2001

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Recommended Citation

White, Brian; Curran, H. Allen; and Wilson, Mark A., "A Sea-Level Lowstand (Devil's Point Event) Recorded in Bahamian Reefs: Comparison with Other Last Interglacial Climate Proxies" (2001). Geosciences: Faculty Publications, Smith College, Northampton, MA.
https://scholarworks.smith.edu/geo_facpubs/81

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REPRINTED FROM:

Benjamin J. Greenstein and Cindy K. Carney (eds.), 2001, *Proceedings of the 10th Symposium on the Geology of the Bahamas and Other Carbonate Regions:* San Salvador, Gerace Research Center, p. 109-128.

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ABSTRACT

The climate of the Last Interglacial may provide a yardstick with which to compare the present interglacial and possible human impacts on its past and future climate. Some proxies for the Last Interglacial climate have indicated a climate subject to rapid fluctuations, but most such proxies lack a sufficiently refined time scale and/or stratigraphic detail to accurately pinpoint millennial or shorter Last Interglacial climatic events. However, well-preserved fossil corals may provide sea-level data (a climate proxy) within a detailed time frame. For this purpose, the Bahamian Devil's Point (Great Inagua Island) and Cockburn Town (San Salvador Island) fossil reefs have the following desirable characteristics: tectonic stability precluding the need to assume rates of uplift; a dry climate favoring preservation of primary coralline aragonite suitable for TIMS dating; Last Interglacial sea temperatures warm enough for coral growth throughout the entire sea-level highstand; outstanding present-day outcrop exposures. This is not the case for other areas such as the Huon Peninsula of Papua, New Guinea (tectonic uplift and diagenetic alteration); Florida (humid climate leading to diagenetic alteration); Western Australia (cool waters restricting Last Interglacial coral growth).

The favorable factors for the Bahamian fossil reefs have allowed us to combine precision age dating and detailed stratigraphic field work to discover a significant, short-lived sea-level excursion, the Devil's Point Event (DPE), during the Last Interglacial that implies rapid sea-level change resulting from equally rapid climate cooling and subsequent warming. The DPE is used to elucidate other Last Interglacial coral records reported in the literature. In addition, this well-dated event serves as a calibration point for the time scales associated with other Last Interglacial climate proxies, e.g., ice cores and the stable isotope stratigraphy of deep-sea sediments. For example, there has been considerable controversy regarding the validity of the rapid climate fluctuations reported for the Last Interglacial based on studies of the GRIP ice core recovered from the Greenland ice cap. Comparison with the climate changes recorded in the Bahamian coral reefs suggests that the GRIP ice core record can be extended reliably back through much of the Last Interglacial. Both the fossil coral and ice core records indicate that the warm climate of the Last Interglacial was interrupted by at least one approximately thousand-year-long cold interval.

INTRODUCTION

There is considerable interest in using the climate of the Last Interglacial period as a yardstick with which to compare the present interglacial and possible human impacts on its past and future climate. Some proxies for the Last Interglacial climate have indicated a climate subject to rapid fluctuations, others have not. Many proxies lack a sufficiently refined time scale to accurately pinpoint millennial or shorter Last Interglacial climatic events, e,g., ice cores, deep-sea sediments. Well-preserved fossil corals, on the other hand, simultaneously provide sea-level data (a climate proxy in tectonically stable areas) and a detailed time frame. We summarize here the results of studies of two Bahamian fossil coral reefs located in an area with the following characteristics: tectonic stability precluding the need to assume rates of uplift; a dry climate favoring preservation of primary coralline aragonite used in TIMS dating; Last Interglacial sea temperatures warm enough for coral growth throughout the entire sea-level highstand; and outstanding present-day outcrop exposures. These factors have allowed us to combine precision age dating and detailed stratigraphic field work to discover a significant, short-lived sea-level excursion (the Devil's Point Event [DPE]) during the Last Interglacial that implies rapid sea-level change resulting from equally rapid climate cooling and subsequent warming. A major aspect of this paper is a review of the literature of some other potential Last Interglacial climate proxies, including fossil corals from tectonically stable and unstable areas, deep-sea sediments and ice cores. In addition to its intrinsic importance, we believe that the well-dated DPE can serve as a calibration point for the time scales associated with other climate proxies, and we discuss various Last Interglacial sequences in the context of the DPE in an attempt to correlate and refine the timing of apparent Last Interglacial climate fluctuations.

The interval between the two most recent glaciations is variously known as the Eemian in Europe, the Sangamon in North America, substage 5e on the marine isotope scale (MIS) and the last interglacial. We have generally used the term Last Interglacial to designate this interval, although we have used some of the other terms in discussing the literature where they are more appropriate.

THE DEVIL'S POINT EVENT

The Devil's Point Fossil Reef, Great Inagua Island

A planar, wave-cut erosion surface separates older and younger fossil corals (herein named 5eII and 5eI reefs respectively – numbers increase towards the past to conform with the MIS numbering scheme) within the Devil's Point fossil coral reef of Last Interglacial age on Great Inagua Island in the southeastern Bahamas (Figure 1; Chen et al., 1991). This surface can be traced laterally to a prominent erosional disconformity within contiguous outcrops of the Devil's Point fossil reef. We call the fall and subsequent rise of sea level that produced this disconformity, and

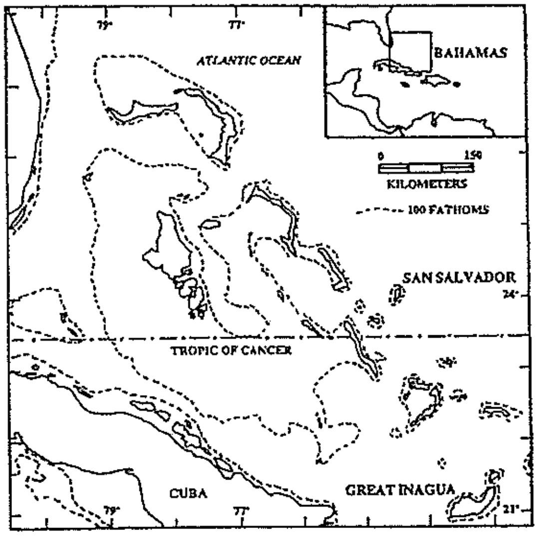

Figure 1. Location of San Salvador and Great Inagua islands.

associated features, the Devil's Point Event (DPE). The planar wave-cut surface exhibits many *in situ* 5eII fossil corals, including *Montastraea "annularis"* and *Diploria* spp., that have lost several decimeters of their original height by erosional truncation during the DPE sea-level lowstand. The surface of the erosional disconformity has well developed rhizomorphs, in some cases directly on top of planed-off 5eII corals, which were produced by terrestrial plants during the emergence phase of the DPE. These plant trace fossils are encrusted and overlain by *in situ* 5eI fossil corals that recolonized the erosional surface when sea level rose again (White et al., 1998). The younger fossil corals grew in a shallow subtidal environment, which contained fossil patch reefs and marine carbonate sands, forming the base of a shallowing-upward sequence that passes stratigraphically upward into beach deposits overlain by wind-deposited sands. The facies change from shallow subtidal to nearshore terrestrial reflects falling sea level resulting from the growth of land-based ice sheets in the early stages of the most recent glaciation (White and Curran, 1995).

The Cockburn Town Fossil Reef, San Salvador Island

That the DPE was not a localized phenomenon is shown by the occurrence of a similar discontinuity of the same age and at the same stratigraphic position in the well-known fossil coral reef at Cockburn Town on San Salvador Island in the central Bahamas, some 330 km to the north-northwest of Great Inagua (Figure 1; White et al., 1998, Wilson et al., 1998).

The gently undulating erosional disconformity surface within the Cockburn Town fossil reef is cut in places by karstic caves and erosional channels that formed during the sea-level lowstand. Following the subsequent sea-level rise, these cavities were filled by subtidal sands, which in some places have red paleosols overlying the fissures and the infilling sediments. Such paleosols mark the boundary between the Pleistocene and Holocene (Carew and Mylroie, 1995a), and they provide further proof of the Pleistocene age of these features (White et al., 1998). Large lithophagid borings in the disconformity surface contain an internal stratigraphy of cemented marine sands overlain by a thin layer of reddened paleosol and followed by marine bivalves (Wilson et al., 1998). This sequence encapsulates in miniature the regression-transgression pattern of the DPE. In places, lithophagid and associated sponge borings are overlapped by encrusting *in situ* corals belonging to the younger 5eI reef (Wilson et al., 1998). As in the Devil's Point fossil reef, rhizomorphs occur directly on eroded 5eII corals on the disconformity surface at the Cockburn Town fossil reef. These plant trace fossils are in some cases directly overlain by younger corals that form the base of a shallowing-upward sequence of subtidal to beach to wind-deposited carbonate sediments.

Age of the Devil's Point Event

Preservation of pristine original aragonite allowed precise age determinations of corals from the Devil's Point and Cockburn Town fossil reefs by TIMS U/Th analyses (Chen et al., 1991). Detailed stratigraphic control of the reefal sequences permits us to separate precisely dated corals into 5eII reefs which grew before the DPE sea-level fall and 5eI reefs that recolonized the eroded surface of 5eII reefs during the ensuing marine transgression (Table 1). These data show a time window of 1,500 years or less at approximately 125 to 124 ka, during which the DPE occurred.

Species	Locality	Reef	$\delta^{234}U(T)$	Age Ka
Montastraea “annularis”	San Salvador	5eI	149.4±6.8	119.9±1.4
Diploria strigosa	San Salvador	5eI	161.6±8.0	120.7±1.5
Montastraea “annularis”	San Salvador	5eI	155.7±7.7	122.0±1.5
Montastraea “annularis”	Great Inagua	5eI	148.2±4.2	122.1±1.3
Montastraea “annularis”	Great Inagua	5eI	149±4	122.2±1.3
Montastraea “annularis”	San Salvador	5eI	156.0±4.5	122.3±1.0
Acropora palmata	San Salvador	5eI	159.9±6.7	122.7±1.4
Montastraea “annularis”	Great Inagua	5eI	155.0±6.7	122.8±1.6
Diploria clivosa	San Salvador	5eI	160.7±4.9	123.3±1.3
Diploria clivosa	Great Inagua	5eI	147.4±6.9	123.3±1.5
Diploria clivosa	Great Inagua	5eI	148±7	123.4±1.5
Diploria strigosa	San Salvador	5eI	155.4±5.9	123.6±1.2
Diploria strigosa	Great Inagua	5eI	142.9±5.0	123.8±1.1
Montastraea “annularis”	Great Inagua	5eI	146.7±7.6	123.8±1.5
Acropora palmata	San Salvador	5eI	154.5±6.4	123.8±1.7
Acropora palmata	San Salvador	5eI	163.8±7.2	124.0±1.6
Montastraea “annularis”	San Salvador	5eI	154.6±6.1	124.2±1.2
Devil’s Point Event (DPE)				
Montastraea “annularis”	Great Inagua	5eII	153.9±4.5	124.9±2.1
Montastraea “annularis”	Great Inagua	5eII	154±4	125.1±2.1
Acropora palmata	San Salvador	5eII	158.2±8.3	125.3±1.7
Diploria strigosa	Great Inagua	5eII	156.9±8.3	125.4±1.7
Montastraea “annularis”	San Salvador	5eII	158.4±5.9	127.2±1.5
Montastraea “annularis”	San Salvador	5eII	163.7±4.8	127.3±1.0
Diploria strigosa	San Salvador	5eII	148.1±5.8	127.9±1.2
Montastraea “annularis”	Great Inagua	5eII	154.1±4.5	128.4±1.2
Montastraea “annularis”	San Salvador	5eII	163.9±4.8	128.5±1.0
Acropora palmata	Great Inagua	5eII	158.5±4.9	130.3±1.3
Diploria clivosa	San Salvador	5eII	152.3±5.2	130.4±1.1

Table 1. TIMS ages from the Devil’s Point reef, Great Inagua and the Cockburn Town reef, San Salvador separated into younger 5eI corals, which post-date the Devil’s Point Event (DPE) erosional disconformity and older 5eII corals, which predate the DPE. See Chen et al. (1991) for information about TIMS dating of corals.

Sea-level Changes During the Devil’s Point Event

In our stratigraphic studies we use the position of modern mean sea level as a survey datum. This allows us to determine the relative changes of sea level during the DPE (Figure 2). The highest 5eII marine deposits are 2.25 m above present mean sea level. These are erosionally truncated corals in growth position. Thus, some of the original upper parts of the coral reefs and any marine sediments which may have overlain them as a result of the regression are missing due to erosion during the DPE. The lowest sea-level position reached during the DPE regression is not known. Trace fossils produced by terrestrial plants and evidence of soil formation occur on the erosional surface down to at least present mean sea level. For the plants to have grown out of the reach of killing salt water, the sea level must have been at least 0.75 m below present levels. Thus, sea level prior to the DPE regression was at least 3 m higher than

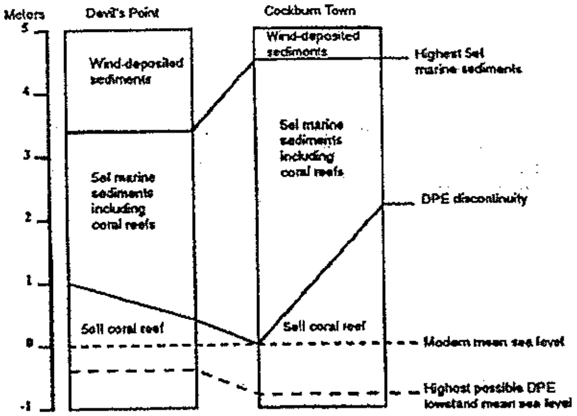

Figure 2. Changes of relative sea level during the Devil's Point Event

the lowstand level. Marine sediments deposited during the subsequent transgression occur up to 4.5 m above present sea level and at least 5.25 m above the lowstand level. This implies rapid rates of sea-level change that may have approached 100 mm per year (White et al., 1998).

During the late Quaternary the Bahamian Archipelago has been tectonically stable, but subsiding isostatically at a rate of 1 to 2 cm per 1,000 years (Carew and Mylroie, 1995a, 1995b, 1999). This rate is insufficient to affect the relative sea levels determined above for the DPE. However, it does provide a method of estimating absolute sea levels for the DPE data. Using this subsidence rate for the approximately 125, 000 years that have elapsed since the DPE, the Bahamas archipelago should have subsided some 1.25 to 2.50 m. Sea level prior to the DPE was at least 3.5 to 4.75 m above present sea level. Because the upper part of the 5eII sequence is erosionally truncated, this is a minimum height. A more precise determination awaits the discovery of a more complete 5eII sequence. The highest possible sea level during the DPE regression was 0.50 to 1.75 m above present sea level, and it probably was somewhat lower than that. Sea level rose to 5.75 to 7 m above present mean sea level during the growth of 5eI coral reefs and the deposition of associated marine sediments.

OTHER LAST INTERGLACIAL FOSSIL CORAL REEFS

Tectonically Stable Regions

In tectonically stable regions past changes in sea level cannot be explained by uplift or down faulting of fossil coral reefs, so they must reflect eustatic sea-level fluctuations. Relevant Last Interglacial fossil coral reef occurrences from such stable areas are examined in the following sections.

The Bahamas.

The detailed history established for the Devil's Point and Cockburn Town fossil reefs permits increased understanding of other fossil reefs found in the Bahamas. The Sue Point fossil patch reef on San Salvador (White, 1989) has dated corals that are younger than the age of the DPE lowstand of sea level (Chen et al., 1991). This is true also for reefs found on several islands in the southern Bahamas (Halley et al., 1991). It may be that some 5eII coral reefs were subsequently eroded during the DPE lowstand and that fossil 5eI coral reefs of post-DPE age are more likely to have been preserved. Older 5eII corals can be expected to have had a more complex diagenetic history than the younger 5eI corals, thus decreasing the chances that reliable TIMS ages can be obtained. These factors may be true for Last Interglacial coral reefs of other passive margins, e.g. Western Australia.

Florida.

An erosional discontinuity of unknown origin occurs within a fossil coral sequence of the Key Largo Formation of the Florida Keys, another area of tectonic stability (Fruijtier et al., 2000). TIMS ages of corals from immediately below the erosion surface are 125.1 and 126.0 ka and the authors correlate the disconformity with the one described here from Great Inagua and San Salvador. Ages of corals from above the disconformity are some 5 ka older than those from below, and this anomalous situation is explained as being due to diagenetic alteration of the fossil corals and a consequent increase in the measured ages. The disconformity is at approximately 3.2 m above present mean high tide. It is suggested that 125 ka is the maximum age of a short-lived sea-level lowstand within the last-interglacial (5e) highstand (Fruijtier et al., 2000).

Caribbean.

A brief report suggested that the late Pleistocene Falmouth Formation on Jamaica is comprised of two shallowing-upward parasequences that represent reefal development during two separate sea-level highstands of substage 5e (Precht, 1993). Uranium-series dating of aragonitic corals showed that the lower parasequence corresponds to a sea-level highstand at 134-127 ka, and the upper sequence to a highstand at 124-119 ka. Further research may reveal that these two parasequences are separated by the DPE.

The Mediterranean Region.

A significant erosional disconformity is present within a sequence of coastal deposits, including fossil coral reefs, exposed along the shores of the Red Sea (Plaziat et al., 1998). A Last Interglacial age is confirmed by U/Th dates that range from 115 to 125 ka. This disconformity may have been produced by the same series of sea-level changes that caused the intra-reefal disconformity in the Bahamian fossil reefs; however, the published ages do not permit discrimination of the units from beneath and above the disconformity.

Seychelles.

Patches of limestones, including fossil corals, occur as encrustations and cavity-fillings of granitic boulders at the Pte Source d'Argent section on La Digue Island in the tectonically stable Seychelles Islands (Israelson and Wohlfarth, 1999). Different elevations for the locations of TIMS-dated corals are given in their Tables 3 and 4 and Fig. 4, making comparisons with sea-level indicators from elsewhere difficult. However, the vertical relationships can be ascertained and all corals appear to be lower than 4 m above present sea level. The topographically highest corals range in age from approximately 126 to 131 ka. A meter or so lower, corals overlie an erosion surface and are dated at approximately 122 to 124 ka. The inverted stratigraphic relationships are explained as being due to successive coral growth during a sea-level regression and the erosion surface is attributed to a storm (Israelson and Wohlfarth, 1999). An alternative explanation would be that the erosion surface represents the DPE and the two distinct coral populations grew during two separate highstands within the Last Interglacial.

Western Australia.

Last Interglacial coral reefs developed at various locations along the tectonically stable coast of Western Australia. TIMS dating of coral samples collected from above present sea level at widely scattered localities in the Houtman-Abrolhos islands yielded four reliable ages ranging from approximately 116 to 124 ka (Zhu et al., 1993), i.e. younger than the DPE. Other precisely dated corals from the Houtman-Abrolhos islands indicate that sea level rose above present levels between 130 and 127 ka, reached a maximum of at least 3.3 m above present at approximately 124 ka, and fell below present datum at approximately 116 ka. No evidence of a sea-level excursion was noted, but the duration of any such undetected

Sample #	Location	Elevation	$\delta^{234}U(T)$	Age in ka	vs DPE
RN-FB-3	Rottnest Is.	+ 0.45m	152±1	123.5±0.8	Post
RN-FB-4	Rottnest Is.	+ 1.77m	150±2	126.2±0.8	Pre
RN-FB-6	Rottnest Is.	+ 1.83m	154±2	125.4±0.9	Pre
RN-FB-7a	Rottnest Is.	+ 2.43m	150±1	127.3±1.0	Pre
RN-FB-7b	Rottnest Is.	+ 2.43m	151±2	126.0±0.8	Pre
LP-91-1b	Leander Pt.	+ 2.16m	150±2	126.6±0.9	Pre
LP-93-3	Leander Pt.	+ 1.67m	154±2	121.8±0.8	Post
LP-93-4	Leander Pt.	+ 1.28m	153±2	123.7±0.8	Post
LP-93-5	Leander Pt.	+ 0.70m	154±2	123.8±0.9	Post
LP-93-6	Leander Pt.	+ 1.80m	154±3	123.3±0.9	Post
LP-93-8	Leander Pt.	+ 0.68m	153±3	124.2±0.9	Post
LP-93-10	Leander Pt.	+ 2.20m	171±3	123.3±0.9	Post

Table 2. U/Th ages for West Australia fossil corals (modified after Stirling et al., 1995). Restricted to samples with dates regarded as reliable by Stirling et al. (1995).

regressions was constrained to 1.0 ka, or less (Eisenhauer et al., 1996).

TIMS data from widely separated coastal regions of Western Australia indicate Last Interglacial coral growth restricted to 128 to 121 ka (Stirling et al., 1995; 1998; Tables 2 and 3 of this paper), a shorter interval than recorded in Bahamian reefs. Sea-water temperature is one of the factors limiting coral growth in this region, and coral reefs do not grow there during the present interglacial in some of the locations where Last Interglacial reefs developed (James et al., 1999; Veron, 1995). Thus, sea level may have been higher for a longer interval during the Last Interglacial, with only part of that time having sea temperatures warm enough for coral growth. Interestingly, all but one of the reliable coral ages from Rottnest Island are older than the DPE. All reliable coral ages from Burney Point and, with one exception, from nearby Leander Point some 400 km to the north of Rottnest Island are younger (Stirling et al., 1995; 1998). Coral reef formation may have been restricted to the earlier part of the Last Interglacial in the more southerly, and cooler, part of the Perth Basin, whereas the reefs in the northern part are dominantly post-DPE in age. Thus, individual reef exposures of the Perth Basin may not encompass coral reef growth during the whole of the Last Interglacial, or incorporate evidence of the sea-level excursion recorded in the Bahamian reefs. Farther north in the Carnarvon Basin, Last Interglacial corals are more affected by diagenesis, perhaps due to higher rainfall. Reliable ages from localities adjacent to the Cape Range Peninsula range from approximately 115 to 129 ka (Stirling et al., 1998). Both reliable coral ages from Tantabiddi Bay and three out of four from Mangrove Bay are younger than the DPE; whereas four out of five corals

Sample #	Location	Elevation	$\delta^{234}U(T)$	Reliability	Age in ka	vs DPE
GR-93-1	Burney Pt.	+ 1.73m	153±2	Good	122.2±0.4	Post
GR-93-2	Burney Pt.	+ 3.09m	151±3	Good	123.5±0.5	Post
GR-93-3	Burney Pt.	+ 3.00m	148±2	Good	121.7±0.5	Post
GR-93-4	Burney Pt.	+ 3.04m	147±2	Good	123.0±0.5	Post
CR-VH-26	Vlaming Hd.	+ 1.71m	157±2	OK	115.0±0.4	Post
CR-TB-5	Tantabiddi	+ 1.24m	166±7	OK	120.3±1.3	Post
CR-TB-9	Tantabiddi	+ 1.20m	156±2	OK	124.3±0.4	Post?
CR-MB-3b	Mangrove Bay	+ 1.35m	152±2	Good	119.2±0.5	Post
CR-MB-7f	Mangrove Bay	+ 0.47m	152±2	Good	118.2±0.5	Post
CR-MB-12f	Mangrove Bay	+ 0.36m	151±2	Good	116.1±0.3	Post
CR-YC-3	Yardie Creek	+ 2.72m	149±2	Good	121.1±0.6	Post
CR-YC-7p	Yardie Creek	+ 3.27m	146±2	Good	119.8±0.4	Post
CR-YC-12	Yardie Creek	+ 2.44m	155±4	Good	121.1±0.7	Post
CR-YCS-6	Yardie Creek	+ 1.87m	151±3	Good	121.6±0.5	Post
CR-VH-7	Vlaming Hd.	+ 3.08m	161±2	OK	128.5±0.5	Pre
CR-VH-22b	Vlaming Hd.	+ 0.92m	152±3	Good	125.4±0.6	Pre
CR-VH-28	Vlaming Hd.	+ 2.88m	161±2	OK	126.5±0.5	Pre
CR-MB-6b	Mangrove Bay	+ 1.79m	158±2	OK	125.4±0.5	Pre
CR-YC-9	Yardie Creek	+ 2.37m	154±2	Good	126.8±0.3	Pre
CR-YC-13	Yardie Creek	+ 2.44m	163±6	OK	128.9±1.1	Pre
CR-YCS-1	Yardie Creek	+ 2.30m	150±2	Good	124.7±0.4	Pre
CR-YCS-5a	Yardie Creek	+ 0.70m	158±2	OK	128.6±0.4	Pre
CR-VH-D4	Drillcore coral	+ 1.18m	159±2	OK	124.9±0.4	Pre

Table 3. U/Th ages for West Australia fossil corals (modified after Stirling et al., 1998). Duplicates and samples not considered reliable or samples from below present sea level removed. This table rearranged to show relationship to the Devil's Point Event using 124 ka as the cut-off.

from Vlaming Head are older. The eight reliable dates from Yardie Creek are equally divided between pre- and post- DPE ages, but their precise stratigraphic relationships are not given (Stirling et al., 1998), and evaluation in the context of the DPE cannot be made.

Tectonically Unstable Regions

Other studies of fossil coral reefs that bear on the question of sea-level fluctuations during the Last Interglacial are based on examination of tectonically uplifted reef terraces in New Guinea and elsewhere. Older reefs that would otherwise be submerged may be raised above present sea level by tectonic uplift, thus making them more easily studied. Disadvantages include difficulties in determining rates of uplift that are needed to make estimates of the rate of sea-level change, and freshwater diagenesis of aragonitic corals that prevents accurate radiometric age dating.

Indonesia.

Studies of uplifted reef terraces on Timor and Atauro Island indicated a sea-level high at approximately 131 ka and a younger one at approximately 119 ka. The two sea-level highstands were believed to be separated by a regression of perhaps 7 to 15 meters (Chappell and Veeh, 1978).

New Guinea.

Similar results were obtained by Aharon et al. (1980) from the Huon Peninsula, New Guinea, with highstands reported at 133 ± 4 ka (reef VIIa) and 120 ± 3 ka (reef VIIb). Reefs VIIa and VIIb were thought to be separated by an erosional disconformity. The dating of these deposits was not precise enough to directly compare this disconformity with those found in Bahamian reefs; however, the data indicate that the VIIa reef pre-dates the DPE and the VIIb reef post-dates it. The outcrop containing the disconformity was visited by an international expedition in 1988. Although this disconformity surface suggested interruption in reef growth, no evidence of subaerial exposure was found and the question of whether sea level fell between the growth of reefs VIIa and VIIb was not resolved (Stein et al., 1993).

More recent studies of uplifted coral terraces at the Huon Peninsula suggested that sea level was 60 to 80 m lower than present at 130 ± 2 ka, but that it rose very rapidly to approximately present levels by 129 ka (McCulloch et al., 1999). This contrasts with the age data from Bahamian coral reefs which indicate that sea level was a few meters above present levels at 128-132 ka and that no such extremely rapid sea-level rise actually occurred. A discontinuity is shown within the Last Interglacial reef in Figure 1 of McCulloch et al. (1999); however; it is not discussed in their text. The Last Interglacial reef at the Huon Peninsula is also discussed in a companion paper (Esat et al., 1999). In their Figure 1 a disconformity is shown within the Kwambu profile of reef terraces that appears similar to the one shown in the figure previously mentioned (McCulloch et al., 1999). In addition, a profile is shown from Kwangam that also contains a disconformity within the Last Interglacial reef. In the caption for this diagram it is noted that this disconformity was observed on the eastern side of Kwangam gorge and that it is believed to separate two transgressive sequences within the Last Interglacial reef. In a footnote the disconformity is described as a fairly planar surface traceable for about 30 m. Corals in growth position occur separately beneath and above the break, but do not grow vertically across it. These are some of the characteristics of the discontinuity found in Bahamian coral reefs on Great Inagua and San Salvador islands. The disconformity present in the Last Interglacial reef at the Huon Peninsula may have been produced during the DPE, although no relevant age data are given to allow evaluation of this possibility.

Barbados.

A few reliable coral ages are reported from the uplifted reef terraces of Barbados.

Gallup et al., (1994) concluded that an *A. palmata* cobble with an age of 117.0±1.8 ka from a deposit that stratigraphically overlies the Last Interglacial forereef records sea-level regression following the Last Interglacial. They also found no evidence of a high sea level prior to 130 ka. Edwards et al. (1997) used a combination of TIMS protactinium and thorium dating to more precisely determine the age of coral samples. The study included five samples from Barbados with concordant ages indicating that sea level was relatively high at 121.0±2.1 and 126.8±2.5 during the Last Interglacial. Thus the age data from Barbados are consistent with those from the Bahamas, but lack the stratigraphic information needed to evaluate the presence or absence of the DPE.

OTHER INDICATIONS OF LAST INTERGLACIAL CLIMATE INSTABILITY

Deep-Sea Data

Numerous attempts have been made to evaluate past climatic fluctuations based on paleontologic, geochemical and sedimentologic analyses of deep-sea sediment cores. A comprehensive survey of the vast literature is well beyond the scope of this paper; however, a brief survey of salient points of this important topic is attempted in order to place in context the data derived from fossil coral reefs.

A Chronology for Deep-Sea Sediments.

A commonly used chronology for deep-sea sediments was developed by Martinson et al. (1987). Two fundamental assumptions are made in developing this chronology. The first is that Pleistocene climatic fluctuations are determined by changes in the orbital parameters of the earth with respect to the sun (commonly called Milankovitch cycles) and that an accurate time scale for these astronomic cycles can be determined. The second is that the geochemical composition, especially the oxygen isotope ratios, of deep-sea sediments is a function of climatically determined terrestrial ice volume. This parameter commonly is measured from the tests of foraminifera. Martinson et al. (1987) used four orbital tuning methods to establish a chronology yielding an average error of ± 2500 years. This was compared with five paleoclimate measures from a core record which generated an independent chronology with an error of ± 3500 years, close to the 2500 year estimate. Transferring the final chronology to the stacked record of $\delta^{18}O$ paleoclimate records of Pisias et al. (1984) added another ± 1500 years, producing a final chronology with an average error of ± 5000 yr. Errors vary with depth. Our Table 4 is extracted from Table 2 of Martinson et al. (1987) for the time interval of most interest in this paper. These are age estimates based on the final chronology determined for the stacked isotope record of Pisias et al. (1984). The basic idea is that by measuring the $\delta^{18}O$ of deep-sea sediments, the age of the sediments can be determined by comparison with the tabulation of Martinson et al. (1987).

Evidence of Climatic Fluctuations During the Last Interglacial.

Variations in the oxygen isotope ratios of deep-sea sediments are reported from the interval that corresponds generally to the Last Interglacial. Comparing such observed changes with those determined from coral reef data is complicated by at least two important factors. The first is the relative insensitivity of the chronology of Martinson et al. (1987), which cannot accurately date small-scale fluctuations in $\delta^{18}O$. For example, Bauch et al. (1996) concluded that no reliable absolute chronology for deep-sea sediments older than about 50,000 years is presently available. In a comprehensive review of the duration of in-

Event	Depth (cm)	Age (yr.)	Error (±yr.)	$\delta^{18}O$ - normalized
5.33	772.6	107,550	4510	- 0.02
5.4	780.0	110,790	6280	- 0.02
5.4	783.4	112,280	7100	- 0.02
5.4	795.0	115,910	6280	0.25
5.4	804.4	118, 690	4910	0.57
5.4	816.0	122, 190	2350	0.76
5.51	818.0	122, 560	2410	0.74
5.51	824.7	123, 790	2610	0.69
5.5	825.0	123, 820	2620	0.69
5.5	834.8	125, 000	2960	0.72
5.53	836.0	125, 190	2929	0.66
5.53	844.6	126, 580	2640	0.27
5.53	855.3	128, 310	2670	-0.04
5.53	864.1	129, 700	3020	-0.25
6.0	865.0	129, 840	3050	-0.28
6.0	873.3	131, 090	3360	-0.57
6.0	884.9	132, 810	3730	-0.37
6.0	894.9	134, 230	4090	-0.71
6.2	901.0	135, 100	4240	-0.80

Table 4. Part of the time scale developed by Martinson et al. (1987) in the vicinity of the Last Interglacial.

terglacials, Winograd et al. (1997) concluded that the SPECMAP $\delta^{18}O$ time series underestimates the duration of the last interglaciation by thousands of years and is incorrectly dated in the vicinity of the marine isotope stage 6 and substage 5e/5d boundaries. The second problem is that the $\delta^{18}O$ of benthic and planktonic foraminifera is a function of both terrestrial ice volume and seawater temperature. Given these two variables, it becomes difficult to quantitatively relate changes in $\delta^{18}O$ to changes in eustatic sea level. Bauch et al. (1996) suggested that benthic oxygen isotope records cannot resolve minor sea-level changes during the Last Interglacial.

Nevertheless, many records of deep-sea sediments show evidence of fluctuations in benthic and planktonic $\delta^{18}O$ during the Last Interglacial (see for example Seidenkrantz et al., 1995; Bauch et al., 1996; Seidenkrantz and Knudsen, 1997; Pillans et al., 1998; Chapman and Shackleton, 1999). Interpretations of these $\delta^{18}O$ fluctuations are generally made based on the assumption that changes of ice volume were not a factor. They are attributed to changes in seawater temperatures arising either from climatic cooling and warming or changes in the thermohaline circulation of the oceans. Maslin et al. (1998) studied a core from off the coast of West Africa. They used the Martinson et al. (1987) time scale modified by shifting the MIS5/MIS6 boundary to an older age of approximately 130.3 ka. On this time scale the generally smooth Last Interglacial benthic $\delta^{18}O$ record is interrupted by one significant 'cool' event at 122 ka that lasted less than 400 years. Significant ice volume change was regarded as unlikely, and it was inferred that fluctuations in the benthic $\delta^{18}O$ record reflect seawater cooling and/or oceanic circulation changes. This cold event may well be equivalent to the DPE, given the errors involved in dating deep-sea sediments.

Clearly, it would be a significant development if techniques could be devised to directly determine the absolute age of deep-sea sediments. Slowey et al. (1996) measured TIMS ages of aragonite fines transported from the Bahamas platform to deeper water. Table 5 is based on their data. The Last Interglacial (Substage 5e) is identified by the extreme values of $\delta^{18}O$ of benthic foraminifera and extends between approximately 175 and 315 cm depth in their core. Based on these data, Slowey et al. (1996) concluded that the Last Interglacial lasted from appproximately 120 to 127 ka and supports the orbital theory of ice ages and the Stirling et al. (1995; 1998) hypothesis of a restricted period of coral growth during the Last Interglacial. These rather sweeping conclusions are based on only five samples, one of which is out of stratigraphic order (see Table 5 of this paper). Their oldest dated sample from the Last Interglacial is 127 ka from a sample at 287 cm, approximately 28 cm above the base of their Last Interglacial section. This leads to their suggestion that the Last Interglacial may have begun 1 to 2 ka earlier than their sample dated at 127 ka. Their youngest Last Interglacial sample is from 180 cm (not far from their MIS5/MIS4 boundary at approximately 175 cm) and has an age of 120.8±0.58 ka, suggesting that the Martinson et al. (1987) age for the end of the Last Interglacial is too young. Their plot of $\delta^{18}O$ shows an increase from - 1.2 at 270 cm to 0 at 280 cm followed by a decrease to – 1.0 at 287 cm. How much of these changes is related to fluctuations in sea-water temperatures or sea-level is unknown. The sharp increase in $\delta^{18}O$ at 280 cm may be related to DPE but the data are not sufficient to address this issue.

Henderson and Slowey (2000) state that there is a clear signature of MIS6/MIS5 in marine oxygen isotope records, but that dating the event has not been possible and that the timing of the 6/5e deglaciation is controversial. They date the mid-point of the deglaciation by TIMS dating of sediments from the Bahamas at 135±2.5 ka - some 8 ka older than Martinson et al. (1987). They believe this date for the deglaciation is broadly supported by coral data. The oldest reliably dated coral from the Cockburn Town fossil reef is 130.4±1.1 ka and from the Devil's Point fossil reef is 130.3±1.4 ka (Chen et al., 1991). This shows that sea level had risen to 1 or 2 meters above present levels by 130 to 131 ka and broadly supports the date for the deglaciation suggested by Henderson and Slowey (2000).

Ice Core Data

Greenland.

By comparison with the Holocene, it was generally believed that the Last Interglacial climate was stable. This assumption was challenged by $\delta^{18}O$ data from the GRIP ice-core, which showed that abrupt changes of temperature occurred in Greenland during that time (GRIP members, 1993; Johnsen et al., 1995). Three warm substages of (MIS) 5e with temperatures about 2°C higher than Holocene were identified and named 5e1 (about 3 ka long), 5e3 (<1 ka long), and 5e5

Sample depth cm	Location	$\delta^{234}U(T)$	Reliability	Age in ka
80	core 2	164±8	Reliable	71.6±1.03
120	core 2	136±4	Reliable	93.4±0.59
180	core 2	165±5	Reliable	120.8±5.8
200	core 2	160±3	Reliable	124.6±3.7
230	core 2	169±5	Reliable	124.5±2.4
270a	core 2	154±6	Reliable	121.5±3.2
270b	core 2	151±3	Reliable	121.4±3.5
287a	core 2	156±6	Reliable	127.0±4.8
287b	core 2	154±6	Reliable	124.1±5.1
510	core 2	137±8	Reliable	190.3±5.0
530	core 2	144±7	Reliable	190.0±5.7

Table 5. Modified from Slowey et al. (1996).

(about 2 ka long). Intervening cold substages 5e2 (about 1 ka long) and 5e4 (about 6 ka long) were approximately 5°C colder than Holocene. Durations are based on the time scale used by the authors. Considerable focus has been placed on two very cold spikes labelled Events 1 and 2 respectively, but these are not directly relevant to discussion of the DPE. These authors used Martinson et al. (1987) to set their time scale at 110 ka for the MIS-5e/5d boundary, which they think appears at 2788 m down in the core. Looking at the table of Martinson et al. (1987), the closest age to 110 ka is 110,790±6280 years. They believe that the core is undisturbed down to at least 2848 m, i.e. through most of the Eemian, and that their time scale is valid back to 130 ka, but before that is only a first approximation.

The validity of the GRIP ice core record for the Last Interglacial has been questioned, in part because another ice core (GISP2) taken some 30 km away does not show the Last Interglacial climatic fluctuations. Chappellaz et al. (1997) compared the methane content of ice from the GRIP, GISP2 and Vostok ice cores. They reviewed the GRIP vs GISP2 controversy. The two cores correlate well down to a depth of 2750 m and are both considered to be valid. Below that depth the cores differ and it is suggested that one or both are distorted. Chappellaz et al. (1997) measured the methane content of GRIP ice samples from 2790 to 2860 m, the supposed Eemian. They found a good match between $\delta^{18}O$ and methane, so the fluctuations were thought to be real. Methane values vary between 450 ppb (typical of glacial conditions) and 715 ppb (typical of interglacial conditions).

From 2781 to 2789 m the GRIP line seems to follow well the Vostok line, with corresponding EGT timescale age of 113 and 119 ka respectively. The two GRIP minima, 5e2 and 5e4, do not occur as low methane values in the Vostok ice core, leading Chappellaz et al. (1997) to conclude that they are not real signatures of cold intervals during the Last Interglacial and that the GRIP ice core record must be disturbed in some way. Chappellaz et al. (1997) note that no layer with identical isotopic and chemical signature is found twice in the GRIP ice core and that the visible layering has essentially unchanged tilt as far down as the early Eemian (at 2848 m). This appears to rule out the possibility of repetition of layers by folding. They suggest that the Eemian warm stages identified in the GRIP ice core are real and correspond to the period 118 to 128 ka of Vostok EGT chronology, covering the major part of the MIS-5e. They conclude, however, that the cold stages 5e2 and 5e4 are intrusions of cold ice from MIS-5d, or possibly from ice older than 5e. Ice from 2883 to 2901 m has methane and $\delta^{18}O$ values that indicate cold and fairly stable conditions, most likely reflecting MIS-6 between 138 ka (2883 m) and 142 ka (2901 m).

Steffensen (1997) studied the dust content of the GRIP ice core. He found a strong relationship between climate, as defined by $\delta^{18}O$, and dust concentration. In general, there is significantly more dust during colder intervals and sudden changes of climate correlate with sudden changes in dust concentration. Steffensen (1997) also found that the volume distributions of dust of both the "warm" and "cold" intervals in the Eemian are different from the distributions in ice from both below and above the Eemian ice. This implies that the "cold" interval ice in the Eemian is not derived from 5d or older ice.

Johnsen et al. (1997) made a detailed study to evaluate the possible intrusion or folding origin for "cold" periods in the Eemian. They determined that the compositional gradients at the transitions of the cold substages 5e2 and 5e4 are smooth and the dust concentrations over the transitions show no evidence of abrupt breaks. Thus they conclude that the cold strata of the Eemian sequence cannot be due to intrusion. They also ruled out the possibility of folding as an explanation because detailed continuous measurements of chemical parameters and dust showed no evidence for repeated layers in or near the Eemian section. The authors were unable to reconcile the methane data of Chappellaz et al. (1997) with the lack of evidence for mechanical causes of the cold intervals.

Steffensen et al. (1997) made detailed studies of the GRIP ice core, especially of the cold event known as ES1. They determined that the ice of ES1 has a unique chemical and isotopic signature not found elsewhere in the GRIP ice core. They find no layer in the vicinity of the Eemian ice that could be a source of ES1 ice. They conclude that ES1 is real and climatically determined, and that the data support the original interpretation of GRIP members (1993) that the Eemian climate in Greenland indeed was unstable.

In an earlier paper, we attempted to correlate the climatic fluctuations revealed by our studies of Bahamian coral reefs with those reported from the Last Interglacial section of the GRIP ice core (White et al., 1998). In doing so we assumed that the time scales for the fossil reefs and the ice core could be directly related. This meant that we correlated the DPE with cold substage 5e4, the subsequent sea-level rise and re-establishment of coral reefs with the warm substage 5e3 and the termination of reef growth to cold substage 5e2. We noted that there is no record in the coral reefs of warm substage 5e1. As noted above, there are significant error bars associated with the Martinson et al. (1987) chronology and thus of the Last Interglacial part of the GRIP ice core derived from the deep-sea chronology. It seems more likely that the DPE corresponds to cold substage 5e2 and that the subsequent sea-level rise corresponds to 5e1. This implies that the GRIP ice core chronology needs adjusting so that the 5e2 event occurred at approximately 124 ka and that the ice core is undisturbed at least down to the beginning of 5e4 at approximately 131 ka. Figure 3 shows the trends of oxygen isotopes for the Eemian section of the GRIP ice core with the beginning of the DPE marked by the sharp transition from 5e3 to 5e2. The change from 5e2 to 5e1 may be equivalent to the rise in sea level that led to the development of the 5eI reefs in the Bahamas. The rapid change from 5e1 to 5d in the ice core data corresponds to the rapid sea-level fall that led to the death of the Bahamian coral reefs and their entombment in regressive sands (White and Curran, 1995).

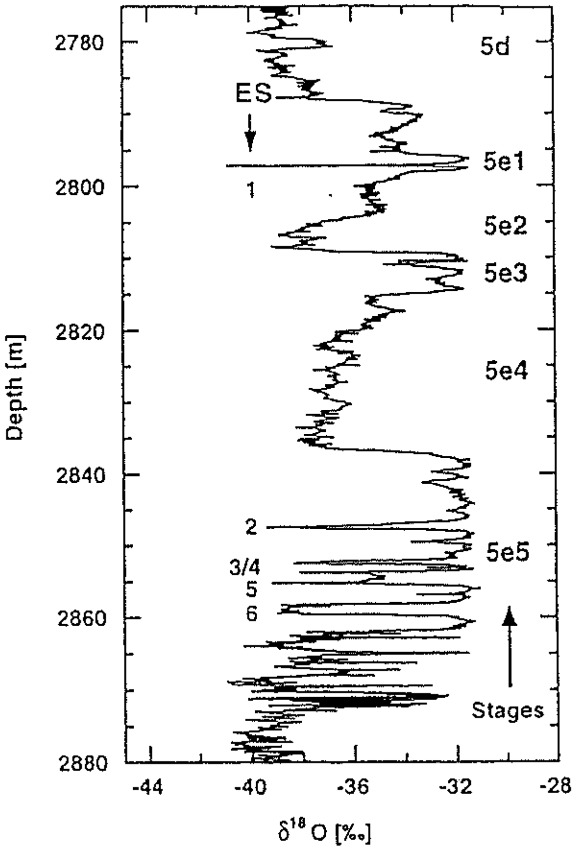

Figure 3. The Eemian part of the GRIP ice core. Modified from Johnsen et al. (1997) Figure 10.

Ram and Koenig (1997) studied dust layers in the GISP2 ice core. They assumed that high dust levels correspond to colder intervals and that dust layers can be used as annual bands to determine a chronology. They concluded that they were able to find the Eemian interval in the GISP2 ice core by locating a low-dust interval of the appropriate duration (approximately 10 ka) at 2815.5 to 2849 m depth in the ice core. Their dating of this interval is 117.4 to 127.6 ka. Two intervals in the Eemian section have somewhat elevated dust levels, the first at 2828.6 to 2830.8 m (121.2-121.9 ka) and the second at 2833.5 to 2834.4 m (122.4-123.0 ka). They also noted that the Eemian is preceded by a cold event at 2849 to 2854 m (127.6 to 129.3 ka) but that it has been suggested that the GISP2 stratigraphy below 2850 m has been disturbed. The higher Eemian dust peaks presumably represent colder intervals and suggest some climate instability. It is possible that part of this climate instability corresponds to the DPE and that the chronology determined by Ram and Koenig (1997) is in error by 2 to 3 ka.

CONCLUSIONS

We have briefly outlined the principal evidence for the Devil's Point Event and have indicated how this short-lived sea-level lowstand is best explained as a result of a colder climatic interval during the Last Interglacial. We have discussed some other Last Interglacial climate proxies that also suggest climatic instability, and have suggested how the precise chronology of the DPE may be used to calibrate the time scale of some of these proxies. We have not discussed here other potential Last Interglacial climate indicators that are beyond the scope of this paper, e.g. lake sediments, loess deposits and the pollen record of terrestrial plants. We believe, however, that these proxies are amenable to the same evaluation as the ones discussed here. The main conclusions of this paper are as follows.

1. Optimum circumstances for studying the effects of sea-level changes during the Last Interglacial on coral reefs include: tectonic stability so that rates of uplift do not have to be assumed; arid to semi-arid climate to re-

duce diagenetic alteration of primary coralline aragonite used in TIMS dating; a location where Last Interglacial sea temperatures were warm enough for coral growth throughout the entire sea-level high stand; and outstanding present-day outcrop exposures. These conditions apply to the Devil's Point and Cockburn Town fossil reefs described here and provide the opportunity for the coupling of precision stratigraphic and dating techniques that allowed the discovery of the Devil's Point Event.

2. We know of no other published accounts of Last Interglacial reefs where an intra-interglacial discontinuity has been documented and fossil corals from known positions above and below the disconformity have been accurately dated. Although significant advances have been made in the technology of precision age determinations of fossil corals, most reported studies lack the stratigraphic precision to distinguish and accurately date intra-interglacial events.

3. Although the circumstances of these two Bahamian reefs are ideal, they are unlikely to be unique. We anticipate that detailed field studies and precision dating of other Last Interglacial reefs from other Caribbean localities and elsewhere, will reveal that the Devil's Point Event was global in extent.

4. As the Bahamas are regarded as lacking tectonic activity to suitably explain relative sea-level oscillations that occur in tandem over the whole archipelago, they must be due to absolute changes in the volume of seawater. Such sea-level fluctuations are most likely caused by increases and decreases in terrestrial ice volume related to changes in global temperatures. Thus, the rise and fall of global sea level can serve as a proxy for climatic change; a relationship widely recognized for the Pleistocene glacial-interglacial cycles.

5. The hypothesis that coral growth was restricted to a relatively short interval during the Last Interglacial is not supported by evidence from the Bahamas, nor indeed from many other places, including Western Australia. Sea level can be high without the growth of coral reefs if sea-water temperatures are too low to permit coral growth, as is true today off southwestern Australia.

6. Despite advantages in some respects especially for older reef sequences, tectonically uplifted coral reefs are not ideal for studies of Last Interglacial climate and sea-level fluctuations because of uncertainties about rates of uplift and the effects of freshwater diagenesis on the preservation of coralline aragonite.

7. Although many records of deep-sea sediments of approximately Last Interglacial age show fluctuations in the oxygen isotope composition of benthic and planktonic foraminifera, the lack of a precise time scale and the difficulty in separating the effects of changes in sea-water temperatures and in terrestrial ice volume make comparisons with the Devil's Point Event difficult.

8. The validity of the Eemian climate fluctuations reported from the GRIP ice core remains a controversial issue. Comparison of the trends of oxygen isotope composition of the ice and the changes of sea level as revealed by the Devil's Point Event suggest that the GRIP ice core data may, in fact, be valid through most if not all of the Eemian.

9. The time scale commonly used in the analysis of deep-sea sediments and ice cores has errors for the interval representing the Last Interglacial that exceed the duration of sea-level and climatic events such as the Devil's Point Event. However, because its timing is precisely determined, the DPE may provide a benchmark to refine this important time scale.

ACKNOWLEDGMENTS

We thank Don and Kathy Gerace, Dan and Nicole Suchy, Kenny Buchan and the staff of the Bahamian Field Station for their kindness, invaluable logistic support and enthusiastic encouragement over the years of our research on San Salvador. Curran and White gratefully acknowledge the Committee on Faculty Compensation and Development at Smith College for partial support of our field work expenses. Wilson acknowledges partial support for this work received from the donors of the Petroleum Research Fund, administered by the American Chemical Society, as well as from the Luce Fund for Distinguished Scholarship at The College of Wooster.

REFERENCES

Aharon, P., Chappell, J., and Compston, W., 1980, Stable isotope and sea-level data from New Guinea supports Antarctic ice-surge theory of ice ages: Nature, v. 283, p. 649-651.

Bauch, H. A., Erlenkeuser, H., Grootes, P. M., and Jouzel, J., 1996, Implications of Stratigraphic and Paleoclimatic Records of the Last Interglaciation from the Nordic Seas: Quaternary Research, v. 46, p. 260-269.

Carew, J. L., and Mylroie, J. E., 1995a, Depositional model and stratigraphy for the Quaternary geology of the Bahama Islands, *in* Curran, H. A. and White, B., eds., Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda: Geological Society of America Special Paper 300, p. 5-32.

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

Carew, J. L., and Mylroie, J. E., 1999, A review of the Last Interglacial sea-level highstand (Oxygen isotope substage 5e): Duration, magnitude, and variability from Bahamian data, *in* Curran, H. A. and Mylroie, J. E., eds., Proceedings of the 9th Symposium on the Geology of the Bahamas and Other Carbonate Regions: Bahamian Field Station, Ltd., San Salvador, Bahamas, p. 14-21.

Chapman, M. R., and Shackleton, N. J., 1999, Global ice-volume fluctuations, North Atlantic ice-rafting events, and deep-ocean circulation changes between 130 and 70 ka: Geology, v. 27, p. 795-798.

Chappell, J., and Veeh, H. H., 1978, Late Quaternary tectonic movements and sea-level changes at Timor and Atauro Island: Geological Society of America Bulletin, v. 89, p. 356-368.

Chappellaz, J., Brook, E., Blunier, T., and Malaize, B., 1997, CH_4 and $\delta^{18}O$ of O_2 records from Antarctic and Greenland ice: A clue for stratigraphic disturbance in the bottom part of the Greenland Ice Core Project and the Greenland Ice Sheet Project 2 ice cores: Journal of Geophysical Research, v. 102, p. 26,547-26,557.

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., Cheng, H., Murrell, M. T., and Goldstein, S. J., 1997, Protactinium-231 dating of carbonates by thermal ionization mass spectrometry: Implications for Quaternary climate change: Science, v. 276, p. 782-786.

Eisenhauer, A., Zhu, Z. R., Collins, L. B., Wyrwoll, K. H., and Eichstätter, R., 1996, The Last Interglacial sea level change: New evidence from the Abrolhos islands, West Australia: Geologische Rundschau, v. 85, p. 606-614.

Esat, T. M., McCulloch, M. T., Chappell, J., Pillans, B., and Omura, A., 1999, Rapid fluctuations in sea level recorded at Huon Peninsula during the penultimate deglaciation: Science, v. 283, p. 197-201.

Fruijtier, C., Elliott, T., and Schlager, W., 2000, Mass-spectrometric ^{234}U-^{230}Th ages from the Key Largo Formation, Florida Keys, United States: Constraints on diagenetic age disturbance: Geological Society of America Bulletin, v. 112, p. 267-277.

Gallup, C. D., Edwards, R. L., and Johnson, R. G., 1994, The timing of high sea levels over the past 200,000 years: Science, v. 263, p. 796-800.

GRIP members, 1993, Climate instability during the last interglacial period recorded in the GRIP ice core: Nature, v. 364, p. 203-207.

Halley, R. B., Muhs, D. R., Shinn, E. A., Dill, R. F., and Kindinger, J. L., 1991, A + 1.5 m reef terrace in the southern Exuma Islands, Bahamas: Geological Society of America Abstracts with Programs, v. 23, p. 40.

Henderson, G. M., and Slowey, N. C., 2000, Evidence from U-Th dating against Northern Hemisphere forcing of the penultimate deglaciation: Nature, v. 404, p. 61-66.

Israelson, C., and Wohlfarth, B., 1999, Timing of the Last-Interglacial high sea level on the Seychelles Islands, Indian Ocean: Quaternary Research, v. 51, p. 306-316.

James, N. P., Collins, L. B., Bone, Y., and Hallock, P., 1999, Subtropical carbonates in a temperate realm: Modern sediments on the southwest Australian shelf: Journal of Sedimentary Research, v. 69, p. 1297-1321.

Johnsen, S. J., Clausen, H. B., Dansgaard, W., Gundestrup, N. S., Hammer, C. U., and Tauber, H., 1995, The Eem stable isotope record along GRIP ice core and its interpretation: Quaternary Research, v. 43, p. 117-124.

Johnsen, S. J., Clausen, H. B., Dansgaard, W., Gundestrup, N. S., Hammer, C. U., Andersen, U., Andersen, K. K., Hvidberg, C. S., Dahl-Jensen, D., Steffensen, J. P., Shoji, H., Sveinbjörnsdottir, A. E., White, J., Jouzel, J., and Fisher, D. 1997, The δ^{18}O record along the Greenland Ice Core Project deep ice core and the problem of possible Eemian climatic instability: Journal of Geophysical Research, v. 102, p. 26, 397-26,410.

Martinson, D. G., Pisias, N. G., Hays, J. D., Imbrie, J., Moore, Jr., T. C., and Shackleton, N. J., 1987, Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy: Quaternary Research, v. 27, p. 1-29.

Maslin, M., Sarnthein, M., Knaack, J.-J., Grootes, P., and Tzedakis, C., 1998, Intra-interglacial cold events: An Eemian-Holocene comparison, *in* Cramp, A., MacLeod, C. J., Lee, S. V., and Jones, E. J. W., eds., Geological Evolution of Ocean Basins: Results from the Ocean Drilling Program, Geological Society, London, Special Publications 131, p. 91-99.

McCulloch, M. T., Tudhope, A. W., Esat, T. M., Mortimer, G. E. Chappell, J., Pillans, B., Chivas, A. R., and Omura, A., 1999, Coral record of equatorial sea-surface temperatures during the penultimate deglaciation at Huon Peninsula: Science, v. 283, p. 202-204.

Pillans, B., Chappell, J., and Naish, T., 1998, A review of the Milankovitch climatic beat: Template for Plio-Pleistocene sea-level changes and sequence stratigraphy: Sedimentary Geology, v. 122, p. 5-21.

Pisias, N. G., Martinson, D. G., Moore, T. C., Jr., Shackleton, N. J., Prell, W., Hays, J., and Boden, G., 1984, High resolution stratigraphic correleation of benthic oxygen isotope records spanning the last 300,000 years: Marine Geology, v. 56, p. 119-136.

Plaziat, J-C., Reyss, J-L., Choukri, A., Orszag-Sperber, F., Baltzer, F., and Purser, B. H., 1998, Mise en évidence, sur la côte récifale d'Egypte, d'une régression interrompant brièvement le plus haut niveau du Dernier Interglacaire (5e): Un nouvel indice de variations glacio-eustatiques à haute fréquence au Pléistocène?: Geological Society of France Bulletin, v. 169. p. 115-125.

Precht, W. F., 1993, Stratigraphic evidence from reef studies for a double high sea stand during the last interglacial maximum: American Association of Petroleum Geologists Bulletin, v. 77, p. 1473.

Ram, M., and Koenig, G., 1997, Continuous dust concentration profile of pre-Holocene ice from the Greenland Ice Sheet Project 2 ice core: Dust stadials, interstadials, and the Eemian: Journal of Geophysical Research, v. 102, p. 26, 641-26, 648.

Seidenkrantz, M.-S., Kristensen, P., and Knudsen, K. L., 1995, Marine evidence for climatic instability during the last interglacial in shelf records from northwest Europe: Journal of Quaternary Science, v. 10, p. 77-82.

Seidenkrantz, M.-S. and Knudsen, K-L., 1997, Eemian climatic and hydrographical instability on a marine shelf in Northern Denmark: Quaternary Research, v. 47, p. 218-234.

Slowey, N. C., Henderson, G. M., and Curry, W. B., 1996, Direct U-Th dating of marine sediments from the two most recent interglacial periods: Nature, v. 383, p. 242-244.

Steffensen, J. P., 1997, The size distribution of microparticles from selected segments of the Greenland Ice Core Project ice core representing different climatic periods: Journal of Geophysical Research, v. 102, p. 26,755-26,763.

Steffensen, J. P., Clausen, H. B., and Hammer, C. U., 1997, The chemical composition of cold events within the Eemian section of the Greenland Ice Core Project ice core from Summit, Greenland:

Journal of Geophysical Research, v. 102, p. 26,747-26,754.

Stein, M., Wasserburg, G. J., Aharon, P., Chen, J. H., Zhu, Z. R., Bloom, A., and Chappell, J., 1993, TIMS U-series dating and stable isotopes of the last interglacial event in Papua New Guinea: Geochimica et Cosmochimica Acta, v.57, p. 2541-2554.

Stirling, C. H., Esat, T. M., McCulloch, M. T., and Lambeck, K., 1995, High-precision U-series dating of corals from Western Australia and implications for the timing and duration of the Last Interglacial: Earth and Planetary Science Letters, v. 135, p. 115-130.

Stirling, C. H., Esat, T. M., Lambeck, K., and McCulloch, M. T., 1998, Timing and duration of the Last Interglacial: Evidence for a restricted interval of widespread coral reef growth: Earth and Planetary Science Letters, v. 160, p. 745-762.

Veron, J. E. N., 1995, Corals in Space and Time, Ithaca, New York, Comstock/Cornell, 321 p.

White, B., 1989, Field guide to the Sue Point fossil coral reef, San Salvador Island, Bahamas, *in* Mylroie, J. E., ed., Proceedings of the Fourth Symposium on the Geology of the Bahamas: Bahamian Field Station, San Salvador, Bahamas, p. 353-365.

White, B, and Curran, H. A., 1995, Entombment and preservation of Sangamonian coral reefs during glacioeustatic sea-level fall, Great Inagua Island, Bahamas, *in* Curran, H. A. and White, B, eds, Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda, Geological Society of America, Special Paper 300, p. 51-61.

White, B., Curran, H. A., and Wilson, M. A., 1998, Bahamian coral reefs yield evidence of a brief sea-level lowstand during the Last Interglacial: Carbonates and Evaporites v. 13, p. 10-22.

Wilson, M. A., Curran, H. A., and White, B., 1998, Paleontological evidence of a brief global sea-level event during the last interglacial: Lethaia, v. 31, p. 241-250.

Winograd, I. J., Landwehr, J. M., Ludwig, K. R., Coplen, T. B., and Riggs, A. C., 1997, Duration and structure of the past four interglaciations: Quaternary Research, v. 48, p. 141-154.

Zhu, Z. R., Wyrwoll, K-H., Collins, L. B., Chen, J. H., Wasserburg, G. J., and Eisenhauer, A., 1993, High-precision U-series dating of Last Interglacial events by mass spectrometry: Houtman Abrolhos Islands, western Australia: Earth and Planetary Science Letters, v. 118, p. 281-293.