PROCEEDINGS OF THE EIGHTH SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

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Front Cover: View to the SSE on White Cay in Grahams Harbour off the north coast of San Salvador, Bahamas. At this spectacularly scenic site one can see that marine erosion has removed the entire windward portion of these early Holocene eolianites (North Point Member, with an alochem age of ~5000 radiocarbon years B.P.) that were deposited when sea level was at least 2 meters below its present position.

Back Cover: Stephen Jay Gould, keynote speaker for this symposium, holds a *Cerion rodregoi* at the Chicago Herald Tribune's 1891 monument to the landfall of Christopher Colombus, which is located on the windward coast of Crab Cay on the eastern side of San Salvador Island, Bahamas. The monument consists of an obelisk constructed from local limestone which houses a carved rock sphere depicting the globe with the continents. The inscription carved in a marble slab, reads: "On this spot, Christopher Columbus first set foot upon the soil of the New World."

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LATE STAGE 5 CORAL REEFS, SOUTHEAST FLORIDA SHELF: SEA LEVEL, HIGH PRECISION DATING AND ASSESSMENT OF FORCING MECHANISMS

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ABSTRACT

Massive Pleistocene "Outlier" reefs fronting the southeast Florida margin were cored in two transects and U-Th dated by TIMS. Outlier Reefs developed during Last Interglacial substages 5c, 5b and 5a, representing multiple generations corresponding to sea-level highstands. Early Holocene reef growth occurred from 8.9 to 5.0 ka, capping an exposure/soil horizon on top of the Pleistocene reefs. Due to water quality/transparency, depth over reefs, and local environmental constraints, no later Holocene reef framework occurs at these sites.

Synthesis of dated sea-level indicators from the stable Florida/Bahamas region, and from Barbados, allowed reconstruction of substage 5b-5a sea-level history. Dated speleothem from the Bahamas provided necessary constraints on maximum sea levels reconstructed from reefs. Outlier Reef growth began before 86 ka, pre-dating 65°N and 15°N insolation maxima at 82-83 ka. Sea level reached a maximum —9.0 m MSL by 80 ka, as constrained by Bahamian speleothem data, and by water-depth limitations specific to Florida. Sea level rapidly dropped to -18 m MSL by 79 ka (constrained by speleothem), causing reef termination and subaerial exposure. Sea-level rise during substage 5a was apparently forced by insolation increase. Rapid sea-level fall during peak insolation may be consistent with decreased obliquity.

INTRODUCTION

The Florida Keys formed as a reef and ooid tidal-bar system during the peak of the last interglacial (substage 5e), when sea level reached +6 m MSL at 125 ka (Bloom et al., 1974; Chappell, 1974; Mesollela et al., 1969; Neumann and Moore, 1975; Chen et al., 1991). The modern Florida reef tract occurs just landward of the present shelf break (Enos, 1977). Massive Pleistocene reefs occur seaward of the modern reef tract, situated below the main shelf on a terrace fronting the southeast Florida margin (Lidz et al., 1991; Figure 1). This ancient, or "Outlier" reef tract formed during the late last interglacial, after the Keys formed. This tract lies seaward of, and separated from, the shelf-edge and the modern reef tract near Sand Key in the lower Keys (offshore of Key West), and near Carysfort in the upper Keys (offshore of Key Largo). Latest Pleistocene reef growth is relegated to shelf edge buildups in the middle Keys. Outlier Reefs were discovered from shore-normal bathymetric surveys of the Keys margin (Enos, 1977) and were later re-surveyed using seismic reflection techniques (Lidz et al., 1991).

Cored transects from the Sand Key Outlier Reef and the Carysfort Outlier Reef were studied to reconstruct the upper portion of the reef tract's history. Cores enabled delineation of the reef tract stratigraphy and subaerial exposure horizons, the timing of episodes of reef building, and sea-level

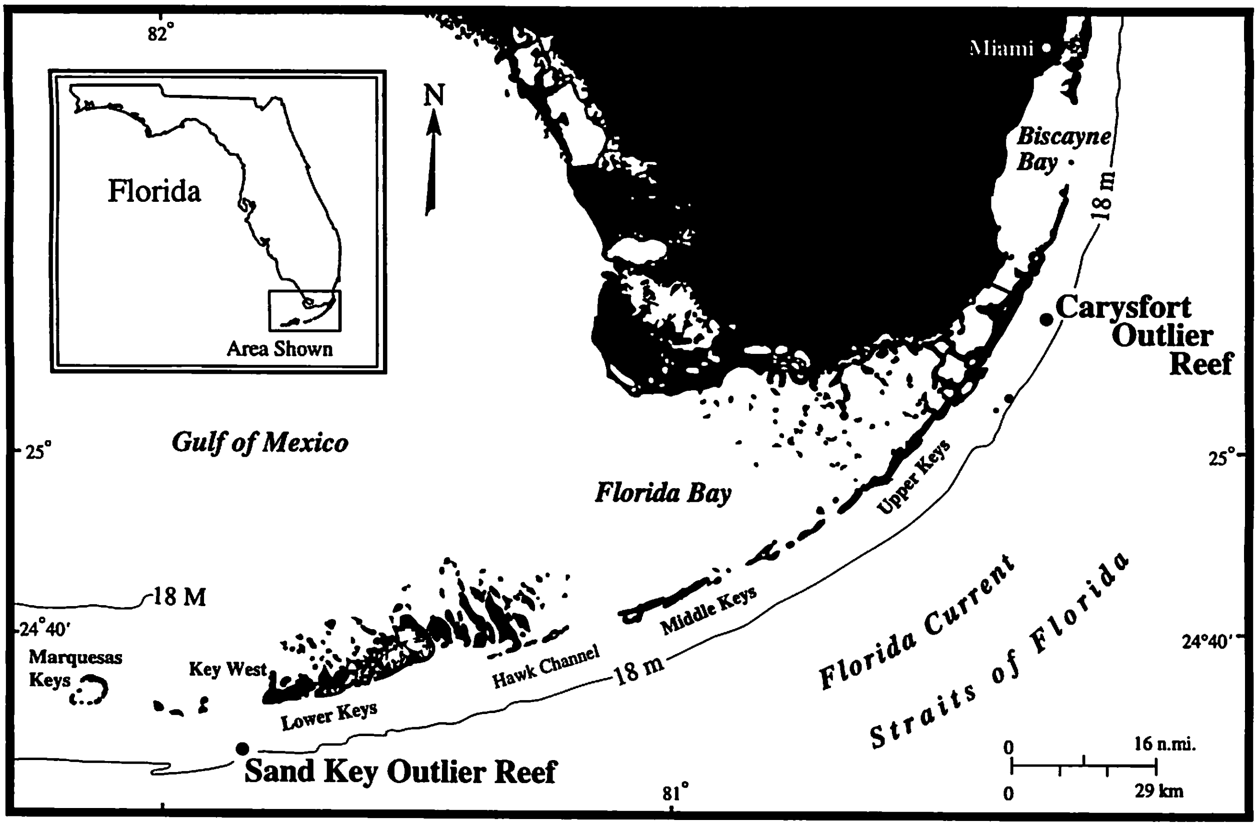

Figure 1. Location Map, Southeast Florida. Cored transects are located in the lower Keys at Sand Key and in the upper Keys at Carysfort.

elevations and paleoclimatology for the late Pleistocene and the early Holocene (Toscano, 1996). This paper addresses late Pleistocene sea-level elevation utilizing data from Outlier Reefs, and from the stable Florida-Bahamas region.

METHODS

Seismics

Seismic reflection profiles in the Sand Key area were collected jointly by the United States Geological Survey (USGS) and the University of South Florida Department of Marine Sciences-(USF-DMS) using a single-channel analog profiler. Line 16a was used as the base line for coring and construction of cross sections. Seismic data from the Carysfort area consist of 3 lines (USGS unpublished data). Line 31 was the primary base line for coring and stratigraphic reconstruction. Because reef stratigraphy in seismic profiles is obscured by the high reflectivity of carbonates and the jumbled nature of reefal deposits, cores were essential for determining internal reef stratigraphy.

SCARID Drilling

Core locations were chosen from seismic profiles to complement the locations of previously-drilled USGS cores, resulting in two main transects (Toscano, 1996). In 1994, cores were taken using the diver-operated *S*ubmersible *C*oring *A*pparatus for *R*emote *I*nsular *D*rilling (*SCARID*) system developed in 1989 at the West Indies Laboratory, St. Croix, U.S. Virgin Islands, in cooperation with the NOAA National Undersea Research Program (Hubbard, 1994). The hydraulic drill system has a tripod with a vertical frame to maintain core orientation, a centimeter scale on the frame to measure intervals of changing subsurface rock/sediment character, and a wireline-winch core retrieval system.

TIMS U-Th Dating

Twenty-eight Outlier Reef *Acropora palmata* and head corals were U-Th dated via Thermal Ionization Mass Spectrometry (TIMS), a high-precision technique (Edwards et al., 1987), following procedures outlined in Li et al. (1989). For TIMS dating to be accurate, corals must have retained their primary skeletal aragonitic mineralogy ($\leq$0.5 wt% calcite), exhibit $^{234}U/^{238}U_{init}$ within the modern seawater range (1.144±0.008; Gallup et al., 1994), and have low detrital Th ($^{230}/^{232}$). Corals growing in a marine environment far removed from significant terrestrial sediment input (such as the Florida Keys) typically do not incorporate detrital Th. All dated samples showed 0.0% calcite on calibrated X-ray diffraction analyses. $^{234}U/^{238}U_{init}$ ratios fell within 1% of the modern seawater value, with few exceptions. Typical precisions on determined ages were ±1% (2σ). U-Th data are included in Table 1.

STRATIGRAPHY

Sand Key Outlier Reef

Sand Key Outlier Reef (Figure 2) forms a 30-m high "keep-up" (vertical) profile, backed by a 40-m deep trough with very little sediment infilling. Predominance of longshore-directed processes, especially the influence of the Florida Current (Lee et al., 1992) accounts for the lack of sedimentation. Smaller reefs of unknown age are found in the trough (Lidz et al., 1991).

Four cores on the main Outlier Reef, and one from the adjacent shelf edge, penetrated only the top one-third of the reef section (Figure 3). SCARID Core SKOR2a reached the maximum depth of -21.3 m MSL. Cores typically had 60% recovery, of which 50% consisted of corals and weakly-cemented sediment. The remaining 40% consisted of unrecoverable sands and voids. Most of the cored section represents fore-reef and shallow back-reef environments, consistent with the Keep-up style profile (Neumann and Macintyre, 1985) of Sand Key Outlier Reef (Figure 2).

No obvious unconformities (caliche, soils, plant-roots, etc.) were noted within the late Pleistocene section (i.e., separating substage deposits). The Pleistocene/Holocene unconformity was placed using TIMS U-Th dates. Thirteen TIMS dates (including three from Ludwig et al., 1996) from the main Outlier Reef section indicate two periods of reef colonization and accretion.

Late Pleistocene

Late Pleistocene reef accretion ranges from the base of the deepest core at -21.3 m MSL to the top of the *in situ* Pleistocene section at -12.2 m MSL (present elevations). The lowermost Pleistocene-dated coral possibly represents reef growth during substage 5c; however, only one dated coral, with a high $^{234}U/^{238}U^{init}$ (Table 1) falls within the 5c age range. Reef growth either was maintained through, or was re-established at, the end of substage 5b (95-90 ka; Table 1; Figure 3), and continued for the duration of substage 5a (86-80 ka). Sand Key Outlier Reef records 26 kyrs of reef development, disregarding possible hiatuses between substages 5c/5b and 5b/5a.

Core SKSE on the main shelf edge documents the same sequence of late Pleistocene reef growth disconformably overlain by early Holocene reef growth. The late Pleistocene section spans -25 to -16 m MSL (present elevations), and records deposition during late substage 5b through substage 5a. An exposure/soil horizon on the relict Pleistocene reef surface was identified macroscopically, and the position of the Pleistocene/Holocene unconformity was confirmed through stable isotopic analyses of bulk rock and sediment suspected of having undergone subaerial exposure at the end of substage 5a (Toscano, 1996).

Carbonates deposited in a marine environment have $\delta^{13}C$ values near 0.0 (PDB) or slightly positive. Marine carbonates altered in a meteoric environment yield negative $\delta^{13}C$ values because they are enriched in ^{12}C from CO_2 gas produced as a result of oxidation of plant debris in soils and by plant respiration (Rossinsky and Swart, 1993). Stable isotopic analysis of bulk rock, suspected caliche, and soil in cores were used as indicators for identification of subaerial exposure horizons, and for the determination of elevations of major unconformities. Samples indicated by shaded circles on Figure 4 fall into two distinct

Table 1. U-Th Dated Corals from Florida Outlier Reefs, Barbados I Reef Crest, Bermuda *Oculina*, and Bahamas and Bermuda Speleothem. †Reworked sample not included in sea-level curve. ‡Subsidence rate of 0.015 m kyr^{-1} for Florida; 0.020 m kyr^{-1} for Bahamas; Barbados elevations as reported, except Ku *et al.* (1990), elevations estimated from other studies. *Ludwig et al. (1996). ¦Richards et al. (1994). +Li et al. (1989); Lundberg and Ford (1994). ▪Harmon et al. (1978). □Edwards et al. (1987). ○Bard et al. (1990). ■Ku et al. (1990). ●Gallup et al. (1994).

	Sample ID	Present Elev.	Corrected Elev.‡ m MSL	U-Th Age ka	Error ± 2σ ka	$^{234}U/^{238}U_{init}$	Coral
Florida:							
5a:	†USGS2	-11.3	-10.0±1.5	86.2	1.01	1.144±0.000	*M. annularis*
	USGS3	-12.3	-11.1±1.5	82.7	0.58	1.156±0.000	*M. annularis*
	USGS1*	-13.4	-12.2±1.5	80.9	1.70	1.144	*M. annularis*
	USGS1*	-17.7	-16.4±1.5	83.2	0.90	1.151	*M. annularis*
	SKOR2A2#7	-14.0	-12.8±0.3	81.4	0.68	1.152±0.000	*C. natans*
	SKOR2A2#8	-14.3	-13.0±0.3	84.5	0.82	1.152±0.000	*M. annularis*
	SKSE 7#3	-17.9	-17.6±0.3	85.9	1.19	1.158±0.000	*M. annularis*
	SKSE13#10	-24.0	-22.7±0.3	85.7	0.71	1.146±0.000	*M. annularis*
	CSFT4 6#8	-15.1	-14.9±0.3	80.2U/U	-----	-------------	*M. annularis*
	CSFT4A 2#10	-15.2	-15.0±0.3	85.3	1.70	1.145±0.000	*A. palmata*
				91.8	1.05	1.162±0.000	*M. annularis*
5b:	SKSE 7#9	-19.2	-18.9±0.3		4.80	1.149±0.000	*M. annularis*
	CDR-1 1982	-19.8	-19.5±1.5	94.4			
	CSFT4A 3#4	-15.5	-15.3±0.3	92.2	0.78	1.151±0.000	*A. palmata*
	SKOR2A3#6	-15.9	-15.7±0.3	90.6	1.58	1.152±0.000	*M. annularis*
5c:	SKOR2A7#9	-21.7	-21.4±0.3	106.5	1.00	1.182±0.000	*M. annularis*
Bahamas:							
	Speleothem¦	-18.1	-16.5±0.1	79.4	1.80	-----	
	Speleothem¦	-18.1	-16.5±0.1	78.1	0.60	-----	
	Speleothem¦	-18.1	-16.6±0.1	76.4	0.50	-----	
	Speleothem¦	-18.1	-16.8±0.1	63.7	1.70	-----	
	DWBAH+	-15 to -10	-13.1 to -8.15±3	92.6	2.50	1.080	
	DWBAH+	-15 to -10	-13.6 to -8.6 ±3	70.6	3.90	1.070	
Bermuda:							
	Speleothem▪	-5.7	-5.7±?	99.0	10.00	-----	
	Speleothem▪	-2.8	-2.8±?	97.0	18.00	-----	
	S'hampton▪	+1.0	+1.0±0.5	85.0	12.00	?	*Oculina* sp.
	S'hampton▪	+1.0	+1.0±0.5	83.0	10.00	?	*Oculina* sp.
	S'hampton▪	+1.0	+1.0±0.5	97.0	12.00	?	*Diploria* sp.
	S'hampton*	+1.0	+1.0±0.5	82.3	3.60	1.1509	*Oculina* sp.
	S'hampton*	+1.0	+1.0±0.5	82.4	0.90	1.1468	*Oculina* sp.
	S'hampton*	+1.0	+1.0±0.5	77.9	0.40	1.1448	*Oculina* sp.
	S'hampton*	+1.0	+1.0±0.5	77.2	2.50	1.1470	*Oculina* sp.
Barbados I/Worthing Terrace:							
	Reef Crest□	?	-18.0	87.5	0.60	1.161	*A. palmata*
	Reef Crest□	?	-18.0	87.9	0.70	1.162	*A. palmata*
	Reef Crest○	+18	-18.0	88.2	0.80	1.166	*A. palmata*
	Reef Crest■	?	-18.0?	78.1	2.40	1.158	*A. palmata*
	Reef Crest■	?	-18.0?	75.5	2.40	1.165	*A. palmata*
	Reef Crest■	?	-18.0?	85.2	2.60	1.160	*A. palmata*
	Reef Crest■	?	-18.0?	83.0	2.60	1.165	*A. palmata*
	Reef Crest■	?	-18.0?	83.2	3.00	1.169	*A. palmata*
	Reef Crest●	+12.0	-15.5±?	83.3	0.30	1.151	*A. palmata*

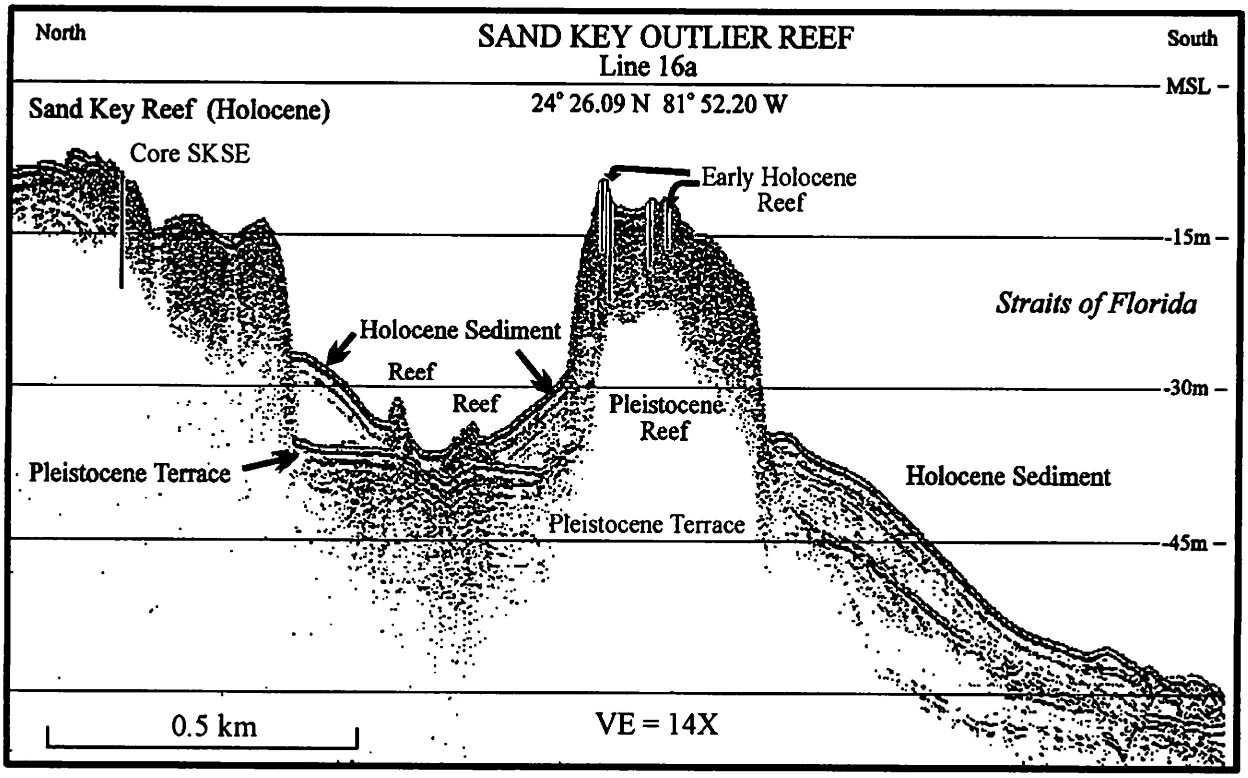

Figure 2. Seismic reflection profile across Sand Key Outlier Reef. Line 16a (Lidz et al., 1991) forms the base profile for the 4-core transect. One additional core is located at the edge of the main shelf near Sand Key Reef (modern).

populations for the shelf edge core (SKSE). Holocene samples (marine exposure only) plotted near or above zero, while Pleistocene samples (marine and subaerial exposure) plotted in the negative range for $\delta^{13}C$. Based on those data, the unconformity was placed at -16 m MSL (present elevation).

Holocene

On the main Outlier Reef, early Holocene colonization of the relict late Pleistocene surface was concentrated in two patches (Figure 3). Holocene reef elevations ranged from -12.2 to -11.1 m MSL for the seaward patch, and from -12 to -9.7 m MSL for the landward pinnacle, or rubble island. Reef framework developed between 8.9 and 6.7 ka. On the adjacent shelf edge, early Holocene reef growth occurred from -16 to -9 m MSL, between 8.6 and 7.6 ka. Termination of reef growth on the main Outlier Reef and on the shelf edge occurred during transgression as: 1.) depth increased, 2.) influx of deleterious waters from the Gulf of Mexico and Florida Bay across the shelf was established through tidal passes between the Keys, and 3.) water quality and transparency decreased (Toscano, 1996). Reef growth was re-established upward and landward in shallower water on the main shelf (Robbin, 1984).

Carysfort Outlier Reef

Carysfort Outlier Reef, located offshore of Key Largo (Figure 1), forms a mature profile (Figure 5) indicative of progradation under stable or slowly-rising sea level (Neumann and Macintyre, 1985). The back-reef trough is shallower and more infilled than its equivalent at Sand Key, due to the influence of onshore processes moving sediments landward in the Northern Keys. Carysfort Outlier Reef peaks in elevation at -7 m MSL, or 2.7 m higher than the Holocene rubble pinnacle on Sand Key Outlier Reef. Five cores penetrated the upper two thirds of Carysfort Outlier Reef from the crest to the

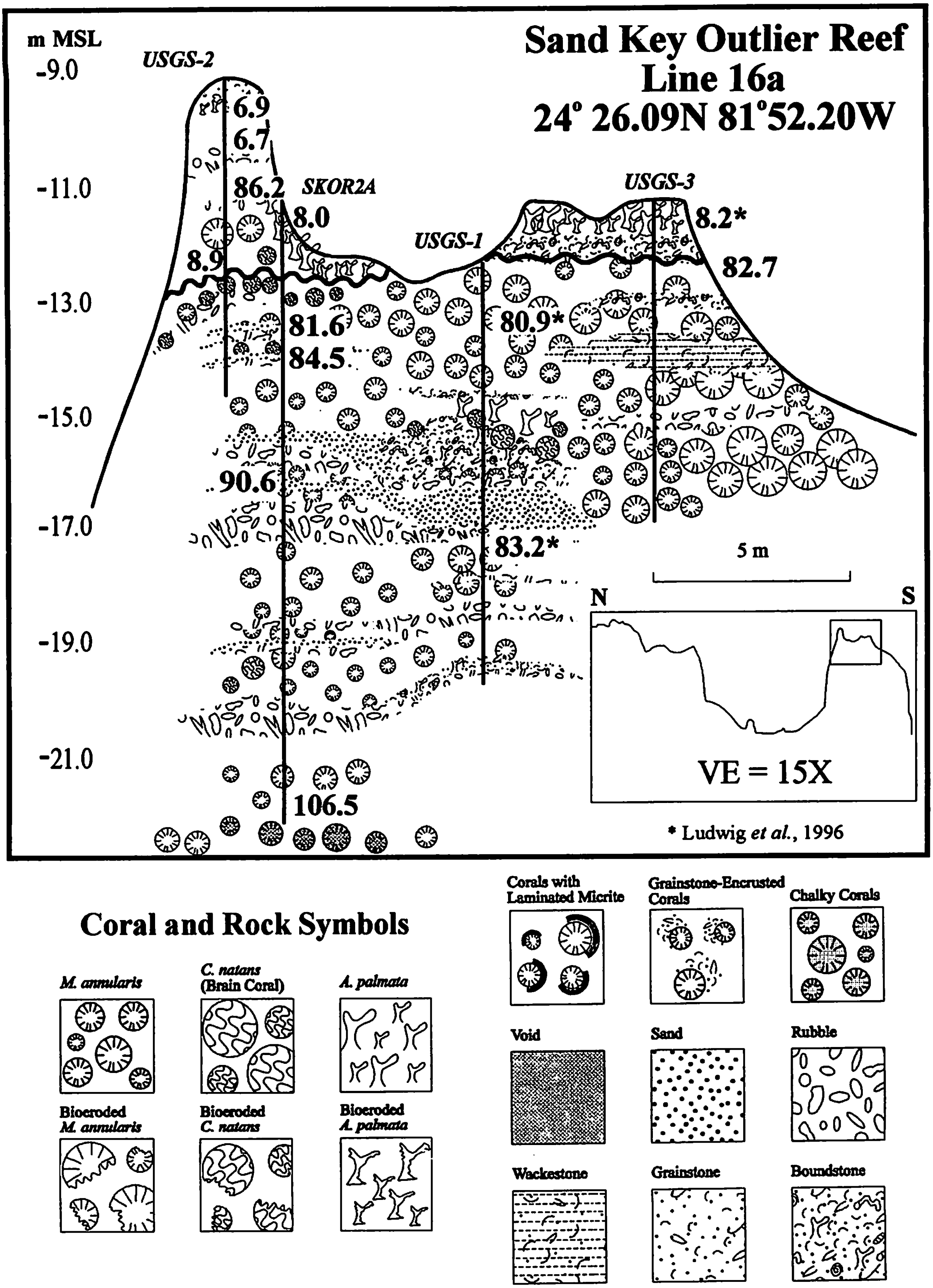

*Figure 3. Interpreted stratigraphic cross section, Sand Key Outlier Reef. Dates marked with * are from Ludwig et al. (1996).*

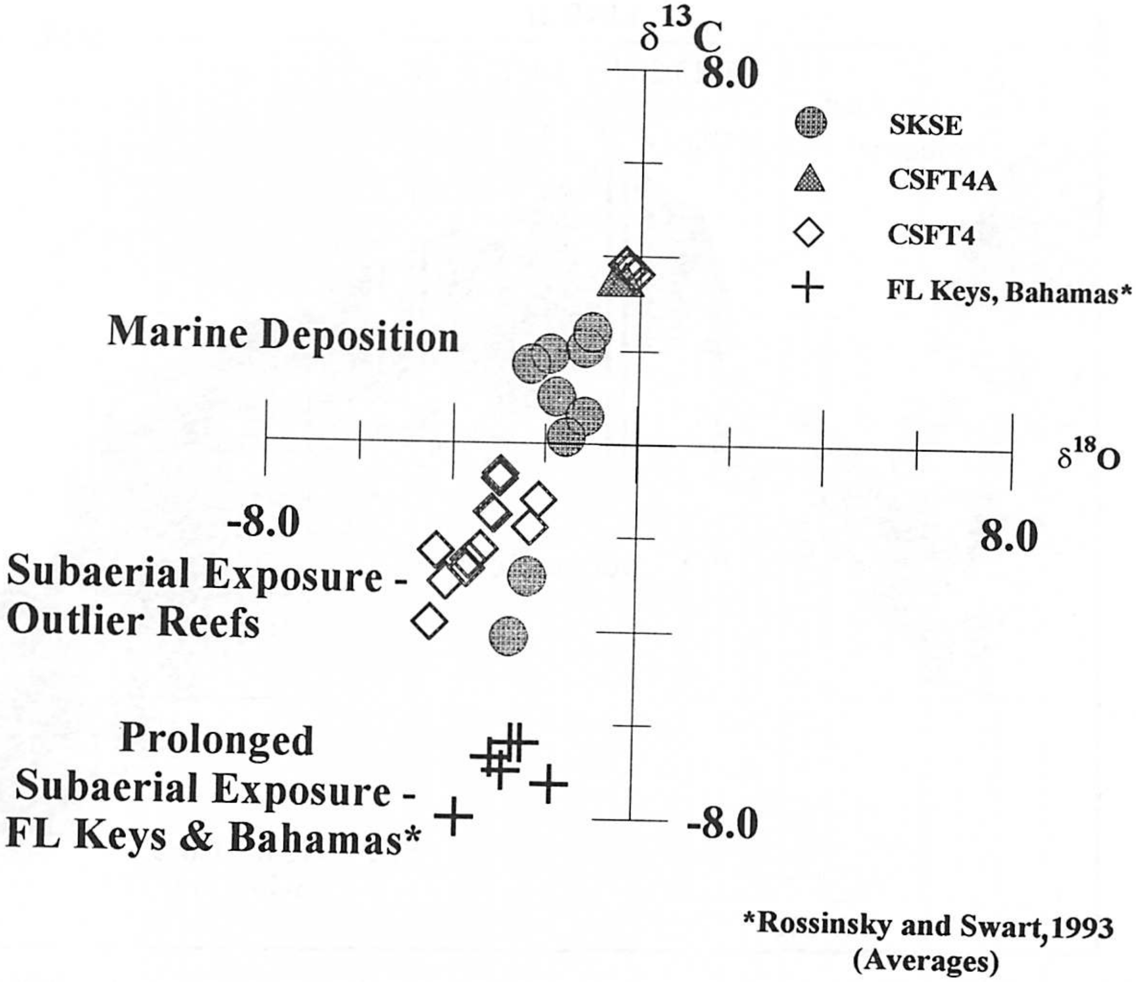

Figure 4. Stable isotopic data from interpreted subaerial exposure/soil horizons in Outlier Reef cores. Positive $\delta^{13}C$ values indicate marine exposure only, while negative $\delta^{13}C$ values indicate subaerial exposure and meteoric diagenesis of marine samples.

deep fore-reef (Figure 5). Reef stratigraphy was similar to that at Sand Key Outlier Reef, consisting of back- and fore-reef facies characterized by head corals with some *A. palmata.* The late Pleistocene section is disconformably overlain by localized soil formation and by early Holocene reef.

Late Pleistocene

The Pleistocene section has an interpreted "reef crest" facies consisting of *A. palmata*, and a 5 m-thick back-reef faciesconsisting of fine-grained sediment with small head corals (Figure 6). Shallow and deep fore-reef facies are interpreted seaward of the reef crest. TIMS U-Th dates indicate reef growth during substages 5b and 5a, with no obvious intermediate unconformity (Table 1).

The Pleistocene/Holocene boundary was placed throughout the cross section using TIMS dates. In addition, the backreef area contained a soil/subaerial exposure horizon developed on the relict Pleistocene reef. A section within core CSFT4 is characterized by thin caliches and corals coated in brown soil. Stable isotopic analyses of these soils and caliches (open diamonds, Figure 4) indicate subaerial exposure, while overlying (Holocene) samples are clearly marine. Samples analyzed from core CSFT4A on the shallow fore-reef (Figure 6) indicated only marine exposure (shaded triangles, Figure 4), confirming the placement of the Pleistocene/Holocene unconformity using dates.

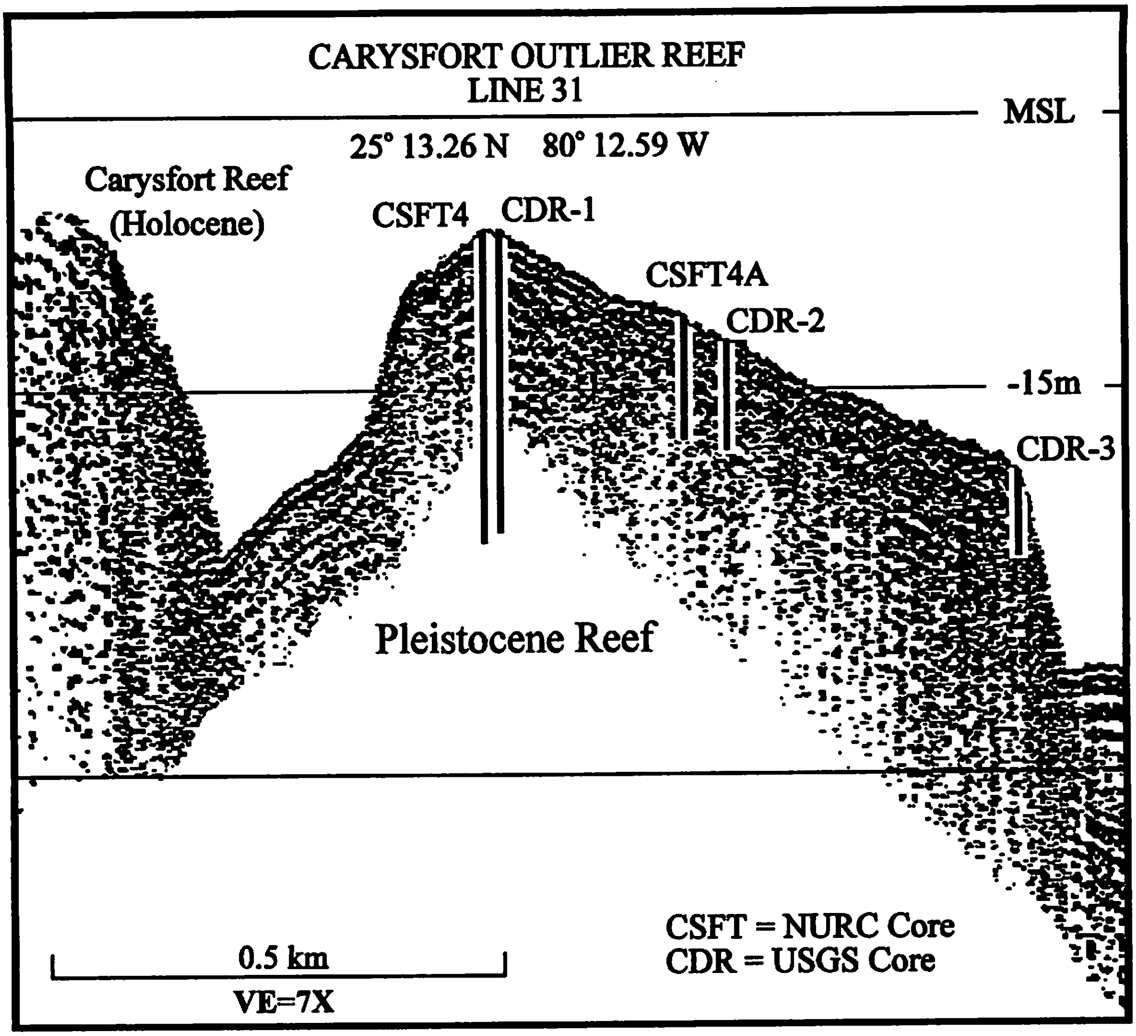

Figure 5. Seismic reflection profile across Carysfort Outlier Reef. Line 31 (USGS unpublished data) forms the base profile for the 5-core transect.

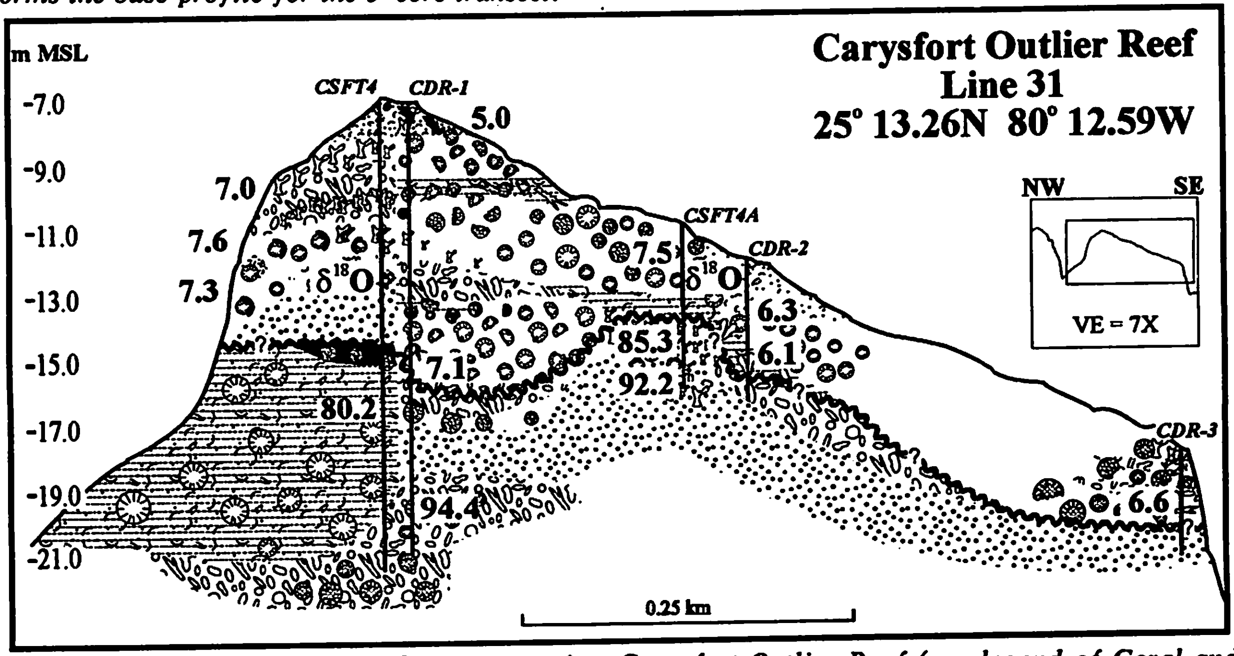

Figure 6. Interpreted stratigraphic cross section, Carysfort Outlier Reef (see legend of Coral and Rock Symbols in Figure 3).

Holocene

Initial Holocene reef colonization occurred near the center of the late Pleistocene surface, followed by seaward progradation over the shallow and deep fore-reef, extending to the edge of the profile (Figure 6). The Holocene section spans 2.6 kyrs, or 300 years longer than at Sand Key, over a more developed, continuous and mature reef profile. Environmental conditions differed substantially between these locations along the reef tract during the later Holocene transgression. Carysfort Outlier Reef was protected from deleterious water influxes from Florida Bay due to the absence of tidal passes in Key Largo. Good water quality and clarity was likely maintained, at least until the transgression breached the shelf/platform top, allowing longer reef duration and seaward progradation.

LATE PLEISTOCENE SEA LEVEL

Importance of Florida and Bahamas

Reef coral age and subsidence-corrected elevation data from the Florida Outlier Reefs were used to constrain the elevation of sea level during late Pleistocene substage 5a. The tectonically-stable Florida/Bahamas platform, with slow subsidence occurring at rates estimated at 0.015-0.020 m kyr^{-1} (Mullins and Lynts, 1977; Lundberg and Ford, 1994; Richards et al., 1994; Carew and Mylroie, 1995) is an ideal setting for paleo sea-level determination. Reefal facies maintain direct and quantifiable relationships to water depth (e.g., Lighty et al., 1982), and are optimal for determining sea-level elevations for dated intervals. In addition, available age and elevation data from presently-submerged Bahamian speleothem deposits, which form only in air-filled caves (i.e., above sea level), are essential to any comprehensive synthesis of sea-level indices. They are especially useful in the attempt to resolve the controversy surrounding the maximum elevation of substage 5a sea level.

Record of Substage 5a Sea Level

No *in situ*, or unequivocal, substage 5a marine deposits have been documented within one meter of present sea level in stable areas (*Bahamas:* Neumann and Moore, 1975; Chen et al., 1991; *Florida:* Toscano, 1996; Ludwig et al., 1996; *Atlantic Coastal Plain:* Toscano and York, 1992; Toscano, 1992; Wehmiller et al., 1992; *Hawaii:* Ku et al., 1974). Unequivocal substage 5a deposits are accessible above sea level only on tectonically-uplifted coasts. Sea-level studies in New Guinea and Barbados produced substage 5a sea-level estimates of -18 to -15 m MSL (Mesollela et al., 1969; Bloom et al., 1974; Edwards et al., 1987; Bard et al., 1990; Gallup et al., 1994). These estimates incorporated corrections for the amount of uplift that occurred since the reef crests were formed, based on the assumption of constant uplift rates, and a substage 5e eustatic sea-level elevation of +6 m MSL. Florida Outlier Reefs occur at elevations higher than the estimated Barbados sea levels of -18 to -15 m MSL for substage 5a (Edwards et al., 1987; Bard et al., 1990; Gallup et al., 1994), suggesting either major differences in sea-level elevation between Florida and Barbados, or that the Barbados model does not hold in other areas. The revised New Guinea curve (Bloom and Yonekura, 1990), resulting from a regression analysis which eliminates uplift rates, produced a substage 5a sea-level maximum of -6.6 m MSL. This estimate is generally consistent with the elevation of Florida Outlier Reefs, allowing for sufficient water over the reefs.

Bermuda Controversy

A controversy concerning the substage 5a sea-level elevation stems from a shallow marine sedimentary (not reefal) deposit found at +1 to +2 m MSL only in the northeast corner of Bermuda (Harmon et al., 1978). The younger marine unit and its associated eolianite of the Southampton Formation was interpreted by Vacher and Hearty (1989) as evidence of a brief pulse of sea level to +1 m MSL at the end of substage 5a. This marine unit was U-Th dated using *Oculina*, a deep water coral that is a rare, detrital component of the sediments. The *Oculina* produced ages from 97±6 to 77.2±2.5 ka using both α-spectrometric (Harmon et al., 1978) and TIMS (Ludwig et al., 1996) methods (Table 1). This 20 kyr age range precludes identification of a rapid sea-level rise to +1 m centered on 85 ka. The suggestion of 5a sea level at 0-+2 m MSL is also contradicted by dated Bermuda speleothem evidence for sea level remaining below -7 m MSL from 110 to 10 ka (Harmon et al., 1978). Ludwig et al. (1996) also TIMS-dated three substage 5a corals from below -12 m MSL in Sand Key Outlier Reef (Figure 3), yet still concluded, using the detrital *Oculina* data from Bermuda, that sea level reached +1 m MSL. Thus, Ludwig et al. (1996) suggest that the *in situ* Outlier Reefs, which are currently unable to support reef framework growth at 7-11 m water depths, were able to actively grow at even greater depth (~1-2 m deeper) during substage 5a.

Late Pleistocene Sea Level, Florida and Bahamas

The regional synthesis of late Pleistocene sea-level indicators for the Florida/Bahamas area (Figure 7) includes 15 Outlier Reef coral TIMS U-Th dates, α-spectrometric and TIMS dates from Bermuda *Oculina* and speleothem, and TIMS-dated

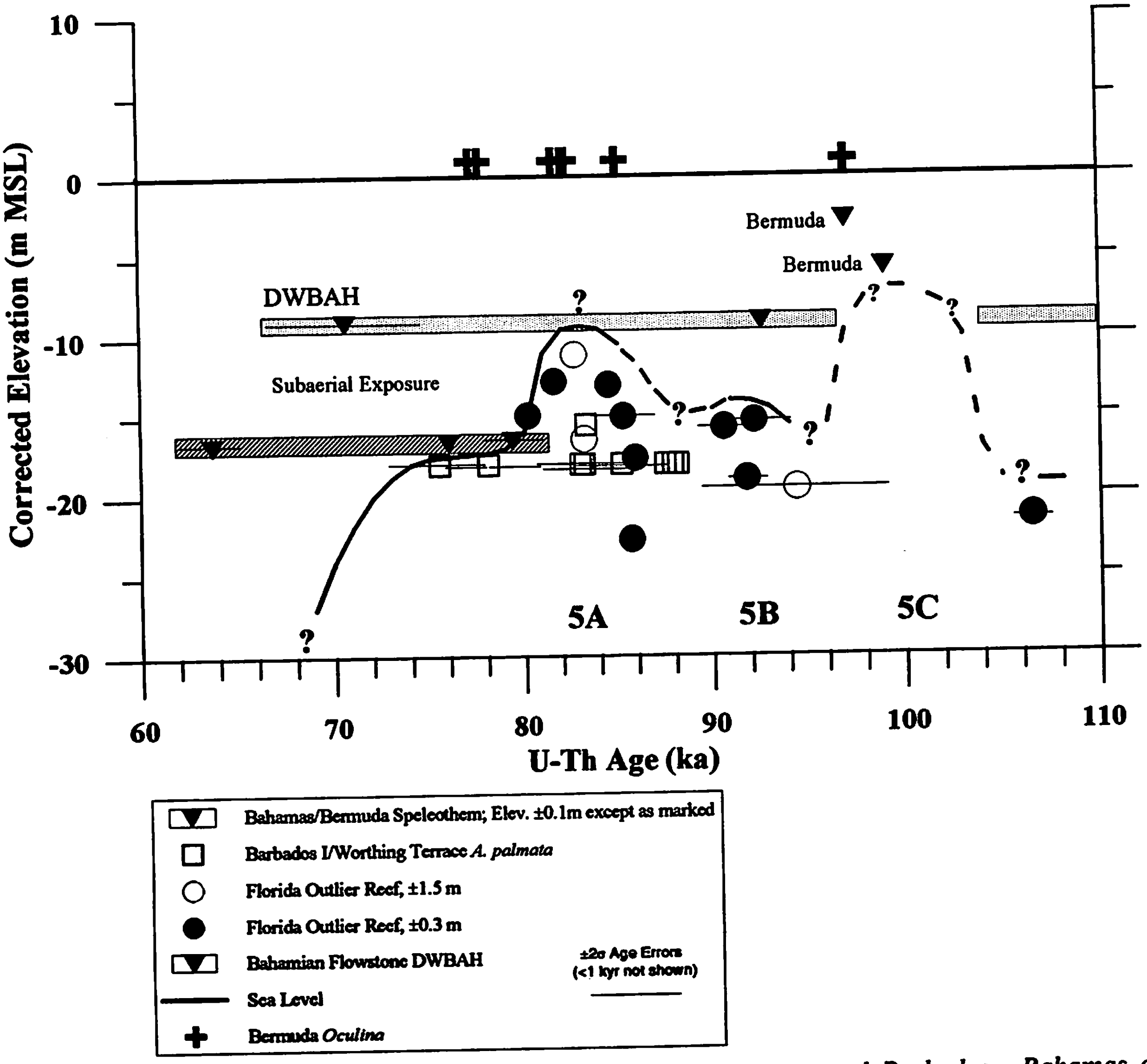

Figure 7. Late Quaternary sea-level data from Florida, Bahamas, and Barbados. Bahamas and Bermuda speleothem data indicate subaerial exposure bracketing reef growth. Outlier Reef growth occurred under relatively high sea levels during substages 5c, 5b, and 5a. Bermuda Oculina data (Harmon et al., 1978; Ludwig et al., 1996) are included for comparison. Refer to Table 1 for age and elevation data and specific errors for data reported here.

Bahamian speleothem (Li et al., 1989; Lundberg and Ford, 1994; Richards et al., 1994). Substage 5a reef data from Barbados are also included.

The maximum elevation of *in situ* Pleistocene reef is -12 ± 1.5 m MSL (-11.8 ± 1.5 m corrected for subsidence) at Sand Key Outlier Reef. Late Pleistocene framework at Carysfort Outlier Reef peaks at -14.7±0.3 m MSL (-14.3±0.3 m MSL corrected for subsidence). The *minimum* elevation of Bahamian flowstone DWBAH (Li et al., 1989; Lundberg and Ford, 1994) was estimated in the field by cave divers as -15 m MSL (-13.1 to -13.6 m MSL corrected for subsidence). When plotted with *in situ* Florida reef data, DWBAH's estimated minimum elevation appears to be several meters too low (i.e., below sea level). A three-meter positive elevation error has been arbitrarily assigned to this sample pending precise field measurement of the elevation of the flowstone (Figure 7). Because DWBAH is believed to have grown continuously throughout substage 5a (92-76 ka, with no marine erosion; Li et al., 1989; Lundberg and Ford, 1994), sea level could not have exceeded its position. Richards et al. (1994) did not document Bahamian speleothem growth during substage 5a, attributing the lack to relatively dry climatic conditions and limited groundwater recharge. Slow, or no, speleothem growth in a drier climate, combined with relatively low sea level would account for the lack of substage 5a dates, as well as the lack of marine erosion or alteration of the existing speleothem.

From the regional synthesis (Figure 7), sea level during substage 5a probably reached -9.0±0.3 m MSL, allowing for 2-3 m water depth over the reefs, but requiring a 3 m increase in the estimated minimum elevation of speleothem DWBAH. A high-end sea-level estimate of -6.8±1.5 m MSL (Toscano, 1996) would allow for up to 5 m water depth at the reef crest. Such a high estimate would require a more drastic vertical error for DWBAH and might result in water over the reefs being too deep to maintain framework growth. No modern reef growth occurs on Outlier Reefs at present sea level, because water depth exceeds the limit for framework growth. Because the late Pleistocene reefs were predominantly framework, the water depths at that time must have been less than they are at present.

DISCUSSION

The data reported here indicate a substage 5a sea-level maximum of -9.0±0.3 m MSL which exceeds recent Barbados estimates (Edwards et al., 1987; Bard et al., 1990; Gallup et al., 1994), but even the high-end estimate of -6.8±1.5 m MSL is significantly below the +1 m MSL 5a sea level suggested by workers in Bermuda (Vacher and Hearty, 1989; Ludwig et al., 1996). The temporally well-defined peak in sea level indicated by *in situ* Outlier Reef data (Figure 7) contrasts sharply with the 20-kyr age spread for *Oculina* from the younger Southampton Formation in Bermuda. Rapid sea-level fall (10 m in 1 kyr; Figure 7) at the end of substage 5a corresponds closely in time to the resumption of speleothem deposition in the Bahamas (Richards et al., 1994).

The substage 5a sea-level maximum correlates well with the 65°N insolation maximum at 82 ka (Berger and Loutre, 1991). Insolation increase coincided with sea-level rise and reef development during substage 5a, indicating a possible direct response to forcing (Figure 8); however, rising sea level during substages 5b/5a was likely initiated by the successive and combined effects of obliquity and precession. The obliquity maximum at 92 ka may have caused high-latitude ice melting beginning in substage 5b. Increasing insolation at 65°N and the precession maximum would have maintained warm water temperatures while the decline in obliquity during peak insolation and precession probably kept sea level below its modern elevation. The rapid drop in sea level at 79 ka coincides with declining insolation after 80 ka (Toscano, 1996).

CONCLUSIONS

TIMS U-Th dating of *in situ* Florida Outlier Reef corals from a stable platform environment has identified the full age range for substage 5a reefs in the Caribbean. In combination with speleothem elevation and age data from the Bahamas, Outlier Reef data define a well-constrained sequence beginning with probable reef growth during substage 5c, subaerial exposure from 100-95 ka, reef growth from 94-90 ka, and again from 86-80 ka. Sea level dropped to ≥-17 m MSL at 79 ka, followed by a prolonged period of subaerial

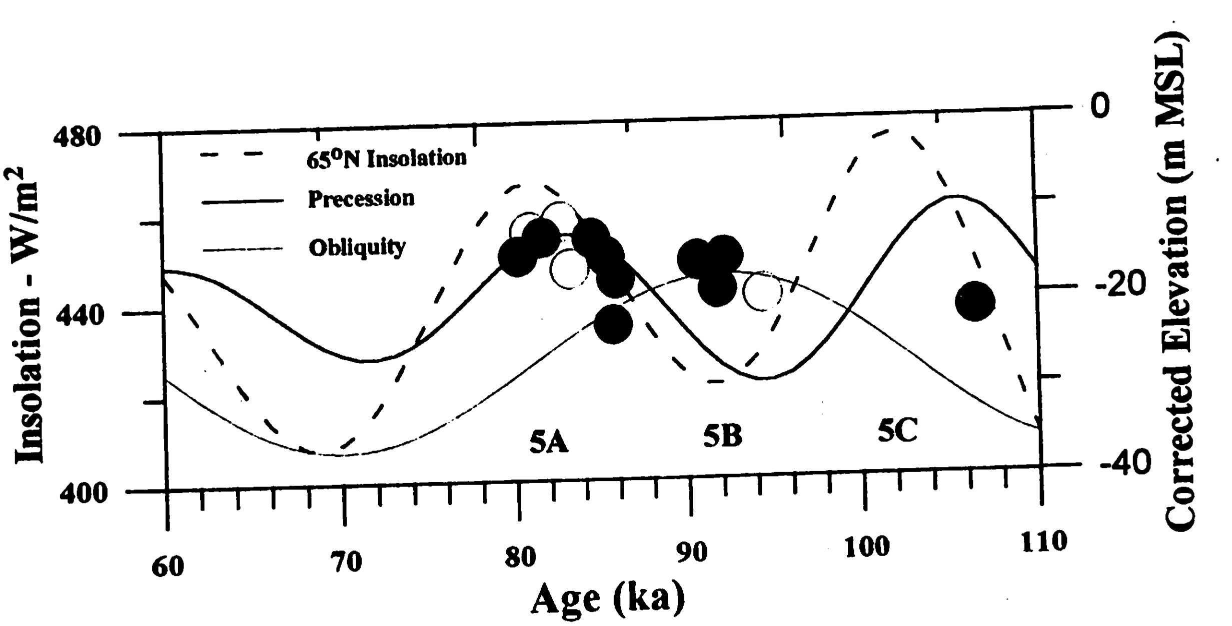

Figure 8. Orbital data (BER90 Solution; Berger and Loutre, 1991) for late Stage 5. Florida Outlier Reef data are included as in Figure 7.

exposure during the last glacial period. Sea level reached a maximum level of -9.0±0.3 m MSL over the Outlier Reefs at ≈83 ka. While shallower than Barbados estimates by 4 to 9 m MSL, the Florida data, obtained from ideal, mineralogically-pristine *in situ* reefs on a stable margin, do not support the higher-than-present sea levels suggested by studies of other deposits and samples, especially those from Bermuda. The wide spread of ages derived from Bermuda samples translates to a lack of compelling evidence for a brief pulse of sea level to +1 m MSL during substage 5a. Analysis of the relationship between obliqutiy and precession peak timing suggests that the observed sea-level changes were orbitally-forced, and that insolation peak timing was consistent with interglacial reef growth at slightly lower-than-modern sea level during late Stage 5.

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REFERENCES

Bard, E., Hamelin, B. and Fairbanks, R. G., 1990, U-Th ages obtained by mass spectrometry in corals from Barbados: Sea level during the past 130,000 years: Nature, v. 346, 456-458.

Berger, A. and Loutre, M. F., 1991, Insolation values for climate of the last 10 million years: Quaternary Science Reviews, v. 10, p. 571-581.

Bloom, A. L., Broecker, W. S., Chappell, J. M. A., Matthews, R. K. and Mesollela, K., 1974, Quaternary sea level fluctuations on a tectonic coast: New $^{230}Th/^{234}U$ dates from the Huon Peninsula, New Guinea: Quaternary Research, v. 4, p. 185-205.

Bloom, A. L. and Yonekura, N., 1990, Graphic analysis of dislocated Quaternary shorelines, *in* Revelle, R., panel chairman, Sea Level Change: Studies in Geophysics, National Research Council, National Academy Press, Washington, DC, p. 104-115.

Carew, J. L. and Mylroie, J. E., 1995, Quaternary tectonic stability of the Bahamian Archipelago: Evidence from fossil reefs and flank margin caves: Quaternary Science Reviews, v. 14, p. 145-153.

Chappell, J., 1974, Geology of coral terraces, Huon Peninsula, New Guinea: A study of Quaternary tectonic movements and sea-level changes: Geological Society of America Bulletin, v. 85, p. 553-570.

Chen, J. H., Curran, H. A., White, B. and Wasserburg, G. J., 1991, Precise chronology of the last interglacial period: ^{234}U-^{230}Th data from fossil coral reefs in the Bahamas: Geological Society of America Bulletin, v. 103, p. 82-97.

Edwards, R. L., Chen, J. H., Ku, T.-L. and Wasserburg, G. J., 1987, Precise timing of the last interglacial period from mass spectrometric determination of Thorium-230 in corals: Science, v. 236, p. 1547-1553.

Enos, P., 1977, Holocene sediment accumulations of the south Florida shelf margin, *in* Enos, P. and Perkins, R. D., Quaternary Sedimentation in South Florida: Geological Society of America Memoir, 147, p. 1-130.

Gallup, C. D., Edwards, R. L. and Johnson, R. G., 1994, The timing of high sea levels over the past 200,00 years: Science, v. 263, p. 796-800.

Harmon, R. S., Schwarcz, H. P. and Ford, D. C., 1978, Late Pleistocene sea level history of Bermuda: Quaternary Research, v. 9, p. 205-218.

Harmon, R. S., Mitterer, R. M., Kriasakul, N., Land, L. S., Schwarcz, H. P., Garrett, P., Larson, G. J., Vacher, H. L. and Rowe, M., 1983, U-series and amino-acid racemization geochronology of Bermuda: implications for eustatic sea-level fluctuation over the past 250,000 years: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 44, p. 41-70.

Hubbard, D. K., 1994, SCARID Drilling System Manual: National Undersea Research Program, Caribbean Marine Research Center, Vero Beach, Florida.

Ku, T.-L., Kimmel, M., Easton, W. H. and O'Niel, T. J., 1974, Eustatic sea level 120,000 years ago on Oahu, Hawaii: Science, v. 183, p. 959-962.

Ku, T.-L., Ivanovich, M. and Luo, S., 1990, U-series dating of last interglacial high sea stands: Barbados revisited: Quaternary Research, v. 33, p. 129-147.

Lee, T. N., Rooth, C., Williams, E., McGowan, M., Szmant, A. F. and Clarke, M. E., 1992, Influence of the Florida Current, gyres and wind-driven circulation on transport of larvae and recruitment in the Florida Keys coral reefs: Continental Shelf Research, v. 12, p. 971-1002.

Li, W.-X., Lundberg, J., Dickin, A. P., Ford, D. C., Schwarcz, H. P., McNutt, R. and Williams, D., 1989, High-precision mass spectrometric uranium-series dating of cave deposits and implications for paleoclimate studies: Nature, v. 339, p. 534-536.

Lidz, B., Hine, A. C., Shinn, E. A. and Kindinger, J., 1991, Multiple outer-reef tracts along the south Florida bank margin: Outlier reefs, a new windward margin model: Geology, v. 19, p. 115-118.

Lighty, R. G., Macintyre, I. G. and Stuckenrath, R., 1982, *Acropora palmata* reef framework: A reliable indicator of sea level in the western

Atlantic for the past 10,000 years: Coral Reefs, v. 1., p. 125-130.

Ludwig, K. R., Muhs, D. R., Simmons, K. R., Halley, R. B. and Shinn, E. A., 1996, Sea-level records at ~80 ka from tectonically stable platforms: Florida and Bermuda: Geology, v. 24, p. 21-24.

Lundberg, J. and Ford, D. C., 1994, Late Pleistocene sea level change in the Bahamas from mass spectrometric U-series dating of submerged speleothem: Quaternary Science Reviews, v. 13, p. 1-14.

Mesollela, K. J., Matthews, R. K., Broecker, W. S. and Thurber, D. L., 1969, The astronomical theory of climate change: Barbados data: Journal of Geology, v. 77, p. 250-274.

Mullins, H. T. and Lynts, G. W., 1977, Origin of Northwestern Bahama Platform: review and reinterpretation: Geological Society of America Bulletin, v. 88, p. 1447-1461.

Neumann, A. C. and Moore, W. S., 1975, Sea level events and Pleistocene coral ages in the northern Bahamas: Quaternary Research, v. 5, p. 215-224.

Neumann, A. C. and Macintyre, I. G., 1985, Reef response to sea level rise: keep-up, catch-up or give-up: Proceedings, 5th International Coral Reef Congress, Tahiti, v. 3, p. 105-110.

Richards, D. A., Smart, P. L. and Edwards, R. L., 1994, Maximum sea levels for the last interglacial period from U-series ages of submerged speleothems: Nature, v. 367, p. 357-360.

Robbin, D. M., 1984, A new Holocene sea level curve for the upper Florida Keys and Florida reef tract, *in* Gleason, P., ed., Environments of South Florida, Present and Past, Miami Geological Society, Miami, p. 437-458.

Rossinsky, V. and Swart, P. K., 1993, Influence of climate on the formation and isotopic composition of calcretes, *in* Swart, P. K, Lohmann, K. C., McKenzie, J. and Savin, S., eds., Climate Change in Continental Isotopic Records: Geophysical Monograph 78, American Geophysical Union, p. 67-76.

Toscano, M. A., 1992, Record of oxygen isotope stage 5 on the Maryland inner shelf and Atlantic Coastal Plain-A post-transgressive highstand regime, *in* Fletcher, C. H. III and Wehmiller, J. F., eds., Quaternary Coasts of the United States: Marine and Lacustrine Systems: SEPM (Society for Sedimentary Geology) Special Publication 48, p. 89-100.

Toscano, M. A., 1996, Late Quaternary stratigraphy, sea-level history, and paleoclimatology of the southeast Florida outer continental shelf. Ph.D. dissertation, Department of Marine Science, University of South Florida, St. Petersburg, Florida, 280 pp.

Toscano, M. A. and York, L. L., 1992, Quaternary stratigraphy and sea level history of the U. S. Middle Atlantic Coastal Plain: Quaternary Science Reviews, v. 11, p. 301-328.

Vacher, H. L. and Hearty. P. H., 1989, History of stage 5 sea level in Bermuda: Review with new evidence of a brief rise to present sea level during substage 5a: Quaternary Science Reviews, v. 8, p. 158-168.

Wehmiller, J. F., York, L. L., Belknap, D. F. and Snyder, S. W., 1992, Theoretical correlations and lateral discontinuities in the Quaternary aminostratigraphic record of the U. S. Atlantic Coastal Plain: Quaternary Research, v. 38, p. 275-291.