisker calcite needles, and (3) a second encrusted grainstone core piece as above. Core MQ-4 (southwest Marquesas area, Fig. 15), sample depth is 13 ft (3.9 m) from top of rock and 53 ft (16.1 m) below sea level. Q units involved are unknown. Fig. 6a: Detail.



graphic designations. Q5e is used for rocks found to be in the general 145- to 120-ka (isotope substage 5.5) range. These rocks can be observed and dated in the Windley Key Quarry (Harmon et al. 1979; Muhs et al. 1992; Fruijtier et al. 2000). Younger coralline units (dated in the present study) that are 112.4 to 77.8 ka (isotope substages 5c and 5a) are grouped together and called post-Q5e unit rocks. These are found only in the subsurface under the shelf and shelf edge (this paper) and beneath Sand Key and Carysfort outlier reefs (Lidz et al. 1991; Toscano and Lundberg 1997).

The oldest Pleistocene dates of 370.2-366.8 ka were obtained in core #1 Pleasant Pt. 1A (Fig. 6) just west of Key Largo and correspond to isotope stages 11 or 9, given the elevated $^{234}\text{U}/^{238}\text{U}$ ratios (Table 1) that indicate possible bias to older ages. Several miles to the north, at RH-4 (Fig. 10), Szabo and Halley (1988) obtained a comparable age of 360 ka (error of -60 ka, +120 ka) from a coral collected from a pre-Q5 unit and concluded the dated coral is at least 300 ka.

In core WL 69 the U content is very low and possibly indicates open system alteration. Core samples WT 41, AQ 115-120 and KL 4-52 have calculated initial $^{234}\text{U}/^{238}\text{U}$ ratios greater than 1.16, which suggests a slight bias to older ages (Gallup et al. 1994).

5.9 Paleokarst features

Cores and outcrop samples of the Key Largo Limestone found in the Florida Keys provide sources of information on

five periods when portions of the present Keys lay exposed to subaerial conditions. Duration and timing of low stands of sea level and increases of airborne dust characterizing subaerial conditions are noted by Petit et al. (1999) in Figure 9. Subaerial features between Q3 and Q4 are common in the Florida Keys, but the Q4 to Q5 interval, although extensive in number of years and recorded dust (Fig. 9), lacks evidence of erosion and thick crusts. This may indicate extensive arid conditions with limited soil and plant formation during this time.

The most common subaerial feature is **subaerial crust**, the origin of which was first determined in the Florida Keys by Multer and Hoffmeister (1965, 1968a). The crust is found in outcrop and cores as porous laminated and dense laminated layers as well as microcrystalline rind (Pls. 44, 45). The thickest crusts are found associated with the top of Q3 intervals in the subsurface. However, thick crusts are also found in surface outcrops of the Q5 Key Largo Limestone and well developed on the Q5 oolite exposed in the lower Keys. **Quartz** is a common but usually minor constituent of subaerial crusts. Bedrock directly underlying subaerial crusts usually displays maximum diagenetic alteration and reduced porosity/permeability. Rounded and angular **black pebbles** from 3-10 mm in diameter are occasionally found within or at the top of subaerial crusts. **Breccia and fossil soils** occur as iron-stained red and gray infillings of depressions, solution pipes and sinkholes commonly associated with subaerial crusts (Shinn and Lidz 1988). The breccias contain angular to rounded, poorly sorted, sometimes subaerially encrusted rock fragments and variable amounts of

Plate 46 Key Largo Limestone, Florida: A Pleistocene shelf-edge facies. Examples of possible framework types capable of producing rigid patch reefs and non-rigid mounds or beds within the Key Largo Limestone (all depths are below core top).

Fig. 1. NON-RIGID STABILIZED THICKET OR BED of branching coral, mollusks, serpulid tubes and red coralline algae in a matrix of subangular quartzose wackestone. Core 25 (Johnson Key, Figs. 1, 5) depth 19 ft (5.8 m), unit Q2.

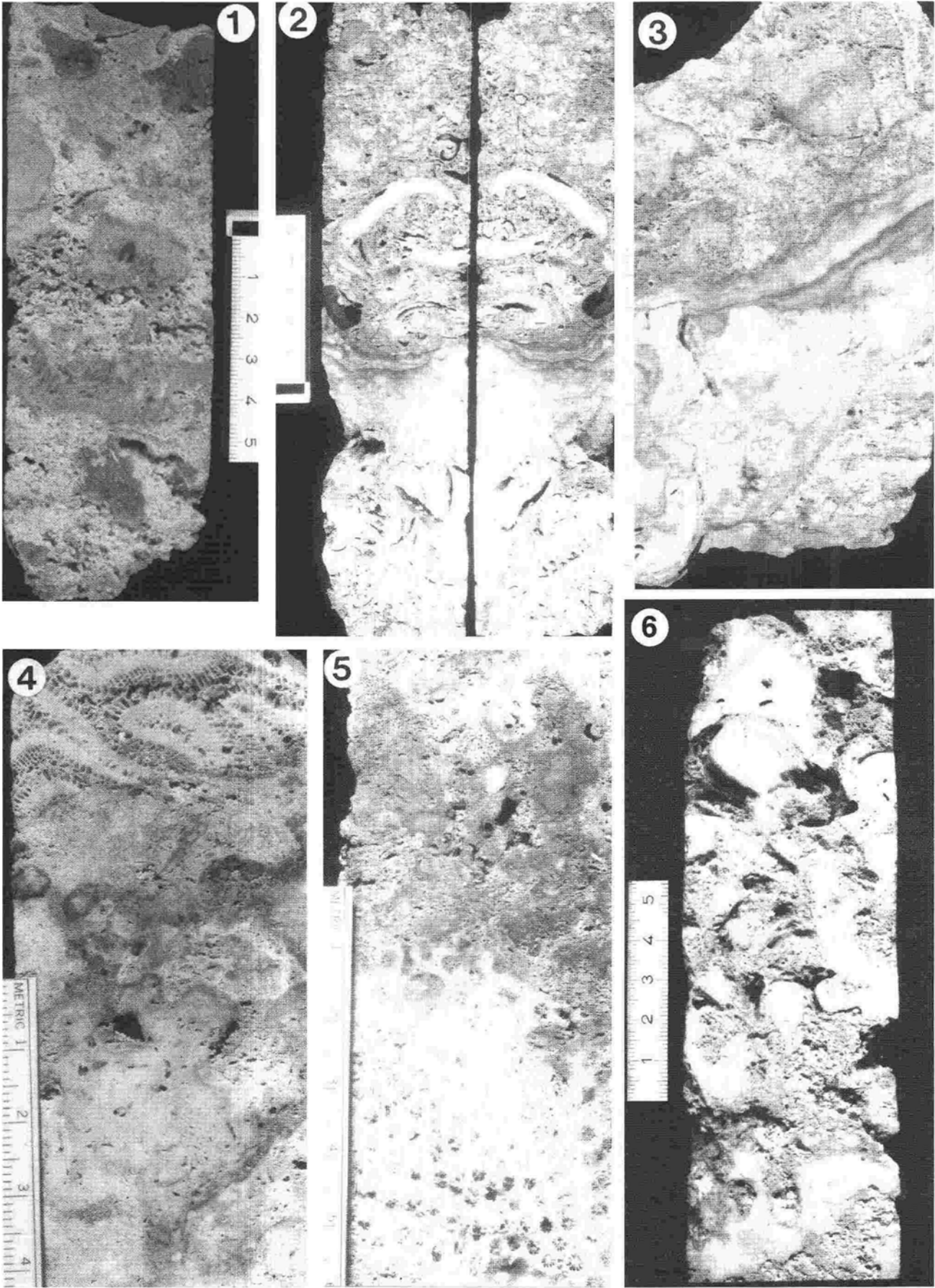
Fig. 2. RIGID FUSED ENCRUSTED THICKET OR BED with coral, red coralline algae, mollusks, peloids and mud infill overlain by subaerial laminated crust incorporating small mollusk shells and black round pebbles. Above crust a NON-RIGID STABILIZED RUBBLE MOUND OR BED of *Porites* coral, mollusks, black pebbles, fragments of laminated crust and reworked grainstone pebbles (containing forams and peloids), interspersed with serpulid tubes and mud. Core 17 (Bob Allen Key-B, near Bob Allen Key-A core, Florida Bay, Fig. 13), depth 2 ft (0.6 m), unit Q3/Q4.

Fig. 3. NON-RIGID STABILIZED RUBBLE of coral (*Montastrea*?), mollusks, forams, bryozoans, peloids and trace of quartz overlain by laminated crust. Above crust is a STABILIZED CORAL THICKET MOUND OR BED of *Porites* coral with mollusks, forams, bryozoans, peloids and a few round black pebbles. Core 16 (Bob Allen Key-A, Florida Bay, Fig. 13), depth 4 ft (1.2 m), unit Q4b/Q4a.

Fig. 4. Possible STABILIZED MUD MOUND OR BED with common mollusk and foram fragments, small rhizoid? holes and larger former root or bore holes filled with skeletal debris, all floating in a wackestone matrix. Overlying this stabilized skeletal mud mound is a RIGID CORAL (*Diploria*) FRAMEWORK. Core 15 (Sprigger Bank, Florida Bay, Fig. 1), approximate depth 15 ft (4.5 m), unit Q4.

Fig. 5. RIGID FUSED PILLAR FRAMEWORK of *Montastrea* coral with overlying NON-RIGID STABILIZED RUBBLE including coral, mollusk, coralline algae, forams, pellets, random quartz grains and unidentified plant? tubes filling interstices; micritic replacement common. Core 10 (John Sawyer Bank, north of Marathon, Florida Bay, Fig. 1), depth 6 ft (1.8 m), unit Q3.

Fig. 6. FUSED ENCRUSTED THICKET of stick corals lying above *Montastrea* (not shown) with skeletal packstone and unidentified tubes partially filling voids between corals which include *Porites* sp. Core W9 (Figs. 1, 3), depth 14 ft (4.3 m), unit Q4b.



black pebbles. Both calcareous and woody **root structures** are also associated with paleokarst intervals. **Soilstone** occurs as gray to black and brown mottled diagenetically altered and locally bored mudstone lenses and stringers with sharp or gradational contact with local bedrock.

5.10 Quartz in the Key Largo Limestone

Quartz is abundant only in the lowermost units of the Key Largo Limestone and in the younger Q4a horizon. However, there are numerous horizons, especially near subaerial exposure surfaces, that contain limited amounts of quartz grains. In Key Largo Limestone grains of quartz are usually subangular and less commonly subrounded. The surfaces of most grains investigated have medium and low relief. Surface textures as observed under SEM (Pl. 43) are largely dominated by both solution marks and crystal overgrowth. Indicators of solution include straight and slightly curved crevasses, oriented V-shaped pits (Krinsley and Doornkamp 1973; Margolis and Krinsley 1974; Higgs 1979), and centipede-type solution marks (Manker and Ponder 1978). Crystal overgrowth of smaller euhedral pyramids of quartz and larger flat-shaped crystals is very common. These surface textures support the contention that the majority of grains in the Key Largo were involved in soil or regolith environments. Less frequently seen structures such as irregular pits and scratches, unoriented Vs, the general subangular-subrounded outline, and the medium relief of grain surfaces suggest subaqueous transport to some degree. Concentration of quartz grains at subaerial-exposure surfaces can be explained by wind, stream feeding, littoral transport, or by dissolution of limestone.

5.11 Florida Bay bedrock

Cores that were taken by the USGS in Florida Bay during the 1990s indicate a predominance of lagoonal packstones and grainstones with presence of some rigid reef frameworks and non-rigid stabilized mounds (Fig. 11). The upper beds are rich in bryozoans and display extensive amounts of bioturbation, burrowing, diagenetic alteration, and surface erosion, often producing karst features such as encrusted solution pits and black pebbles.

5.12 Paleotopography and platform tilting

A contour map (Fig. 12) of the top of the former subaerial surface of unit Q3 reveals several significant paleotopographic features. A distinct re-entrant from the north was present by the end of Q3 time and is seen in core WB (Fig. 5). This re-entrant has implications for ancient drainage patterns and may have provided frequent access to the Atlantic Ocean by the Gulf Loop currents as sea level rose. A second bifurcating re-entrant on the Atlantic side (including core W9) exists in the center of Key Largo island and indicates pathways for drainage and influx of allogenic quartz grains from the north.

Parker and Cooke (1944, p. 19) suggest the probability

that the western half of the south Florida Plateau "has been canted westward." They also indicate (p. 21) that the late Pliocene was a time of crustal instability during which "the Florida Plateau emerged, was probably tilted toward the west, and actively eroded."

Evidence for possible westward tilting of the platform is found in (1) common southwest dips (Fig. 10) of various Q units throughout the Pleistocene, (2) thickening of Q units toward the southwest, which could be from tilting and/or simply from an increase in carbonate productivity in that direction, (3) the fact that the base of the oolite in core W5 under Key West lies about 21 ft (6.3 m) below sea level whereas the same contact is topographically higher in the Miami area to the northeast (Halley and Evans 1983), and (4) "a linear Pleistocene beach deposit that dips along strike to the west suggesting westward tilting during late Pleistocene" (Shinn et al. 1989, p. 5). Evidence for possible shelf-edge tilting to the southeast, compaction or faulting is also indicated when comparing depths below sea level of the same (TIMS-dated) Pleistocene rocks from under the shelf edge (SKSE and WL cores) with those found under the Sand Key and Carysfort outliers (Fig. 7). Shelf-edge rocks appear to be 4 to 6 m lower in elevation than those found under the outliers based on TIMS dating obtained in this study.

6 DISCUSSION

6.1 Variability of facies

During the Pleistocene, dynamic and rapid facies changes were very common in the narrow arcuate shelf-edge environment of the Key Largo Limestone in the Florida Keys. Such variation in facies could reflect changes in availability of allogenic siliciclastics and authigenic carbonates, or periodic sea-level rise over the whole Florida Keys, allowing the Gulf Stream Loop Current and/or strong northerly winds to provide influx of cold waters, mud, and larvae from the Gulf onto the shelf edge (Shinn 1988; Randazzo and Halley 1997). Various subaerial periods also induced diagenetic textural changes to underlying rocks and produced soil for subsequent lithotopes which created deleterious conditions for subsequent biotopes (Multer and Hoffmeister 1968b; Lighty et al. 1978; Schlager 1981; Neumann and Macintyre 1985, p. 107: "reefs shot in the back by their own lagoons"). A series of long-term transgressive and regressive seas caused migration and/or burial of lithotopes and biotopes, including production of various reef types (Neumann and Macintyre 1985; Dullo 1990) and some short-term fluctuations (White and Curran 1995; Locker et al. 1996). Sediment mixing and transport as well as biotope alteration by tropical storm activity (Ball et al. 1967; Perkins and Enos 1968) could have affected bottom sediments and coastlines as they do today in the Florida Keys where they occur at 3-5 year intervals and produce extreme freshwater runoff once every 6-7 years (Meeder and Meeder 1989). Other explanations for observed facies change include burial and/or death of biotopes across reef flats due to influx of excessively salty, muddy and/or excessively hot or cold waters from platform interiors as occur today (Ginsburg and Shinn 1964, 1993;

Core	depth, feet	age, ka	error, ka	^{232}Th , ppm	^{238}U , ppm	error	Initial $^{234}\text{U}/^{238}\text{U}$	error	ActRat $^{230}\text{Th}/^{238}\text{U}$	error	ActRat $^{230}\text{Th}/^{232}\text{Th}$	ActRat $^{234}\text{U}/^{238}\text{U}$	error	lab	Q-units	isotope stages	coral
WL	44	4.8	0.03	0.0026	2.63	0.120	1.1494	0.0020	0.0493	0.0003	151	1.1470	0.0020	KS	Holocene	I	B
WL	50	6.3	0.06	0.0022	2.71	0.110	1.1494	0.0021	0.0640	0.0006	240	1.1463	0.0021	KS	Holocene	I	M
WL	55	6.6	0.03	0.0014	2.68	0.110	1.1488	0.0017	0.0671	0.0003	399	1.1456	0.0017	KS	Holocene	I	M
WL	64	7.3	0.1	0.0008	2.42	0.120	1.1471	0.0016	0.0737	0.0012	705	1.1436	0.0016	KS	Holocene	I	M
WT	27.8	6.92	0.04	0.0020	2.52	0.001	1.1387	0.0016	0.0700	0.0037	7015	1.1360	0.0016	JL	Holocene	I	M
WT	32	7.3	0.09	0.0064	2.73	0.120	1.1479	0.0015	0.0743	0.0008	97	1.1444	0.0015	KS	Holocene	I	M
WT	41	8.8	0.1	0.0100	2.34	0.004	1.1640	0.0050	0.0900	0.0010	1313	1.1600	0.0050	JL*	Holocene	I	M
WT	48	8.7	0.07	0.0115	2.80	0.120	1.1495	0.0025	0.0882	0.0006	66	1.1454	0.0024	KS	Holocene	I	D
WT	51	9.33	0.07	0.0340	2.39	0.003	1.1440	0.0040	0.0935	0.0007	431	1.1400	0.0040	JL*	Holocene	I	M
WXX	62/63	4.2	0.04	0.0100	3.48	0.110	1.1505	0.0013	0.0435	0.0004	47	1.1482	0.0013	KS	Holocene	I	M
WXX	62/63	4.3	0.2	0.0107	3.47	0.120	1.1482	0.0017	0.0442	0.0019	44	1.1460	0.0017	KS	Holocene	I	M
WXX	64/65	2.3	0.1	0.0004	2.66	0.001	1.1363	0.0012	0.0230	0.0010	8594	1.1350	0.0010	JL	Holocene	I	A
MQ 1	16	2.5	0.06	0.0001	2.79	0.120	1.1464	0.0020	0.0256	0.0006	3363	1.1450	0.0019	KS	Holocene	I	D
SB 2	15	3.6	0.04	0.0055	2.42	0.110	1.1463	0.0020	0.0370	0.0004	50	1.1444	0.0019	KS	Holocene	I	U
WX	84	92.3	0.5	0.0036	2.47	0.120	1.1570	0.0025	0.6477	0.0018	1338	1.1205	0.0020	KS	post-Q5c	5c	M
WX	84	91.5	0.4	0.0037	2.47	0.120	1.1559	0.0018	0.6435	0.0017	1286	1.1200	0.0015	KS	post-Q5c	5c	M
WX	86	91.1	0.6	0.0870	2.40	0.001	1.1373	0.0012	0.6330	0.0030	714	1.1060	0.0010	JL	post-Q5c	5c	M
WL	69	77.8	0.4	0.0130	1.61	0.002	1.1310	0.0040	0.5690	0.0020	3524	1.1050	0.0040	JL*	post-Q5c	5a	M
AQ	95-100	87.0	0.4	0.0001	2.42	0.120	1.1510	0.0022	0.6214	0.0013	40210	1.1177	0.0018	KS	post-Q5c	5a/5c	U
KL 5	74.5	92.3	0.7	0.0150	2.12	0.003	1.1450	0.0040	0.6420	0.0030	5711	1.1120	0.0040	JL*	post-Q5c	5c	U
AQ	115-120	112.4	1.3	0.4460	2.25	0.003	1.1590	0.0040	0.7280	0.0050	258	1.1160	0.0040	JL*	post-Q5c/Q5e	5c/5e	U
KL 4	52	124.2	0.6	0.0028	2.97	0.120	1.1605	0.0019	0.7680	0.0018	2458	1.1126	0.0014	KS	Q5c	5c	U
WP	72	128.1	0.5	0.0140	2.10	0.001	1.1475	0.0019	0.7730	0.0008	5406	1.1030	0.0020	JL	Q5c	5c	M
Ppt	0	370.2	11.7	0.0041	2.43	0.100	1.3423	0.0097	1.1236	0.0042	2026	1.1203	0.0019	KS	Q3	9	M
Ppt	0	366.8	8.7	0.0038	2.43	0.120	1.3182	0.0065	1.1124	0.0030	2180	1.1128	0.0016	KS	Q3	9	M

KEY: JL = measured by Joyce Lundberg, Carleton University, Ottawa, Ontario, Canada; KS = measured by Kathleen Simmons, USGS, Denver, Colorado, USA;
 * = MC-ICP-MS dating; all other dates are by TIMS.

Table 1: New radiometric dates from corals with >95% aragonite from cores investigated during this study. Depths noted are in feet below sea level. Isotope stages noted are tentative. Coral column identifies source of dates as follows: M=*Montastrea annularis*-group; B=*Brain coral*; A=*Acropora palmata*; D=*Diploria* sp.; U=unidentified coral.

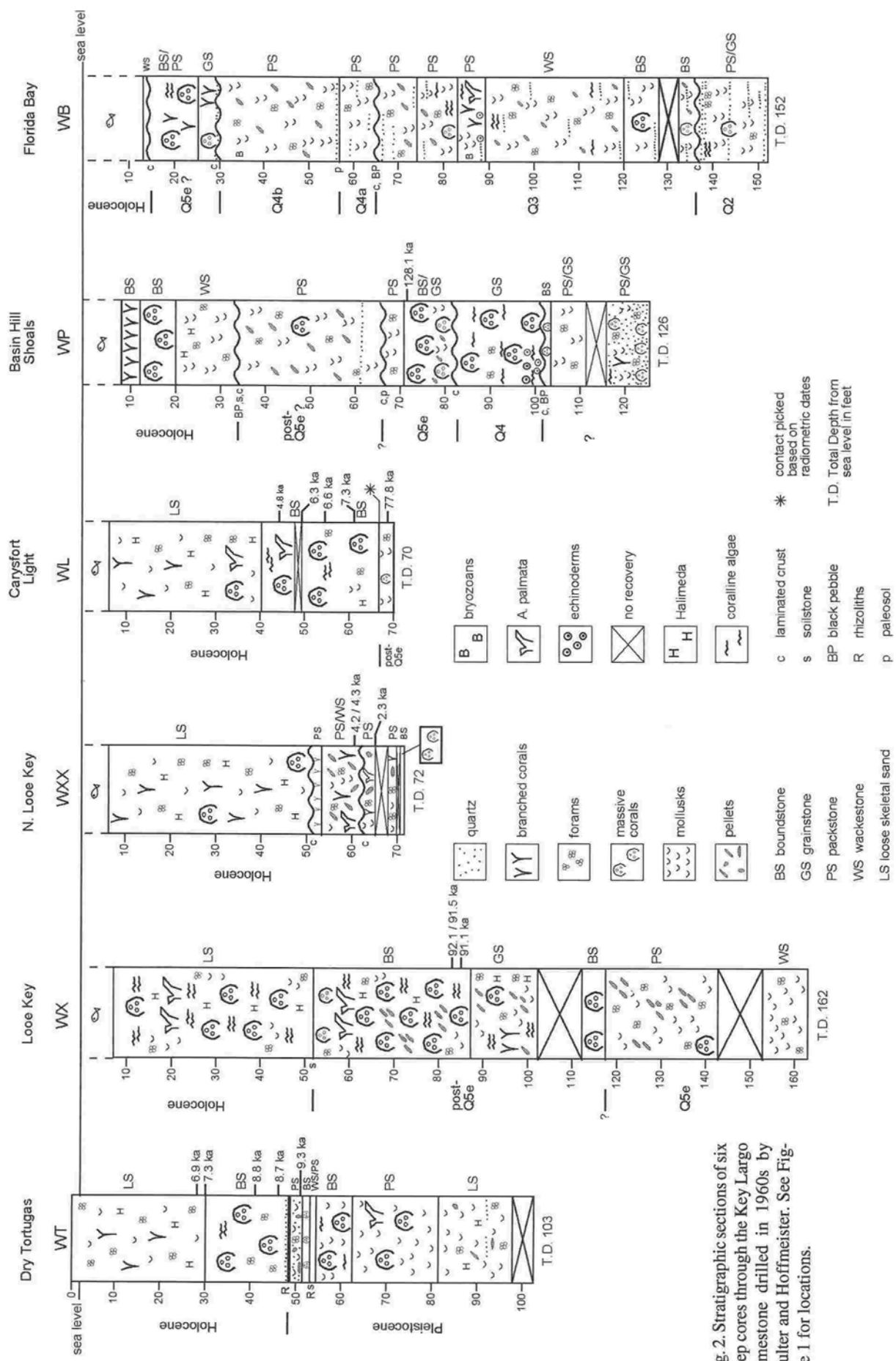


Fig. 2. Stratigraphic sections of six deep cores through the Key Largo Limestone drilled in 1960s by Multer and Hoffmeister. See Figure 1 for locations.

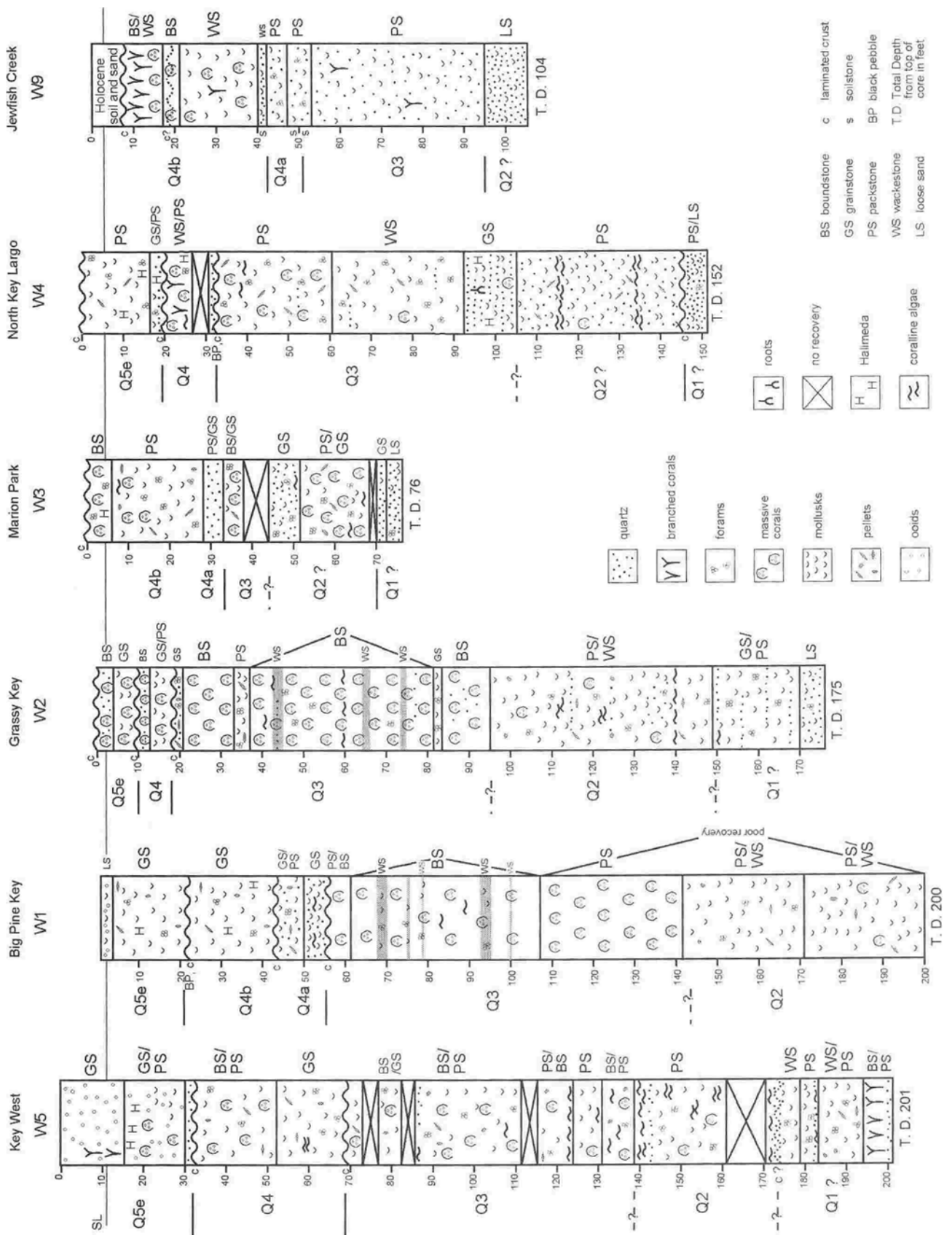


Fig. 3. Stratigraphic sections of six deep cores through the Key Largo Limestone drilled in 1960s by Multer and Hoffmeister. See Figure 1 for locations.

Shinn 1966; Jaap 1979; Shinn et al. 1989). A final unique set of shallow-water tidal conditions allowed production of oolite toward the end of Key Largo time.

6.2 Q1 and Q2: early facies evolution

The early stratigraphy of the Pleistocene Key Largo Limestone was influenced by the geometry and composition of the underlying Upper Miocene/Pliocene Long Key and Stock Island Formations (Guertin et al. 1996; Cunningham et al. 1998). Siliciclastic debris from repeated influx to the southernmost part of the Florida shelf provided both an undulating topography and a quartz-rich sediment source for deposition during early Key Largo time. Inferred extension (Cunningham et al. 1998) of these two deposits seaward of the Florida Keys also formed the foundation for both the Key Largo Limestone and the overlying Holocene reef tract.

The existence of pre-Pleistocene quartz sands had been noted by Vaughan (1910), Matson and Sanford (1913), Gomberg (1976) and Perkins (1977). More recent studies by Ginsburg et al. (1989), Warzeski et al. (1996), Cunningham et al. (1998), and Guertin et al. (1999) have revealed the true thickness, extent, and significance of these pre-Pleistocene siliciclastic packages in the area of the Florida Keys. The exact southern route that siliciclastics took to reach the Florida Keys area is a continuing source of debate summarized by Warzeski et al. (1996) and recently illustrated by Cunningham et al. (1998) as a corridor from west of Lake Okeechobee south to the Florida Bay area. Droxler and Schlager (1985) found bulk sedimentation rates, turbidite accumulation rates and frequency all considerably higher during the highstand shedding period on Bahamian carbonate platforms. They also noted that in contrast to carbonate-rich areas, some siliciclastic ocean margins store sediment on the inner shelf during highstands, passing it on to abyssal plains during lowstand periods. Both of these mechanisms may well have been operating at the south Florida shelf edge during Key Largo time.

Deposition of an initial deep-water arenaceous facies on the Florida shelf edge was followed by the accumulation of successive skeletal-grain beds which reduced water depths and increased water temperature. These factors may have encouraged more carbonate skeletal production by shallow-water organisms. As found by shelf-edge studies in the Florida Keys and various Caribbean areas today (Purdy 1974; Shinn et al. 1977; Multer and Zankl 1988; Gischler and Hudson 1998), initiation of various types of reefs in the Key Largo Limestone was strongly influenced by the presence of topographic highs. These were probably initially developed on pre-Q-unit topography by subaerial erosion or by current, tidal, or storm actions during successive onlap/offlaps of the sea along the shelf edge.

Once the shallow-water conditions were established by late Q2 time, 45-degree cross-bedded grainstones developed (core W3 beneath Key Largo), and corals began to form on top of at least a few topographic highs. A shallow core (Little Maderia Bay-A # 33) from northern Florida Bay as well as those under Park and East Keys as described by Fuhr (1988)

show corals on possible bedrock highs. Coral is also reported by Perkins (1977) in the Q2 unit below Windley Key and was found by Multer and Hoffmeister (1968b) beneath Key West (core W5). McNeill et al. (1996) note coral below Stock Island in what is believed by the present authors to be Q2 mollusk packstone.

Even though we did not obtain radiometric dates from Q1 and Q2 deposits during the present study, we speculate that Pleistocene carbonate production at the margin of the Florida platform may have started during the interval between 420 and 360 ka (isotope stage 11), which is regarded as the longest and warmest period during the past 500 ka (Droxler and Farrell 2000; Kroon et al. 2000).

6.3 Q3: flourishing reef facies

Q3 time was a period of maximum coral reef development for the Key Largo Limestone. Most of the 12 deep cores and the 57 shallow cores examined by the present authors display frequent coralline lithology for the Q3 period. Q3 coral patch reefs in the form of rigid fused pillars and thickets in windward (W1, W2 in Fig. 3) areas (including *Montastrea annularis*, *Diploria* sp., *Porites astreoides*, *Porites porites*) and non-rigid mounds of stabilized thickets and rubble (Fig. 11; Pl. 41/5; Pl. 46/1, 2) in more leeward areas, often flourished beneath the present emergent Florida Keys. These reefs and their distribution had many similar characteristics to today's living reefs off eastern Antigua described by Multer and Zankl (1988).

Early Q3 reef development seems to have occurred along the shelf edge where karst highs, late Q2 reef mounds and storm ridges/mounds were suitable for early patch reef development. Submerged former coastal sand dunes stabilized by grasses and encrustations could have also served as initial substrates. Four separate East Key area cores described by Textoris (1988) and Merriman (1988) contain patch reef corals about 40 ft (12 m) thick, which also evolved laterally. Lateral growth in these patches and in others along the shelf edge is believed to have contributed to the development of at least some Q3 bank-barrier reefs. Shallow-water conditions that were present especially during minor sea-level fluctuations within Q3 time were favorable for lateral development of patch reefs, in contrast to vertical growth. Such minor sea-level fluctuations produced thin subaerial crusts and solution features such as described by Textoris (1988) in the East Key area. Some 10 miles (16 km) to the southwest, the present authors found evidence for a similar regression in a soilstone layer within Q3 coralline packstone at Lignumvitae Channel core #23. From a Q3 age core along this same shelf edge beneath Big Pine Key, Perkins (1977) described 95 ft (28.5 m) of highly coralline facies. In nine successive cores from Grassy Key (W2) to north Key Largo (W4), thick coral-rich zones believed to belong to the Q3 unit occur, indicating a considerable persistence of reef framework beneath the present emergent Keys. In the upper and middle Keys, as noted by Shinn et al. (1994), the coral reef facies beneath the present emergent Keys gives way to (a)

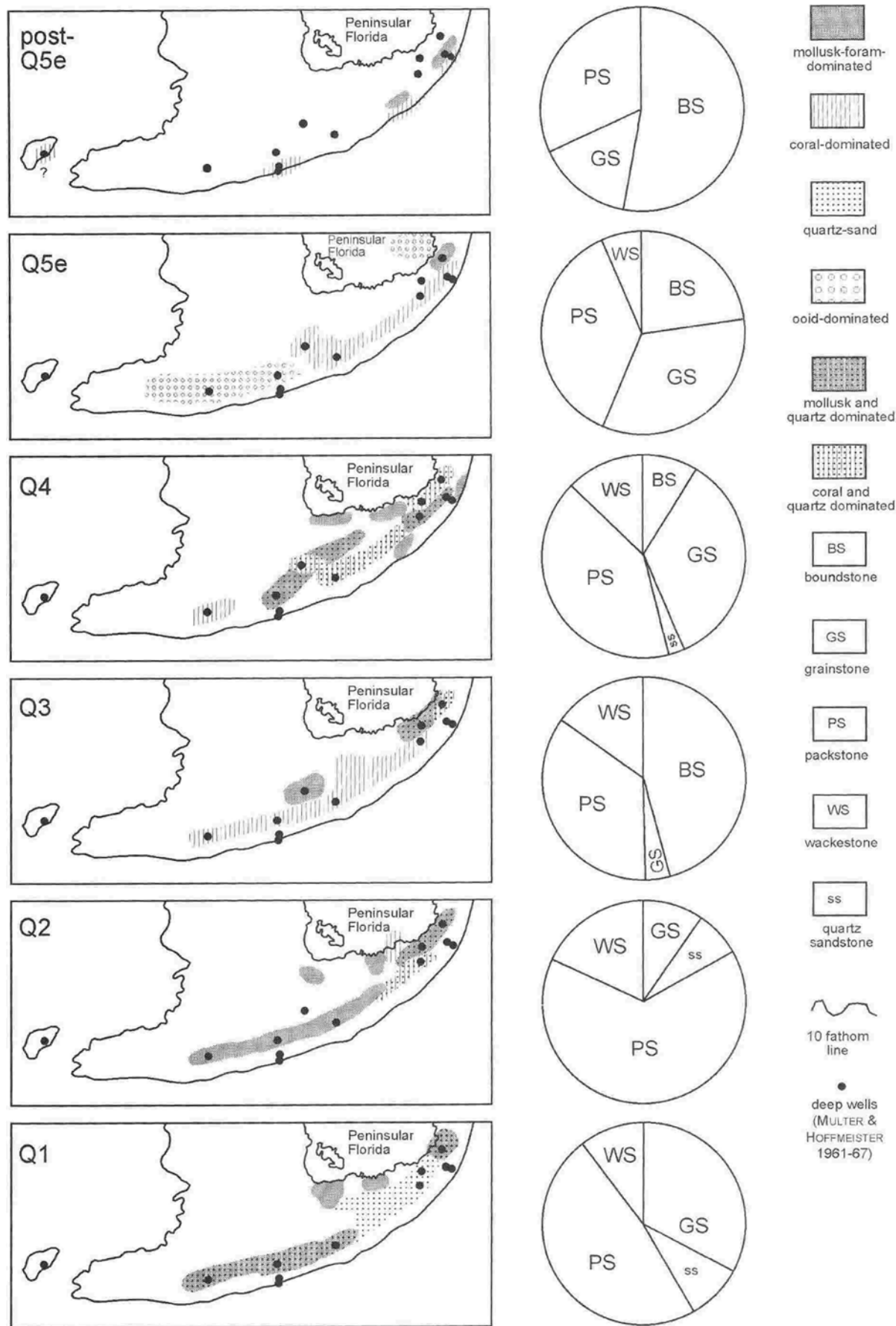


Fig. 4. Pie diagrams showing approximate percentage of various lithologies found in deep cores shown in Figures 2 and 3. Map patterns represent the most dominant facies for each Q unit based on extrapolation of data from all available deep and shallow cores. Pie diagrams are based on the following numbers of cores: Q1: 4, Q2: 7, Q3: 8, Q4: 8, Q5e: 7, post-Q5e: 2.

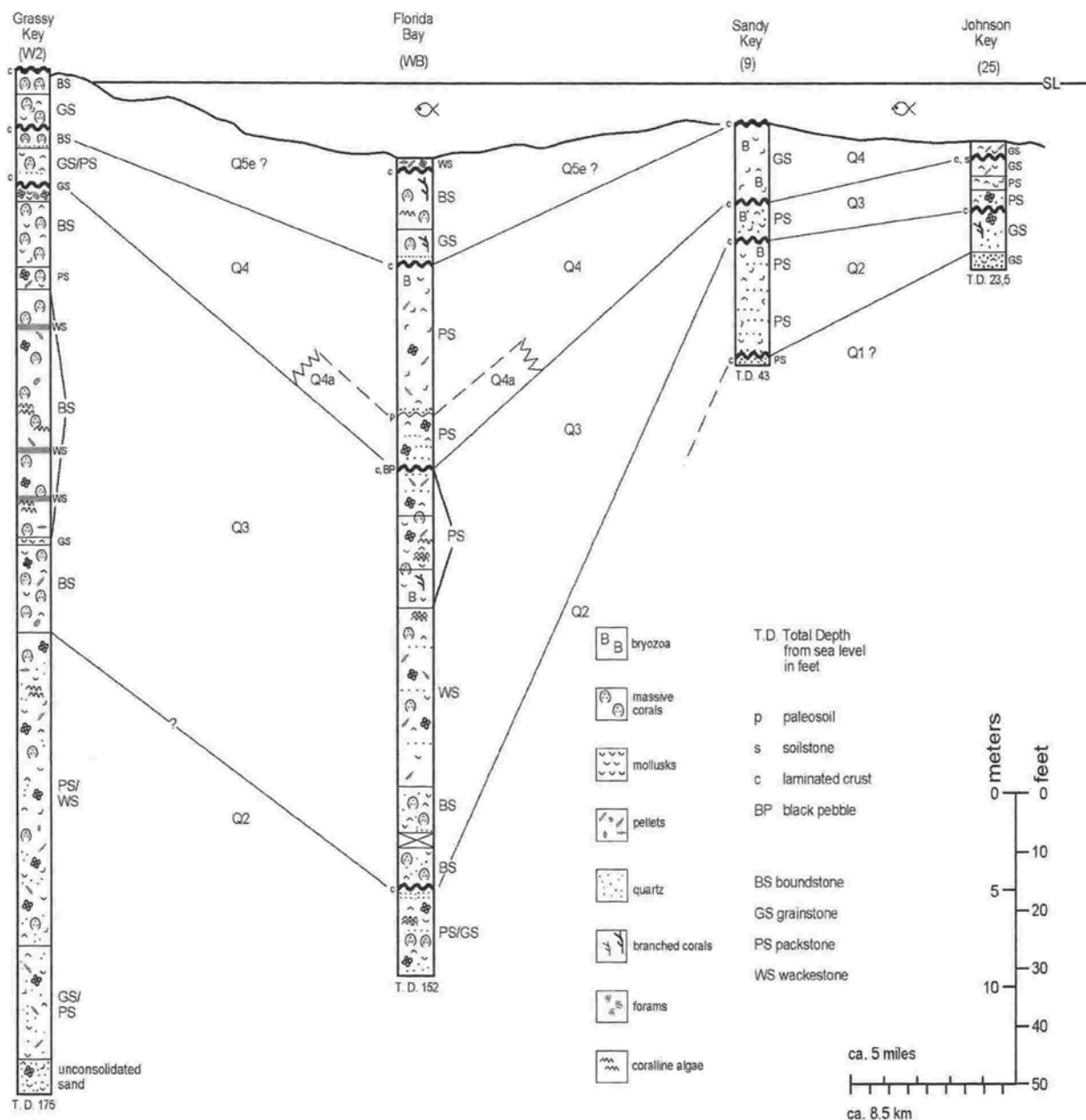


Fig. 5. North-to-south stratigraphic cross section across western Florida Bay from Grassy Key to Johnson Key.

mudstone facies on the Florida Bay side, and (b) mixed grainstone, packstone and wackestone facies on the seaward side beneath Hawk Channel.

A second area for rigid patch reefs and non-rigid mound development during Q3 as well as Q4 times was on the broad platform that extended beneath what is now Florida Bay. Shallow cores from under the bay area were used to identify scattered coral and mound-rich areas occurring on the dominantly packstone/grainstone Q3 and Q4 lagoonal floor.

Identification of specific types of reef patches and mounds from the more common horizontal beds by use of core analysis is difficult and subjective. However, an attempt was made utilizing the fact that animals and plants that produce rigid patch reefs and non-rigid mounds tend to colonize on or form high topography away from adjacent lower muddy floors. Once formed, the bedrock highs are the first exposed when sea level drops and the last

submerged as sea level rises, providing them the maximum time and opportunity for cementation and development of hard encrusted surfaces that favor colonization during the next onlap. This vertical "mimicking" of such framework sites has been documented in cores by Shinn et al. (1977) and Multer and Zankl (1988).

In case such vertical repetition persisted to the surface in Florida Bay, the present authors examined sites that were cored on topographic highs within the bay and that showed successive coralline and/or rubble and/or sub-aerial crustal horizons. Plate 46 gives illustrations and Figure 11 attempts a classification of the frameworks and/or beds that were found. Other examples of possible patch reefs were found at Old Dan Bank (core 6) and Bayside Well Cluster #2 (core 30). Possible patch reefs found far to leeward under the west end of Florida Bay (core WB) contain successive crusts and coral-rich zones. In this core

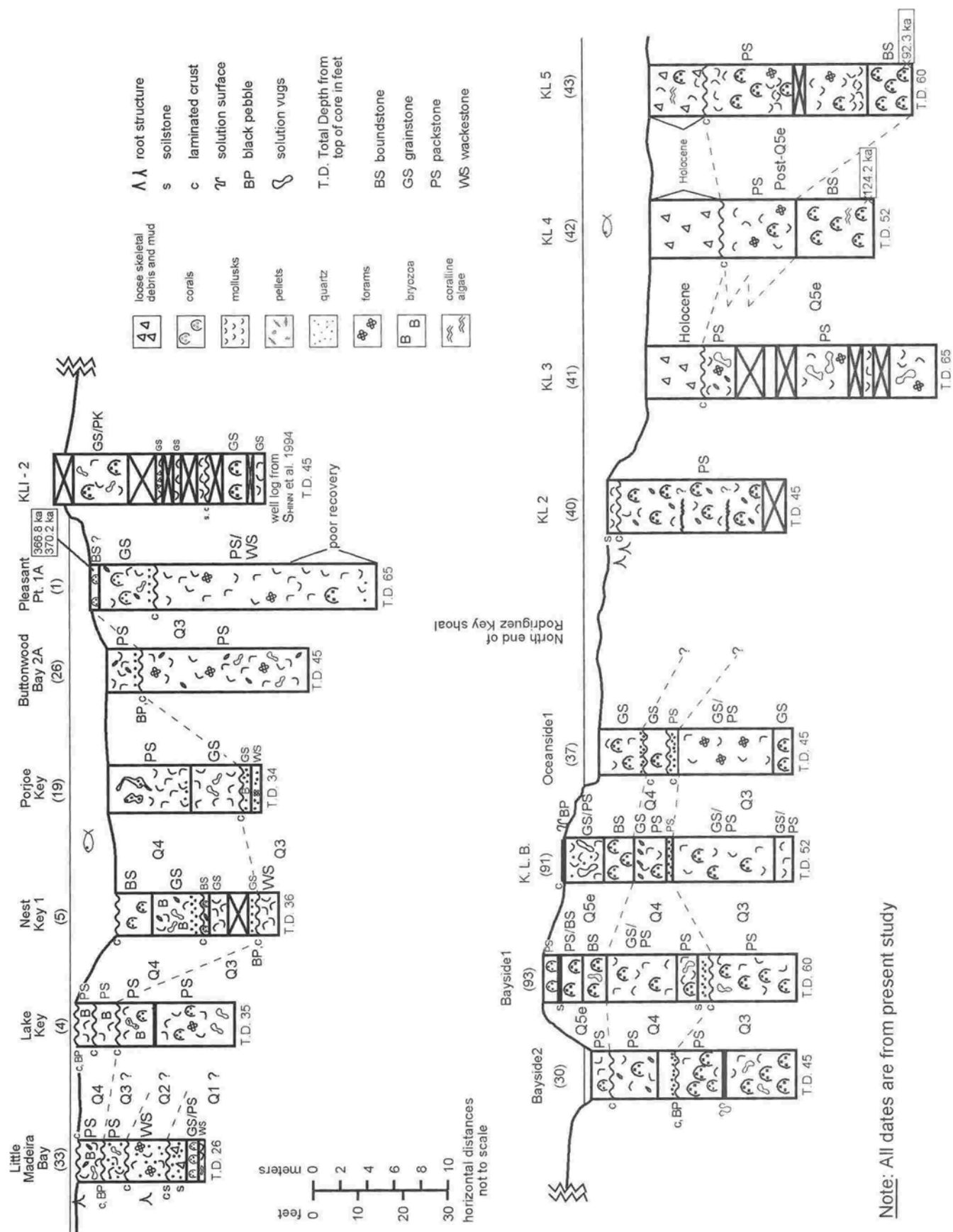


Fig. 6. North-to-south stratigraphic cross section from the north shore of Florida Bay to the shelf edge which is underlain by a shelf-margin wedge of post-Q5e packstones and boundstones.

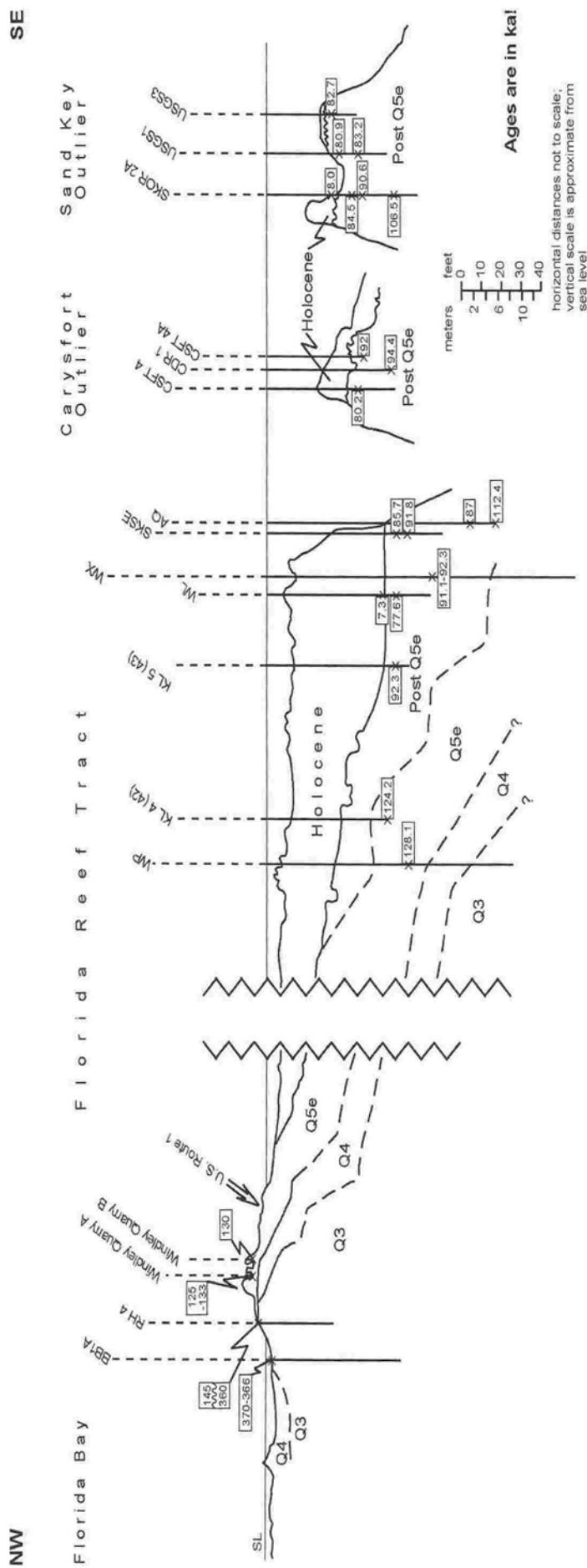


Fig. 7. Generalized schematic tabulation of the Florida Keys shelf area (not to horizontal scale; vertical scale approximate) showing dated cores. **PLEASE NOTE:** this is not a normal cross section because cores involved come from distant (Carysfort to Sand Key) areas along the entire shelf, and subsurface facies can change radically along this trend. This diagram represents only one possible subsurface picture based on very limited control existing today along about 120 miles (193 km) of shelf.

Core sources: Ppt: Pleasant Point 1A, drilled by Shinn, TIMS date this paper. RH-4: Key Largo Canal West, drilled by Harrison and Halley (1979), date from Szabo and Halley (1988). Windley Key Quarry A: sampled and TIMS date by Fruijtier et al. (2000). Windley Key Quarry B: sampled and dated by Osmond et al. (1965). WP: Basin Hill patch reef, drilled by Multer, TIMS date this paper. KL4: approx. 2 miles (3.2 km) SE of Rodriguez Key and KL5: approx. 2 1/4 miles (3.6 km) SE of KL4, both drilled by Shinn, TIMS dates this paper. WL: below Carysfort lighthouse and WX: Looe Key, both drilled by Multer, TIMS dates this paper. SKSE: Sand Key, drilled by Toscano and Hubbard, TIMS date from Toscano and Lundberg (1997). AQ: Aquarius/Conch Reef, drilled by Shinn, TIMS date this paper. CSFT4, CDR-1, CSFT4A, Carysfort outlier reefs, drilled and TIMS dates by Toscano and Lundberg (1997). SKOR2A: Sand Key Outlier drilled and dated by Toscano and Lundberg (1997). USGS1, Sand Key outlier reefs drilled by Shinn, dates from Ludwig et al. (1996). USGS3, Sand Key outlier reefs drilled by USGS, dates by Toscano and Lundberg (1997)

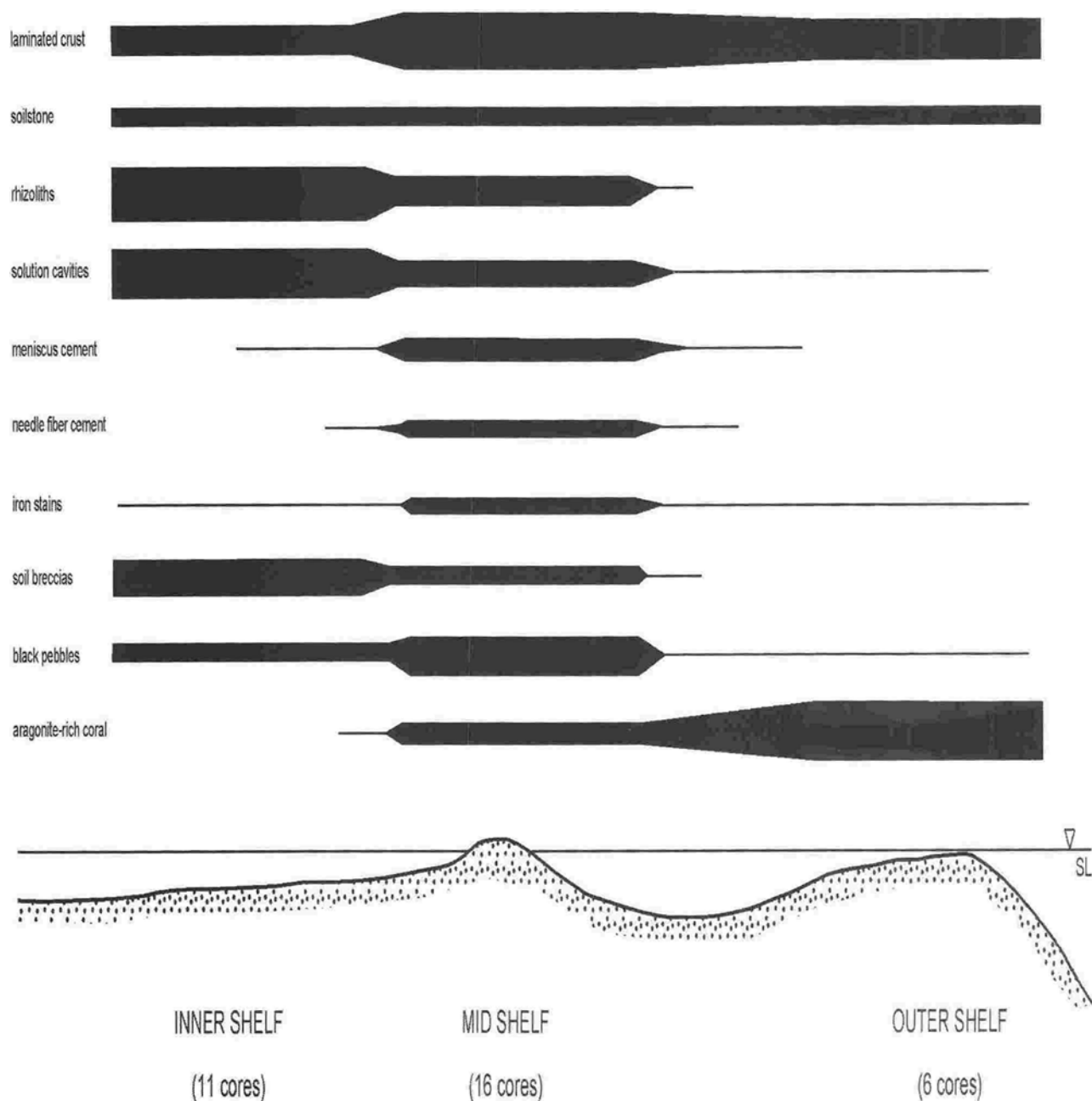


Fig. 8. Diagenetic trends in the Key Largo Limestone.

corals include *Montastrea annularis*, *Porites* sp., *Acropora cervicornis*, and the rare *Acropora palmata* at 88 ft (26.4 m), identified by Dr. Stanley Frost (personal communication). At the bottom of the WB core, perhaps illustrating the "mimicking theory," is more coral with Q2 quartzose grainstones and packstones. This widespread development of corals (including some evidence of *Acropora palmata*) supports the idea of past periods of open sea conditions with unimpeded flow of Gulf waters over the Florida Keys, as suggested by Shinn (1988) and Randazzo and Halley (1997). Non-rigid mounds tend to be found under the eastern areas of the bay (perhaps due to past protection by bank barriers) in contrast to rigid patch reefs which are found in more open, higher-energy areas. A major high in the northern Keys, extending from Nine

Mile Bank (53A) eastward to the Shell Key (core 21) area, was present from Q2 to Q5 times (see Fig. 13) and is herein designated the **Northern Keys High** (Fig. 1). The presence of such a high has been indicated by previous investigators (Perkins 1977; Harrison and Coniglio 1985; Halley et al. 1997). It is also interesting to note that a Miocene age Arcadia Formation high as shown in Figure 4 of Cunningham et al. (1998) apparently exists beneath the same area. When covered with shallow seas, carbonate production on top of this high (which continued in Q4 and Q5 times) was probably excessive, with off-platform shedding filling surrounding areas.

Based on the limited radiometric dates available and Pleistocene sea-level history, we speculate that the Q3 was deposited during the high sea levels of isotope stage 9

(Fig. 9). At least one sea-level fluctuation within Q3 time reworked and shifted reef environments, leaving a discontinuous subaerial laminated crust. This may have been a relatively short-term episodic event such as those identified in late Quaternary times in the Florida Keys (Locker et al. 1996) and the Bahamas (White and Curran 1995). The hiatus between Q3 and Q4 deposition, however, seems to have produced the most extensive subaerial crust karstification found within the entire Key Largo Limestone formation. This soilstone and crust capping the Q3 has probably had a major influence on ground water flow and diagenesis in the Florida Keys.

6.4 Q4 and Q5e: lagoonal/patch reef facies

Following a long period of emergence in south Florida, Q4 seas (presumably during isotope stage 7) inundated low areas of the shelf-edge topography and finally covered some higher areas. However, two cores indicate the lack of Q4 rocks along the north shore of Key Largo Key (Fig 7). In core RH4 what may be Q3 rocks are unconformably overlain by Q5e rocks. Several miles to the south, Q4 rocks are also missing above Q3 coral in the Ppt core just offshore Key Largo. The missing Q4 sediments in these two cases could be the result of sea levels too low to cap the area of today's emergent Keys (an area also of the former Northern Keys High). Pleistocene sea-level curves based on ice volume (Fig. 9) indicate that some Q4 sea levels (isotope stage 7) were lower than those of Q5 or Q3 (Petit et al. 1999).

A Q4 basal quartz sand containing varied amounts of coarse skeletal debris was first reported by Harrison and Halley (1979) beneath the island of Key Largo in cores directly above a "conspicuous discontinuity," which they indicate lies at a minimum depth below the rock surface of 7-8 m. This quartz-rich unit named Q4a (Harrison et al. 1984) was found in the present study in various cores from north Key Largo (core W4) southwest along the trend of the emergent Keys with decreasing quartz content to Grassy Key (core W2). Cores drilled in the northeastern corner of Florida Bay such as at Jewfish Creek (core W9), Shell Key (core 21), and Nest Key (core 5) contain the quartzose unit, as does the deep WB core at the western edge of Florida Bay. The source of the quartz is unknown but its (1) intimate association (Pl. 45/3) with an underlying, often quartz-rich major disconformity (top of Q3), (2) associated well-sorted, mollusk-foram grainstone with inclined beds (such as in Shell Key A-1 core #21 and core W3), and (3) medium to coarse subrounded well-sorted quartz all suggest a shallow-water and/or beachrock environment. The inclined beds resemble Dry Tortugas beachrock (Ginsburg 1953; Multer 1971a). Former longshore or fluvial currents from the north and insoluble residues from long-term Q3 surface weathering are possible sources of this quartz. Once deposited and allowed to become cemented in a shallow/supertidal environment, this unit became solid limestone that coral and other benthic organisms colonized as sea level rose during Q4 time.

Molluscan-peloid-bryozoan-rich packstones and grainstones dominate the upper Q4 unit (named Q4b by Harrison et al. 1984) with some patch reefs (*Montastrea annularis*, *Porites* sp.). Evidence of rapid facies changes and grainstone-rich channels into the backreef areas are also present in the cores.

Unit Q5e was deposited during the highstand of isotope substage 5e. The Q5e rock units included oolite that developed in the lower Keys from tidal currents passing around the Key Largo Limestone reefs onto the shallow backreef platform (Hoffmeister et al. 1967; Coniglio 1981; Harrison et al. 1982a; Kindinger 1986; Shinn et al. 1989). Temperature, tidal currents, and supersaturation much like that found today on the edges of the Bahama Platform (Purdy 1963) allowed oolitic facies to form from just east of Big Pine Key to Key West. Eventually these oolite banks dominated the platform, inundated the reefs and extended westward beyond the Marquesas Keys (Shinn et al. 1990). The contact between the oolite and coralline packstones/grainstones is transitional in nature (Hoffmeister and Multer 1968; Harrison et al. 1982) at Big Pine Key and as seen in the W5 core at Key West. Steinker and Floyd (1975) note bryozoans in an oolitic matrix from dredged samples at Stock Island and other areas of the lower Florida Keys.

In the upper Keys, Q5e patch reefs, grainstones and packstones became well developed on the highest elevations of the Northern Keys High. Some can be seen today exposed in the Windley Key Fossil Reef State Park (formerly called the Windley Key Quarry) and along the Key Largo Cross Canal. Q5e rocks were found in this study as coral boundstone dated at 128.1 ka beneath the Holocene in mid-shelf core WP and as a coral boundstone of 124.2 ka seaward from Rodriguez Key in core KL4. North and east of the Florida Keys (not included in the present study area), Q5 rocks include banks of oolite in the Homestead to Miami areas (Hoffmeister et al. 1967; Halley and Evans 1983; Evans and Ginsburg 1987) behind which bryozoans flourished, underlying large areas of today's Everglades.

6.5 Post-Q5e: shelf-margin wedge

After the Q5e maximum highstands of sea level, a series of lower highstands occurred toward the end of the Pleistocene that provided coralline-rich units on the shelf and the upbuilding of offshore outlier reefs. Lidz et al. (1991), using high-resolution seismic-reflection techniques, mapped a series of these ridges (first depicted in line drawings by Enos 1977) and found by coring that some were pre-Holocene (>38 ka). Lidz et al. (1991) coined the term "outlier reefs" for these ridges that developed on a 30-40 m deep upper-slope terrace. Subsequent investigations by Lidz et al. (1997b) and Toscano and Lundberg (1997, 1999) indicate a series of Pleistocene outlier reefs existed at various times (106.5 to 80.2 ka). Holocene coralline carbonates cap the Pleistocene outliers (Toscano and Lundberg 1997). The outliers are believed to have begun growing on cemented beach-dune ridges (Lidz et al. 1997b).

The Key Largo Story

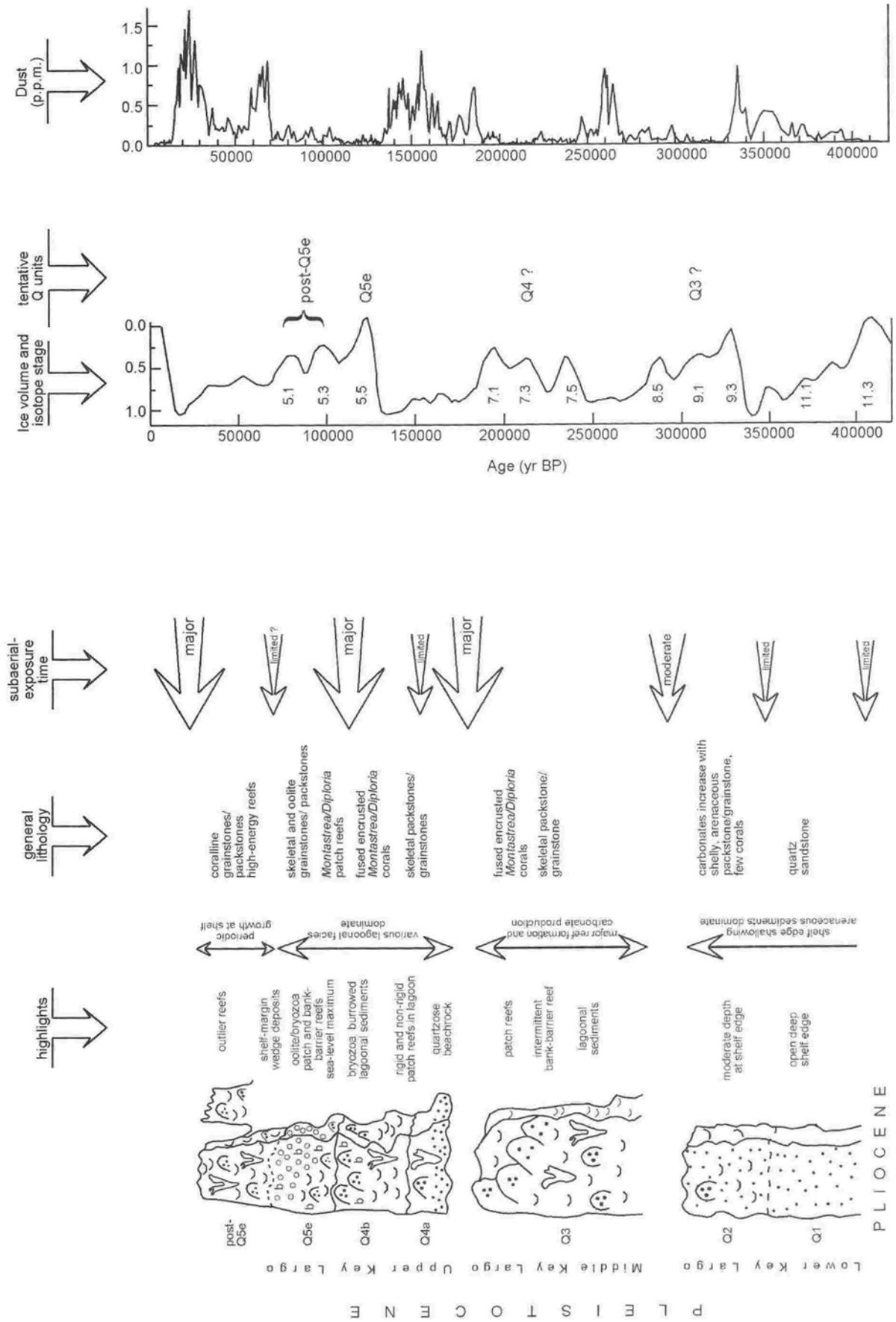


Fig. 9. Summary overview of various aspects of the lower, middle and upper Key Largo Limestone intervals as designated in this study. Ice volume, isotope stage and dust data from Petit et al. (1999).

Toscano and Lundberg (1997, 1998) describe *Acropora palmata* at a 50-ft (15.3-m) depth below sea level in the Pleistocene Carysfort outlier reef (92.2 ka) overlain by Holocene carbonates (7.5 ka) that include head corals. Toscano and Lundberg (1997, p. 179) also give dates for a Pleistocene (91.8 to 85.7 ka) coralline sequence in SKSE core on the shelf edge off Sand Key southwest of Key West (Fig. 1).

Data from cores used in the present study indicate various Q5e and post-Q5e units lying beneath the Holocene (Figs. 7, 14). The oldest (128.1 ka) is a Q5e coral boundstone located beneath the present mid-shelf region off northern Key Largo at Basin Hill Shoals core WP (Fig. 2). A probable post-Q5e mollusk-foram packstone unconformably overlies the boundstone. Off southern Key Largo seaward of Rodriguez Key in core KL4 (#67) is a 124.2-ka coral boundstone with possible post-Q5e packstone lying conformably above it. A still younger post-Q5e coralline sequence seems to be restricted along the edge of the shelf as found in the AQ core off Conch Reef (112.4 ka and 87.0 ka), in the WX core at Looe Key (92.3 to 91.1 ka), and in the WL core at Carysfort Reef (77.8 ka). The first two cores may correspond in age to a shelf-edge Pleistocene coralline unit found at Sand Key off Key West as reported by Toscano and Lundberg (1997). Those authors assign substage 5b to a coral from core SKSE dated at 91.8 ka and substage of 5a to corals dated at 85.9 ka and 85.7 ka. The same authors note that the SKSE core records 26 ka of reef development, with possible hiatuses between substages 5c/5b and 5b/5a.

Using various scattered wells with dated cores, a generalized schematic tabulation is given in Figure 7, providing a possible interpretation of Pleistocene deposition across portions of the middle and upper Florida Keys area. The tabulation shows clearly that the post-Q5e deposits form a shelf-margin wedge on the sloping deposits of the Q5e unit and underlie outliers.

6.6 Growth rate

Landon (1975, documented in Multer 1977, p. 201–203), Dodge and Vaisnys (1977), and Hudson (1979) have substantiated that growth rates in the common massive coral *Montastrea annularis* as displayed by coral banding (Hudson et al. 1976) were less for the species during the late Pleistocene than today in both the Florida Keys and Barbados. Hudson (1979) indicates that Pleistocene specimens show average growth rates of 5 mm/year, whereas he notes that modern examples in Florida grow 10 mm/year on the average. See Hudson (1981) and Hudson et al. (1994) for variations in today's growth rates of this coral. A large specimen of *Montastrea annularis* investigated in the present study from the Q4 unit in core W5 (Key West, depth 57 ft / 17.1 m) also exhibits an average growth rate of only 5–6 mm/year. The origin and controls on density banding in corals which reflect growth are under continued investigation (e.g., Weber et al. 1975; Highsmith 1979; Wellington and Glynn 1983; Scoffin et al. 1992; Helmle and Dodge 2000). Natural causes for band-width changes in Holocene *Montastrea annularis* are discussed by Hudson (1981) and Hudson et al.

(1994). These two Florida Keys studies indicate that water depth, turbidity, temperature and domestic sewage can each influence band width. In the Florida Keys skeletal density bands can be correlated to fluorescent bands containing organic acids to show frequency and relative amount of runoff (Halley 1993).

During the late Pleistocene there may have been sustained periods of (1) high nutrient loading, (2) high and low water temperatures, and (3) excessive water turbidity off the wide Florida platform. These could have been produced by strong Gulf and Atlantic tidal currents flowing back and forth over today's Florida Keys with resulting reduced coral growth rates and potential for oolite production. Periodic episodes of African dust may also have affected growth rates (Shinn et al. 2000).

6.7 Platform edge

Pleistocene limestone covered with thin Holocene sediment occurs at the shelf break which displays varying degrees of steepness (Enos 1977; Lidz et al. 1997b). Steeper breaks can be likened to similar Pleistocene slopes described by James and Ginsburg (1979), Ginsburg et al. (1991), and Grammer and Ginsburg (1992) due to repetitive reef growth or erosion at platform rims in Belize and in the Bahamas. However, pervasive submarine cementation at those sites (Grammer et al. 1993) has also been shown to be an effective mechanism for developing steep platform edges. In the Florida Keys Warzeski et al. (1996) have indicated a lack of characteristic reef-associated seismic reflections at the present shelf margin.

Limited core data from the very seaward edge of the Florida Keys platform (Looe Key Reef, Conch Reef, Molasses Key Reef, Carysfort Reef) have indicated that, as found by Beach and Ginsburg (1980) for equivalent age steep Bahama Bank slopes, the Key Largo Limestone probably maintains its steep upper slopes by a combination of submarine cementation and reef growth with coral decreasing in significance in the lowermost sections of the formation.

An early paper by Stanley (1966) described the present emergent Q5 Key Largo Limestone as a former deep-water reef complex (*Montastrea* zones of living West Indian bank reefs and West Indian patch reefs) with high calcilutite content. The lack of *Acropora palmata* provided a rationale for this deep-water possibility. Subsequent research, however, has modified this concept in several ways. (1) Recognition of the upper Key Largo Limestone as equivalent in age to the shallow-water Miami Limestone (Hoffmeister and Multer 1968; Perkins 1977) negated a deep-water interpretation. (2) The fact that mud in reef sediments may also reflect internal micrite production (Reid et al. 1990, 1992) invalidated the need for calcilutite being necessarily an indicator of low energy and/or deep water. (3) Environmental stress from deleterious lagoonal waters could have restricted occurrences of the temperature-sensitive shallow-water *Acropora palmata* during Key Largo Limestone times (Ginsburg and Shinn 1964; Harrison and Coniglio 1985; Shinn et al. 1989).

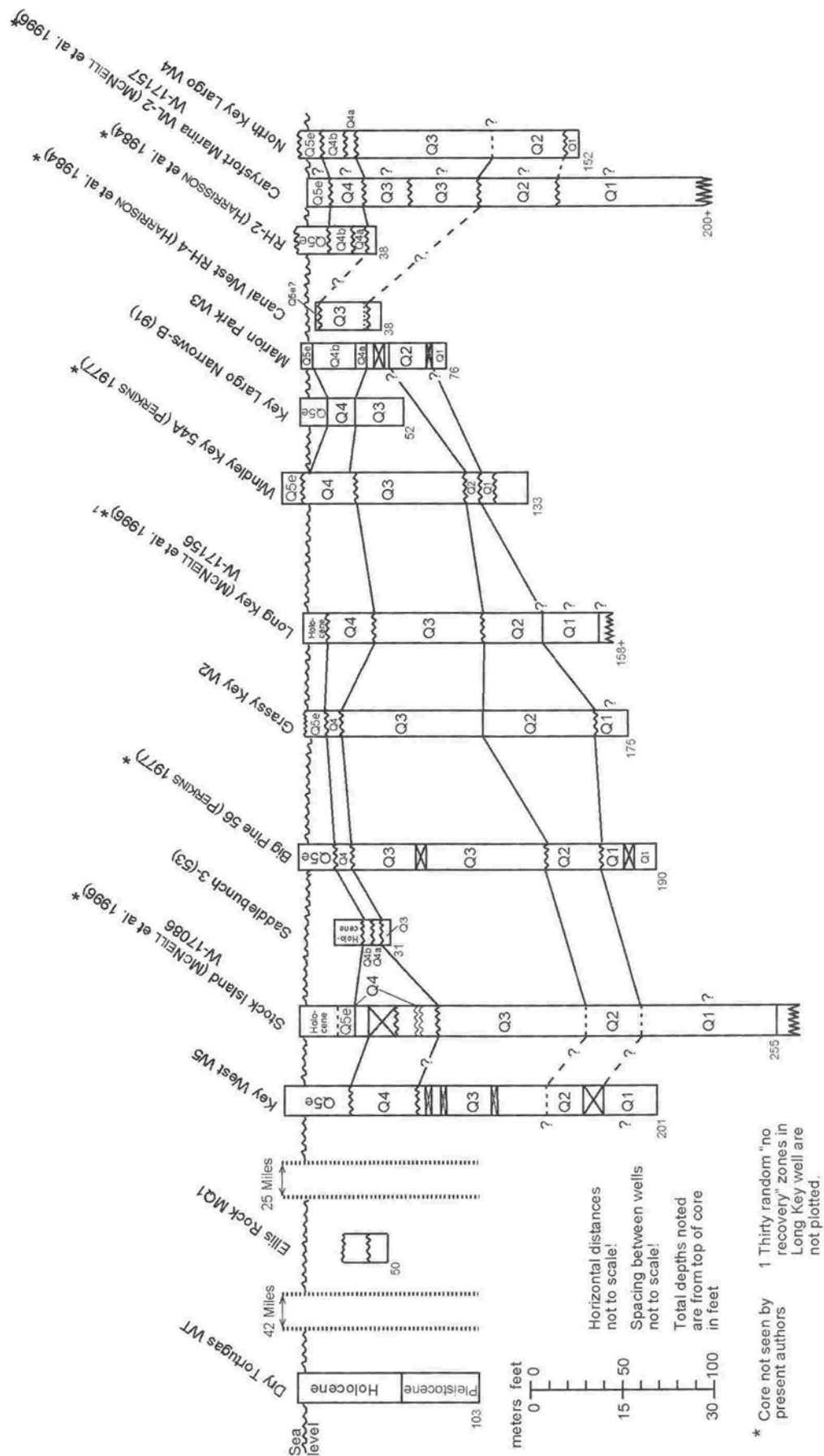


Fig. 10. West-to-east cross section from Dry Tortugas to North Key Largo beneath today's emergent Florida Keys illustrating tentative "Q" unit correlations. See Figure 1 for location.

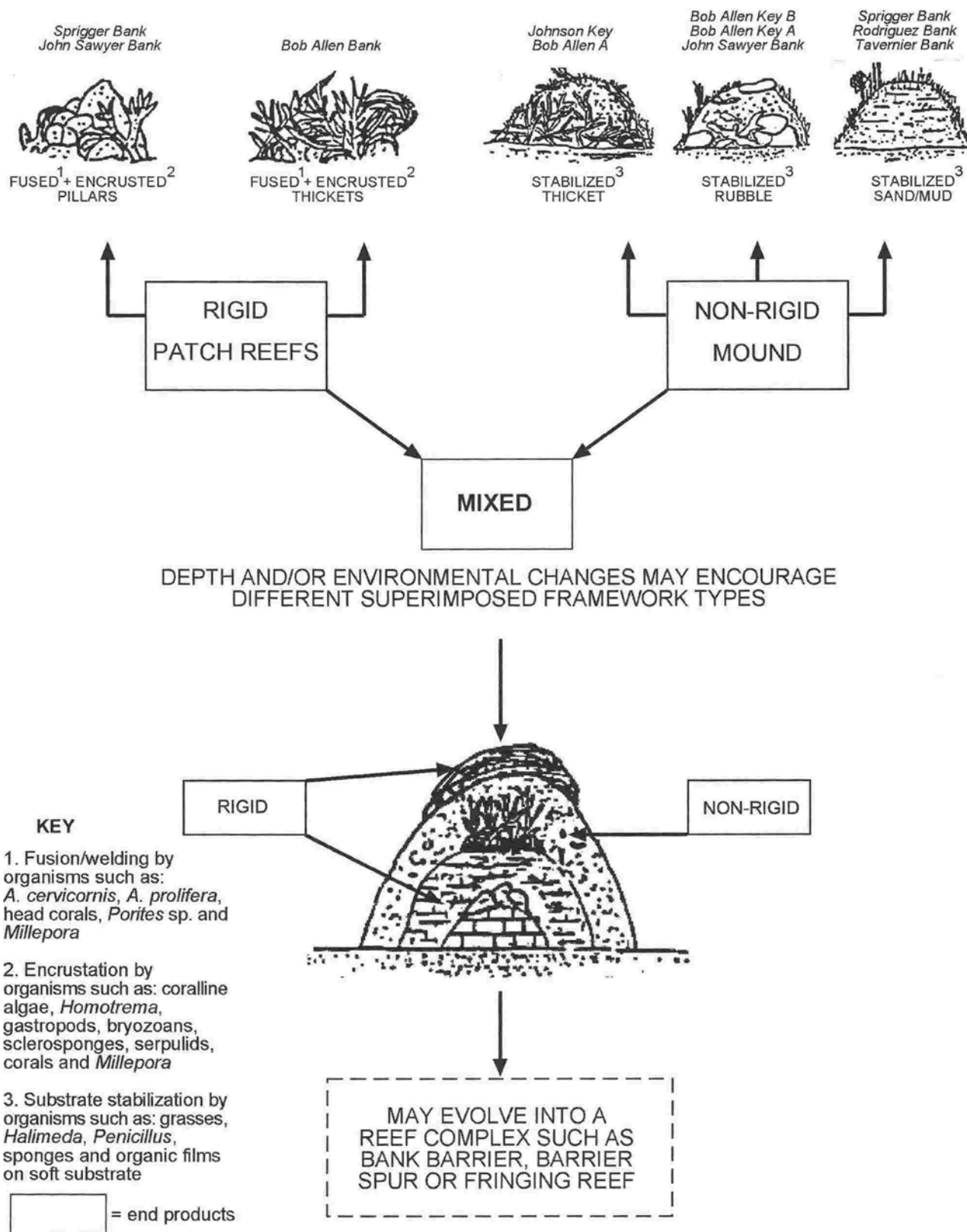


Fig. 11. Framework types that are believed to have been influential in the evolution of Key Largo Limestone patch reefs. Possible examples of specific reefs are noted. Diagram modified from Multer and Zankl (1988).

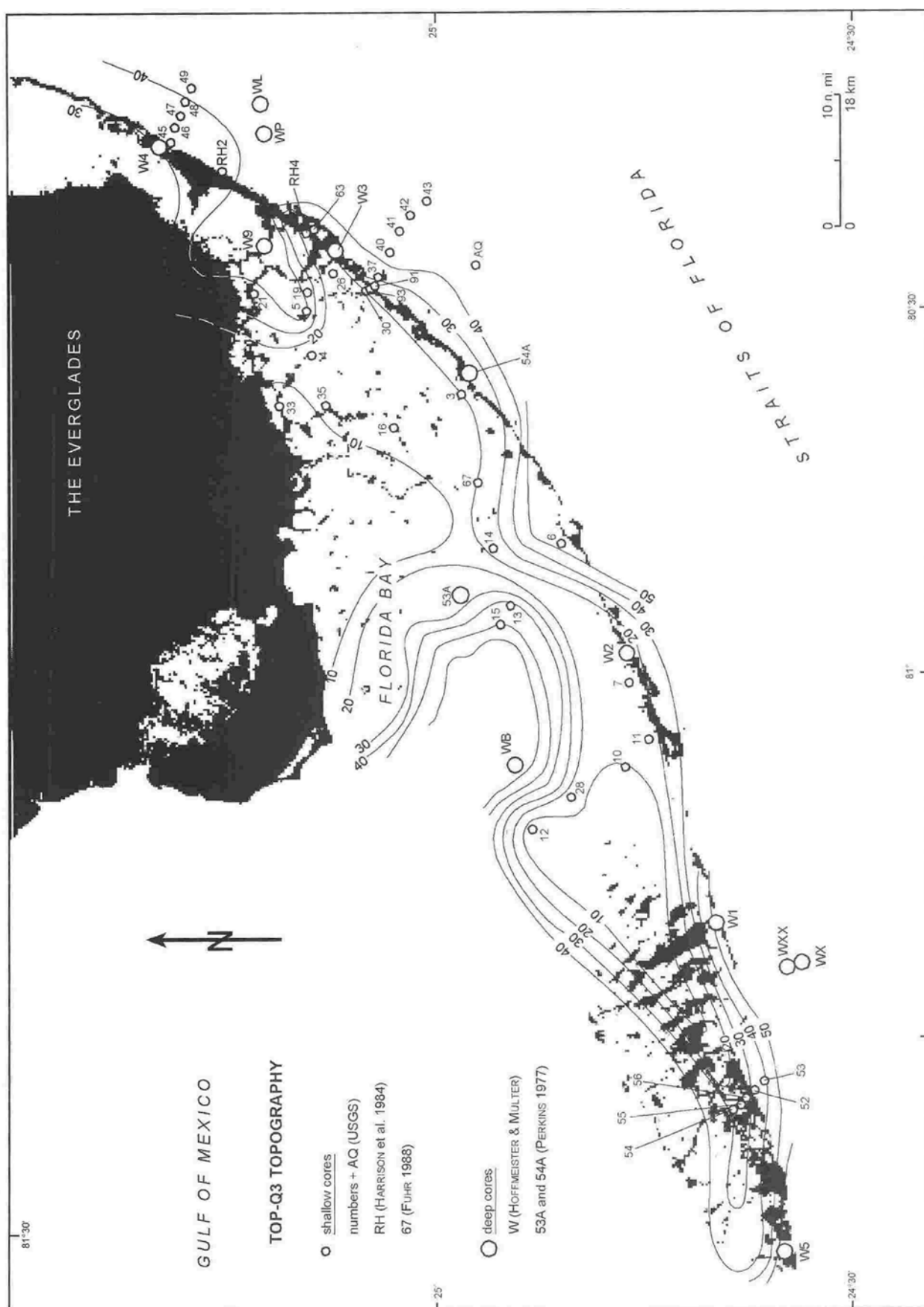


Fig. 12. Structural contours on top of the Q3 unit showing deep embayment from the northwest beneath western Florida Bay (core WB area) and east (under Key Largo and Barnes Sound, core W9 area). Contours in feet below sea level.

Core examination by the present authors has revealed Pleistocene *Acropora palmata* in only three cores: (1) core WB in what is probably late Q3 rocks under western Florida Bay, (2) core WT at 65 to 67 ft (20 m) below sea level, containing fragments of *Acropora palmata* in undated rocks which are believed, however, to be Pleistocene, and (3) core WX in post-Q5e (92.3 to 91.1 ka) rocks at Looe Key Reef, which is the same core as the No. 3 core of Hoffmeister and Multer (1968). The presence of *Acropora palmata* was also reported by Hoffmeister and Multer (1968) in another (second) Looe Key core #4 at 58- and 65-ft (17.4- and 19.5-m) depths below sea level in what was believed (without benefit of radiometric dating) to be Key Largo Limestone. The present study indicates that rocks at these depths in core #4 (named core WXX in this study, Fig. 2) are Holocene.

The present authors, as noted earlier, divide the Q5 Key Largo Limestone into Q5e and post-Q5e units. Figure 7 gives a generalized schematic cross section of the shelf indicating these two units.

A recent study (Fruijtier et al. 2000) found the Q5e Key Largo Limestone at Windley Key Quarry to range in age from 133 to 125.1 ka. From this quarry the limestone dips steeply seaward. At a mid-shelf core (WP), the Q5e at 72-ft/22-m depth below sea level is found as a *Montastrea* coral boundstone dated at 128.1 ka. At the shelf-edge core WX, it is probably represented by a vuggy pelletoid packstone with some coral starting at depths of approximately 117 ft/36 m below sea level. No *Acropora palmata* was recovered from Q5e rocks in the WP or WX cores. During Q5e time when sea level stood at least 20 ft (6 m) above present level at Windley Key Quarry, shelf-edge rocks of the same age were approximately 120 ft (36 m) lower, pointing to a deep, sloping, ramp-type shelf margin. This relatively steep slope appears to be a normal seaward edge of the accumulating Florida Platform. The role of possible tilting or faulting (see section 5.12) along this steep shelf slope is still not known.

The post-Q5e units identified in this study are found only in the subsurface below the shelf, directly beneath Holocene beds. These post-Q5e (112.4 to 77.8 ka) deposits form shelf-margin veneers and/or shelf-edge wedges on Q5e beds, having evolved as sea level fell and fluctuated from Q5e levels. At a mid-shelf core (WP) location, a post-Q5e mollusk-foram-packstone is found at depths of 35-65 ft (10.5-19.5 m) below sea level, apparently unconformably overlying lower Q5e coral boundstone dated at 128.1 ka. The contact between the post-Q5e and Q5e at this mid-shelf core displays pocket-like infilling with brown and black sediment, small unidentified black grains and a limited coarse-banded crust. At the Looe Key Reef shelf edge (core WX), molluscan-rich coral boundstone with *Acropora palmata* is found at a depth of 55 ft (16.5 m) below sea level, capping coral-mollusk-foram grainstones to at least 86-ft (25.8-m) depths where they are dated at 92.3-91.1 ka. These rocks are the same as described by Hoffmeister and Multer (1968) in their core No. 3 as a possible (undated at the time) outer-shelf reef. The 92.3-91.1 ka date obtained in the present study indicates again a possible Pleistocene outer-shelf *Acropora palmata* reef at this site but for a later (post-Q5e) period

when sea level was lower, such as during isotope substage 5c or substage 5a.

It appears that these last Pleistocene post-Q5e lower sea levels supported thriving habitats at a variety of places on the shelf that were shallow enough at times for *Acropora palmata* reefs. Both Carysfort and Sand Key outliers display post-Q5e age coralline rocks (Fig. 7) with the Carysfort outlier showing *Acropora palmata* (92.2 ka) at 50 ft (15 m) below present sea level (Toscano and Lundberg 1997) within a few meters of an upper unconformable contact with Holocene coralline beds (core CSFT 4A). On the Sand Key outlier (Ludwig et al. 1996), core USGS-1 displays *Acropora palmata* below a 80.9-ka *Montastrea* boundstone at 39 ft (12 m) below present sea level. The oldest post-Q5e outlier-reef date (106 ka with a 1.182 $^{234}\text{U}/^{238}\text{U}$ initial ratio) was obtained from 21.4 m below sea level in the SKOR2A core, Sand Key outlier (Toscano and Lundberg 1997).

6.8 Subaerial products

The role of antecedent topography as a controlling influence on sediment deposition and reef distribution in the Caribbean has been well documented (Purdy 1974; Shinn et al. 1977; Macintyre 1988). Evidence for the influence of antecedent topography has proven difficult to find in ancient subsurface rocks due to the lack of control and criteria for identifying the ancient subaerial surface where variability is very common (Harrison 1981). In addition, seismic sound waves rarely penetrate reefs or reef rubble and therefore reflections of rock surfaces beneath reefs and rubble cannot be seen. However, the existence of a series of undulating paleokarst surfaces in the Pleistocene of mainland Florida has been known for many years. Parker and Cooke (1944) and Perkins (1977) graphically show such unconformities.

One of the features of the Key Largo Limestone in the Florida Keys is that it contains various types of physical evidence demonstrating successive marine transgressions/regressions along the shelf edge during the Pleistocene. After each regression, periods of subaerial exposure produced variable karst structures depending on temperature, moisture and winds. The low elevations of the Florida Keys (Lidz and Shinn 1991) and the proximity to the source of marine flooding may have been responsible for shorter periods of subaerial exposure than found in areas to the north.

Thick caliche (crust) profiles (Multer and Hoffmeister 1968a; Perkins 1977; Kahle 1977; Robbin and Stipp 1979; Coniglio and Harrison 1983a) suggest earlier presence of soil and terrestrial plants. Shinn et al. (1994) found soilstone crusts of the Key Largo containing elevated amounts of phosphorous, aluminium, and iron. Such enrichment is similar to that found in soilstones throughout the Caribbean which was determined to be from African dust (Muhs et al. 1990; Shinn et al. 2000). Increased ppm in airborne soil particles (dust) coincide with periods of subaerial exposure, low sea level and high ice volume as shown by Petit et al. (1999; Fig. 9). Black pebbles (Strasser 1984) are sometimes associated with crusts. Shinn and Lidz (1988) recognized

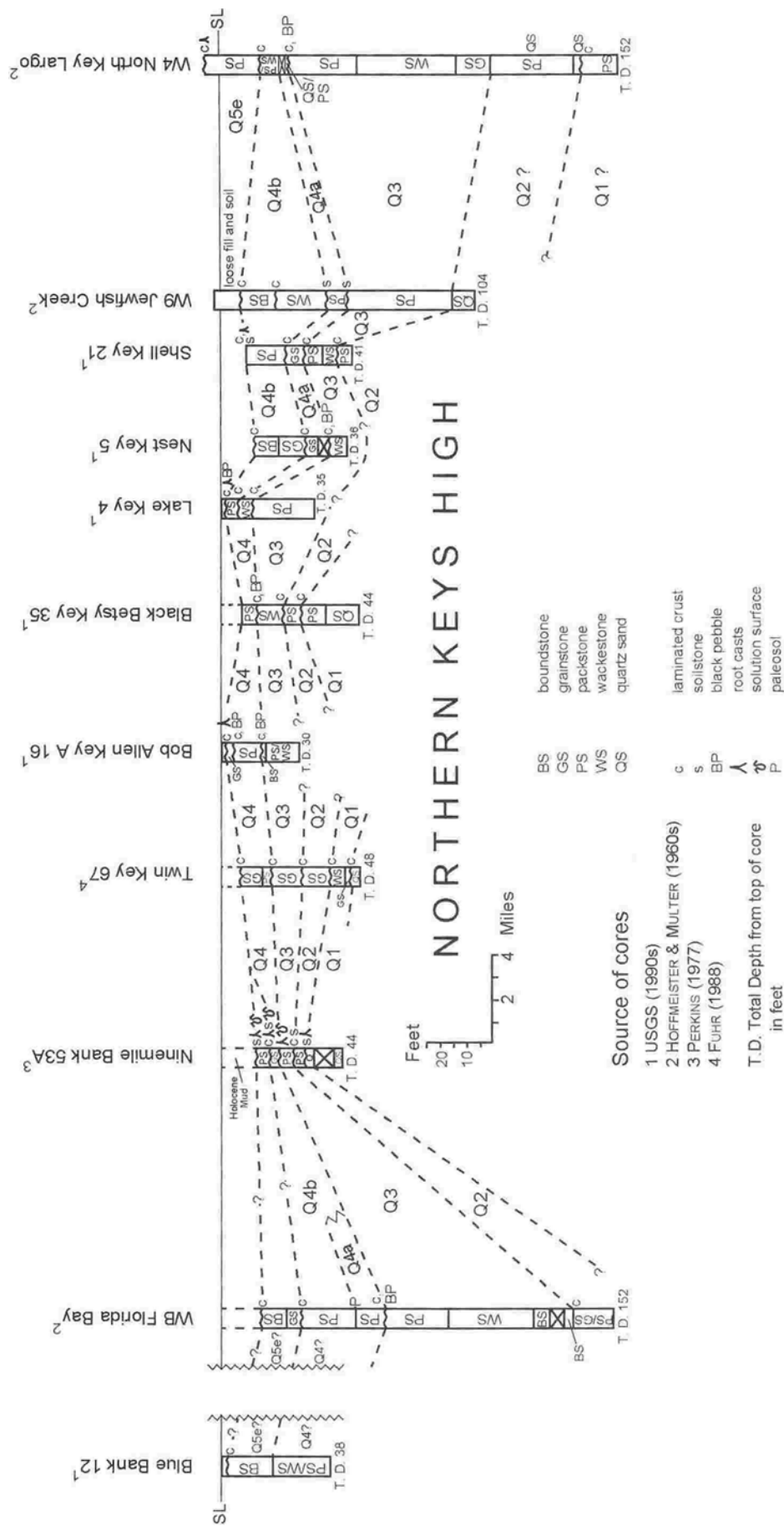


Fig. 13. West-to-east cross section from Blue Bank to North Key Largo through the middle of Florida Bay illustrating tentative "Q" unit correlations and the Northern Keys High. See Figure 1 for location.

that black pebbles were caused by fire, thus identifying sufficient vegetation for natural lightning-induced fires. Sinkholes (Shinn et al. 1996; Lidz et al. 1997a) and other karst features (Dodd and Siemers 1971; Ebank and Bub 1975; Enos 1977; Merriman 1988) developed. At Lignumvitae Channel, core #23 shows evidence of five successive unconformities (laminated crusts) which are believed to reflect an inherited channel system that periodically drained the leeward lagoon into the sea. The course of this channel can be tracked several miles in aerial photos. When depressions are filled with encrusted breccia rubble, they could indicate high-energy events for the transport of large encrusted fragments (Krawiec 1963; Multer 1977). The unusual appearance of quartz sand grains (Harrison and Halley 1979) implies availability of possible wind, stream or littoral mechanisms. However, despite the variety of these subaerial products and the known presence of at least five major unconformities, there are many places where the tops of Q units are still not discernable.

Freshwater limestones (marlstones or lime mudstones) associated with lowstands of the Key Largo seas are less common along the shelf edge of the Florida Keys than in inland areas to the north (Dubar 1974; Halley and Rose 1977; Perkins 1977). Long-term freshwater ponding needed for these rocks to form was probably less likely to occur close to the shelf edge. Freshwater mudstones are reported in a core at Big Pine Key (Perkins 1977) and under Florida Bay (Textoris 1988; Fuhr 1988). The present authors found a light gray mudstone with fresh water *Helisoma* gastropods directly above a subaerial crust at Lignumvitae Channel (core #23).

After each period of normal marine deposition over the south Florida Platform ended and regression began to drain the mainland of Florida, a new subaerially exposed surface progressively developed down-dip in time-transgressive fashion. When the edge of the sea arrived at the Everglades, the tops of topographic highs along the Keys (many reef-bound) were already emerged and undergoing subaerial cementation that would enhance their chance of preservation until the next transgressive cycle.

The impermeability of some paleokarst surfaces can form an effective aquitard such as is found at the top of the Q3 unit beneath the Dade County Landfill (Shinn and Corcoran 1988) where it retards downward migration of leachates. This impermeability can serve as an overlying shield, preventing diagenetic alteration of underlying aragonite-rich substrate. The discontinuous nature of the crust on top of the Q3 horizon is noted by Shinn et al. (1994) who found it lacking in cores drilled more than one mile from shore.

6.9 Florida Bay bedrock

Hoffmeister et al. (1967) named an oolitic- and bryozoan-rich facies covering large areas of the south Florida mainland north of the Florida Keys the Miami Limestone. Neither the age nor composition of the bedrock flooring Florida Bay and Biscayne Bay was determined. The Miami

limestone was later noted by Perkins (1977, p. 140) to be stratigraphically equivalent to the Q4 and Q5 units of the Key Largo Limestone. Perkins (1977) indicated, however, that the bryozoan *Schizoporella floridana* was present in the Q5 packstone/grainstones of the one core (#53) he drilled in central Florida Bay. His cross section (B-B') indicates that Q5 grainstones/packstones form the bay floor.

Subsequent studies (Merriman 1988; Merriman et al. 1989; Textoris 1988; Fuhr 1988; Merriman et al. 1989) indicate that the Q4 bryozoan facies of the Miami Limestone with local patch reefs underlies most of Florida Bay. They describe the bryozoan facies as being composed of pelletal packstones and grainstones that locally contain up to 70% bryozoans, with pellets, miliolids, peneroplids, and ooids. The facies displays local burrowing and the presence of calcareous worm tubes.

The present authors' analysis of their deep Florida Bay core (WB) and many shallow USGS cores in Florida Bay (Figs. 5, 6 and 13) has revealed a highly bioturbated and bored sequence of packstones/grainstones commonly displaying *Schizoporella floridana* bryozoa, although not in percentages reaching 70% by volume as found on the mainland to the north. It is believed that the stratigraphic designation of Q5 (Perkins 1977) and Q4 (Merriman et al. 1989) may both apply, depending on location and amount of preservation from very extensive erosion and bioturbation that this area has received during at least 150 ka. In other words, today's Florida Bay bedrock surface has been subjected to various marine, karst, and lacustrine destructive and constructive processes that have left residual deposits of a mixed nature. Added to this challenge is the fact that the Q4/Q5 discontinuity found throughout the Keys is well known to be a subtle one with the lithology above and below the contact often very similar in composition. In summary, it is believed that the uppermost bedrock flooring Florida Bay today can be both Q4 and Q5 or younger and is the product of intense subaerial and marine erosion, biologic reworking, and diagenetic alteration over a period of more than 150 ka.

6.10 The Marquesas Keys and Dry Tortugas persistent highs

The Marquesas Keys according to Vaughan (1914, p. 62) represent a circular constructional mound of "calcareous detritus mostly of other than coral origin" in contrast to Dry Tortugas which he found (p. 62) to be "composed of calcareous material, of complex origin but largely due to the activity of corals." Located 19 miles (30 km) west of Key West (Fig. 15), the Marquesas Keys are composed of *Halimeda*-rich sands (Hudson 1985) and are currently stabilized by mangroves.

The Marquesas Keys are located at the east end of a submerged carbonate platform west of the lower Florida Keys. This extension is known as the Marquesas-Quick-sands ridge (Shinn et al. 1990). The closest exposed Pleistocene bedrock is found in Key West (core W5) where approximately 30 ft (9 m) of oolite (Fig. 3) display a

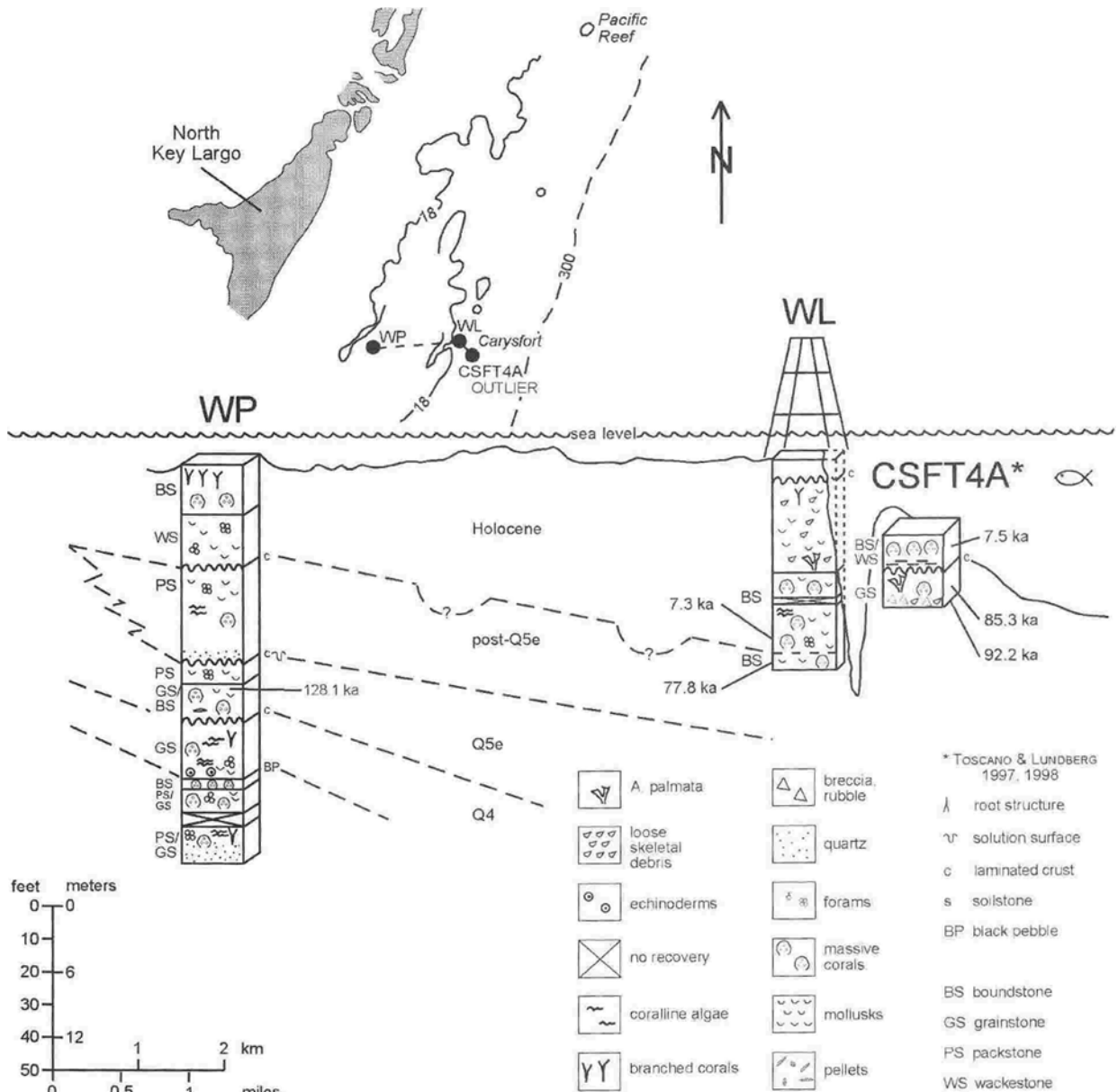


Fig. 14. West-to-east stratigraphic cross section from mid-shelf WP core to Carysfort outlier reef. Note shelf-margin wedge of post-Q5e packstones and boundstones.

transitional contact with the underlying coralline Key Largo Limestone (Hoffmeister and Multer 1968).

Bedrock beneath the central Marquesas Keys area (Fig. 15) consists of a chalky oolitic *Halimeda*-rich packstone occasionally cross bedded in upper portions and separated from a lower coralline (*Montastrea*) skeletal packstone/wackestone by either a thin discontinuous dark brown microcrystalline rind (core MQ3) or a transitional contact (core MQ6). Vugs in this bedrock sometimes are filled with a mixture of pellets, foraminifera, and ooids. The age of these deposits is unknown, but the oolite-over-coralline bedrock sequence resembles that found in Key West (core W5). The coralline bedrock beneath the emergent central Marquesas Keys forms a saucer-shaped depression. The depression allowed initial accumulation of muddy Holocene

sediment and its attendant grass and *Halimeda* meadows, creating habitats for invertebrates and acting as baffles that trapped suspended sediment that in turn could build up into emergent mounds. An east-west northward-dipping ridge of bedded oolitic grainstone is found in three feet of water on the north side of the Marquesas. To the east, a similar beach deposit is exposed at low tide on the north side of the lower Florida Keys. Ridges of oolite on the south border of the Marquesas in five feet of water are highly burrowed and contain no bedding.

At the Ellis Rock area on the northwestern rim of the Marquesas-Quicksands ridge, two cores (MQ1, MQ2) reveal encrusted coralline (*Montastrea*, *Diploria*, *Acropora cervicornis*) grainstone/packstone at about 27 ft (8.1 m) below sea level. A TIMS date for coral at 36 ft (10.9 m)

below sea level in MQ1 core indicated the coral is Holocene (2.5 ka).

The Dry Tortugas is a roughly circular, sediment-covered, subsea mound topped mostly by shallow sand and rubble banks, shoals and lagoons, all contained within a 60-ft (18-m) isobath. Named Las Tortugas ("The Turtles") by Ponce de Leon in 1513 and called an "atoll" by Vaughan (1914), this most western extension of the Key Largo Limestone lies some 70 miles (110 km) west of Key West. Seven small emergent elongate islands of unconsolidated Holocene carbonate sand and rubble are found today at the Dry Tortugas with the only consolidated exposed rock being beachrock on Long Key (Ginsburg 1953; Multer 1971a). For discussion of Holocene sedimentology, see Brooks (1963) who discounts an atoll origin in favor of one related to prevailing seasonal storm patterns, Jindrich (1972), and Halley (1979). For Holocene reef data summaries, see Shinn et al. (1977), Jaap et al. (1989), and Shinn et al. (1989).

The first deep core hole 103 ft (31 m) beneath the Dry Tortugas to bedrock was drilled in 1967 by Multer (core WT) in the center of Fort Jefferson's parade ground on Garden Key (Figs. 2, 15). All depth measurements in this core WT are from 2 ft (0.6 m) above sea level. Loose skeletal sand with coral was found to a 30-ft (9-m) depth. Vuggy coralline (*Montastrea*, *Porites*, *Diploria*) boundstone with mollusks, coralline algae, forams, pellets, and occasional root-like fibers was found to 48 ft (14.4 m). From 48 to 54 ft (15-17 m), a zone of vuggy molluskan packstone/wackestone and coral boundstone was found with quartz in vugs, polychaete tubes, root fibers, and dark brown calcite underlain by soilstone fragments. Coral (*Montastrea annularis*, *Porites* sp., *Acropora cervicornis*) boundstone and vuggy coralline/molluskan packstone persisted down core to 82 ft (24.6 m) with fragments of *Acropora palmata* at depths of 61 to 69 ft (18.3-20.7 m). Loose skeletal sand with coralline algae, *Halimeda*, forams, and pellets with traces of quartz continued to the bottom of the core at 103 ft (31 m).

Without radiometric dates, the top of the Pleistocene was misidentified at 30 ft (9 m) by Hoffmeister and Multer (1968). Subsequent x-ray and dating in the present study (see Table 1) indicate a Holocene aragonitic sequence to about 51 ft (16 m). The top of the Pleistocene under Garden Key is now considered to be at approximately 52 to 54 ft (16 to 17 m) where (1) aragonite is replaced by low-Mg calcite, (2) soilstone and quartz appear, (3) dark brown drusy calcite and rhizoliths are common, and (4) lithology changes from boundstone to dark gray packstone. No laminated subaerial crust was found in this core. Approximately one mile (1.6 km) southeast of Garden Key, core T2 drilled by Shinn et al. (1977) across Southeast Reef (Fig. 15) penetrated the Pleistocene (34.27 ka) at about 50 ft (15.2 m) below sea level beneath thick Holocene reef rock at the eastern edge of the bank.

7 CONCLUSIONS

"Revisiting" the Key Largo Limestone has identified significant studies and several historical summaries of

investigations conducted since the 1960s when the senior author and Edward Hoffmeister began research on this limestone. However, the subsurface story of the Key Largo Limestone has largely remained unexplored. In this paper we have used a combination of previously undescribed cores, new dates and related published data to expand our knowledge of the subsurface of this classic Pleistocene rock unit. A very generalized evolution of the Key Largo Limestone is noted below, followed by a list of specific observations.

During the late Pleistocene all of south Florida was submerged many times as a wide shallow platform whose curving southernmost edge lay isolated, often 100 miles (160 km) from any mainland to the north. Over time, sediment infill produced shallower depths and warmer seas, allowing calcareous animals and plants to flourish along the shelf edge. As sea level periodically fluctuated, a discontinuous arcuate chain of patch and bank-barrier reefs evolved, flourished and died, often providing protection for the development of carbonate sediments that would become widespread leeward mudstones, packstones, grainstones and finally bryozoan- and ooid-rich accretions. Repeated periods of subaerial exposure formed various karst structures including marker beds, sinkholes and probably coastal dunes as well as deleterious soil runoff which hindered coral development during early stages of succeeding transgressions of the sea.

1. Since Q3 time, patch reefs (sometimes merging into bank barriers) formed throughout the Keys on depositional highs such as stabilized sand/mud or rubble mounds, dunes and storm ridges along a trend beneath today's emergent Keys. Once formed, they were the first to be subaerially exposed and encrusted during periods of sea-level regression. During rising sea levels, these depositional highs served as hard-substrate surfaces for coral colonization and as resistant emergent and/or submergent barriers for development of leeward sediment facies.

2. The Northern Keys High served as a "carbonate factory" (Multer 1969, p. 2) during Q3 through Q5 submergent periods, producing abundant sediments that were continually swept off into adjacent basins. These sediments were cemented into grainstones, packstones and mudstones.

3. The middle Keys area with its deep entrenched northwest-trending open basin established at least by Q3 time (Fig. 12) was a site for frequent open water, scattered reefs, channeling and tidal influx of occasionally deleterious lagoonal waters, as occurs today (Ginsburg and Shinn 1964, 1993).

4. The area of the lower Keys was frequently the site of Gulf-dominated currents which also swept over the two "substrate highs" to the west (Marquesas Keys-Quick-sands ridge and Dry Tortugas). High-energy tidal conditions occurred in Q5 time over the lower Keys (perhaps similar to that found in the Cat Cay area at the western rim of the Great Bahama Bank today), allowing precipitation of ooids behind and around seaward patch reefs.

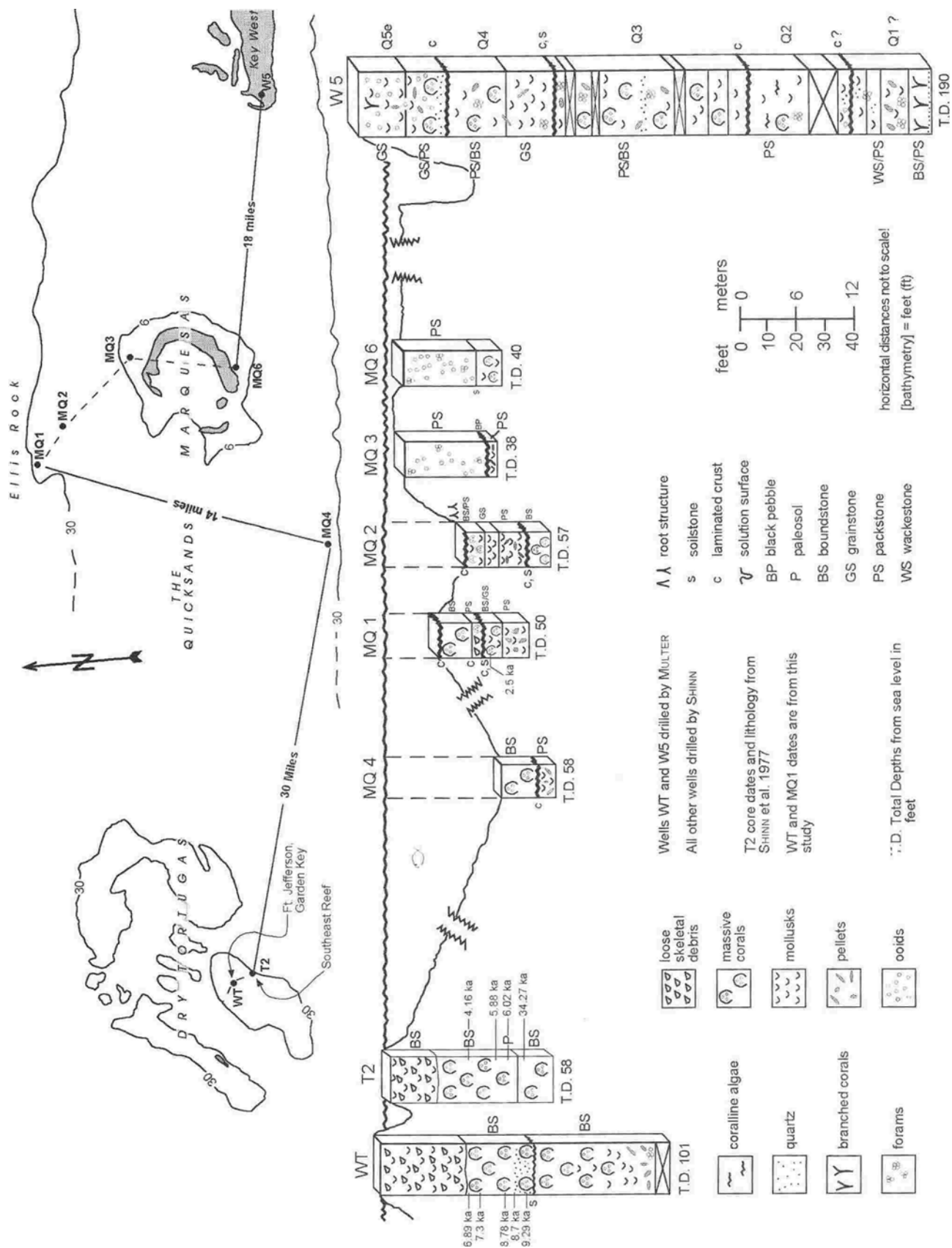


Fig. 15. West-to-east cross section from Dry Tortugas to Key West. Sources of dates in T2 core from Shinn et al. (1977). All other core dates are from the present study.

5. The westernmost evidence for Pleistocene shelf-edge carbonates is the cumulative coralline framework on antecedent highs beneath the Dry Tortugas. Here, banks and shoals of bioclastic storm-controlled sand overlie aragonite-rich Holocene boundstone that evolved on a sequence of recrystallized Pleistocene coral boundstones and vuggy molluscan packstones containing coral. Similar loose storm-controlled carbonate Holocene sediments overlying recrystallized coral boundstone and vuggy packstone, of probable Pleistocene age, are found at the Marquesas Keys between Key West and the Dry Tortugas.

6. Shelf-edge rocks appear to be 4 to 6 m lower in elevation than those of the same post-Q5e age found under the Carysfort and Sand Key Reef outliers. This difference in elevation could reflect past subsidence, faulting or platform tilt.

7. The new Pleistocene radiometric TIMS dates (Table 1) obtained during this study helped assign two new rock units of the Key Largo Limestone (Q5e, post-Q5e) to oxygen isotope substages 5e and 5c/5a highstands of sea level. Unit Q3 rocks were presumably deposited during oxygen-isotope stage 9. Unit Q1, Q2, and Q4 rocks could not be dated, but unit Q4 presumably corresponds to isotope stage 7.

New dates fall into three groups. (1) The oldest date of 370.2–366.8 ka falls in the range of the 360 ka date of Szabo and Halley (1988) (unit Q3? rocks). These dates are biased (older) due to possible open-system behavior. (2) Mid-shelf cores (KL4 and WP) yielded 124.2 ka and 128.1 ka dates corresponding to isotope substage 5e (unit Q5e rocks). (3) WX, AQ, WL and KL5 cores yielding dates of 92.3–91.1 ka, 87 ka, 77.8 ka, and 92.3 ka, respectively, at the edge of the shelf fall mostly in the isotope substage 5a (unit post-Q5e rocks), similar to the dates of the outlier reefs (Lidz et al. 1991; Ludwig et al. 1996; Toscano and Lundberg 1998, 1999). At deeper depths core AQ has a date of 112.4 ka, which is tentatively assigned to isotope substage 5c/5e (unit post-Q5e/Q5e rocks).

8. The Key Largo Limestone in the Florida Keys lends itself to a three-phase evolution based on lithofacies (Fig. 9). The initial phase (Q1 and Q2) represents deep-water quartz-rich facies evolving into a shallower carbonate facies, possibly during the long and warm isotope stage 11 (Droxler and Farrell 2000). A second phase (Q3, equivalent to isotope stage 9?) was that of flourishing reefs, sediment-productive lower Keys and Northern Keys High platforms with the middle Keys often dominated by deep channels and discontinuous reef sites. The third and last Key Largo Limestone phase (Q4, Q5e and post-Q5e, correlating with isotope stage 7, substage 5e, and substages 5c and 5a respectively) represents periods of stabilization with productive leeward lagoons, abundant mudstones, packstones, grainstones and decreasing extent of reefs. High sea level at 140 ka produced reef growth, especially along elevated portions of the upper and lower Keys. Bryozoan- and ooid-rich sediments formed in leeward shelf areas. New core

dates support the argument that the Q5e shelf margin had a ramp-type seaward slope and lacked shallow shelf-margin outer reefs. Following this, however, a series of decreasing Pleistocene sea-level maxima built up (a) shelf sediment veneers and thick shelf-edge sediment wedges (Fig. 7) with *Acropora palmata* outer reefs and (b) off-shore outlier reefs with *Acropora palmata*.

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APPENDIX: List of literature (by subject) on the Key Largo Limestone.

Areal Studies (Florida Keys): Hoffmeister and Multer (1964b, 1968), Hoffmeister (1974), Shinn et al. (1977), Multer (1977), Harrison et al. (1982a, b), Shinn (1984), Harrison and Coniglio (1985), Shinn (1988), Textoris et al. (1989), Halley et al. (1997), Randazzo and Halley (1997).

Chronology: Broecker and Thurber (1965), Osmond et al. (1965), Mitterer (1974, 1975), Imbrie et al. (1984), Kaufman (1986), Shackleton (1987), Szabo and Halley (1988), Muhs et al. (1992), Ludwig et al. (1996), Fruijtier et al. (2000).

Corals: Hoffmeister and Multer (1964a), Cuffey (1972), Schneidermann et al. (1972), Dodd et al. (1973), Sandberg et al. (1973), Hodges (1977), Hudson (1979), Ginsburg and Choi (1984), Textoris et al. (1989), Ginsburg and Shinn (1964).

Core Studies: Multer and Hoffmeister (1968b), Perkins (1977), Harrison and Halley (1979), Hanson (1980), Coniglio (1981), Coniglio and Harrison (1983b), Harrison et al. (1984), Kindinger (1986), Fuhr (1988), Textoris (1988), Merriman et al. (1989), Shinn et al. (1994), McNeill et al. (1996), Warzeski et al. (1996), Cunningham et al. (1998), Guertin et al. (1999).

Diagenesis: Sandberg et al. (1973), Scherer (1975), Coniglio and Harrison (1983a, b), Martin et al. (1986), Carpenter and Lohmann (1994), Melim and Swart (1995). Note: many papers listed under "core studies" also deal in part with diagenesis.

Karst Studies: Multer and Hoffmeister (1968a), Kahle (1977), Robbin and Stipp (1979), Robbin (1981), Harrison (1981), Coniglio and Harrison (1983a, b), Strasser (1984), Shinn and Lidz (1988).

Petrology: Halley and Rose (1977)

Regional Studies - South Florida: Hoffmeister et al. (1967), Perkins (1974, 1977), Shinn et al. (1977), Geister (1980), Mitchell-Tapping (1980), Doyle (1983), Shinn (1984), Missimer (1984), Ginsburg (1987), Ginsburg et al. (1989), Locker et al. (1996), Ludwig et al. (1996).

Shelf Edge/Submerged Terraces/Outlier Reefs: Enos (1977), Holmes (1985), Twichell et al. (1991), Lidz et al. (1991), Locker et al. (1996), Lidz et al. (1997a, b), Toscano and Lundberg (1997, 1998, 1999).

Guidebooks: The first and classic field guidebook (17 stops in 3 days) for the Florida Keys was compiled by Ginsburg (1964) for the Geological Society of America convention in Miami. Included is a discussion of the Key Largo Limestone by Hoffmeister and Multer, which also appeared in Guidebook #3 (Hoffmeister and Multer, 1964b) for the same GSA meeting. A discussion of various aspects of the Key Largo Limestone is found in the Carbonate Rock Environments Field Guide to the Florida Keys and Western Bahamas compiled by Multer (1977). Although not dealing with the subject of this paper, Halley and Evans (1983) and Evans (1987) present an important detailed field guide and discussion that updates research on the Miami Limestone in the Miami area. Shinn et al. (1989) update data on Florida Keys Pleistocene rocks in a field guide entitled "Reefs of Florida and the Dry Tortugas," which summarizes some of the work accomplished at the U.S. Geological Survey Fisher Island Field Station from 1974 to 1989. "Site Characteristics for the Florida Keys National Marine Sanctuary and Environs" (1996) by The Nature Conservancy covers various topics in 10 volumes.