MIS 11 rocks! The "smoking gun" of a catastrophic +20 m eustatic sea-level rise

PAUL J. HEARTY
School of Earth and Environmental Sciences, University of Wollongong, Australia; paulh@uow.edu.au

A sea level rise 20 m higher than present implies disintegration of the Greenland and West Antarctic Ice Sheets and a significant draw down of East Antarctica; as such an increase in ocean volume cannot be attributed to thermal expansion alone. This brief crest of sea level at +20 m occurred around 400 kyr ago during MIS 11, which is one of the Pleistocene interglacials over the past million years that closely resembles our own MIS 1 interglacial, based on orbital parameters modulating Northern Hemisphere insolation. Could aspects of the sea level and climatic shifts of 400 kyr pertain to the future of MIS 1? Could anthropogenic spiking of atmospheric CO_2 to Cretaceous levels amplify the course of events to even greater extremes than in MIS 11? Given such cataclysmic prospects, it is critical to document as accurately as possible all aspects of this middle Pleistocene (mP) sea level event. The record of a +20 ± 2 m highstand is preserved as geomorphic and geologic imprints along coastlines of the world's oceans. The tangible and datable rocks are the most accurate and reliable scientific means of quantifying ocean and ice-volume changes. This record of sea-level changes does not require validation by the iterative and circumstantial data offered by proxy methods, although such an approach may be instrumental in providing corroboration.

Three or more ocean basins

Complex geomorphic, stratigraphic, and sedimentary records indicating a +20 mP highstand are best exposed in Bermuda (BDA; 2 sites), Eleuthera Bahamas (ELU; 2 sites) (Hearty et al., 1999; Kindler and Hearty, 2000), Oahu, Hawaiian Islands (OHU; 2 sites) (Hearty, 2001), and near Exmouth, Western Australia (XWA) (Hearty and O'Leary, in review). Additional mid-Brunhes highstand sequences of similar magnitude have been described from the North Slope and Nome coastal plains, Alaska (NSA) (Kaufman and Brigham-Grette, 1993), Lazio, Italy (LZI) (Karner et al., 2001), and at Boxgrove in the United Kingdom (BUK) (Bowen, 1999). Whether tectonically stable or subsiding (BDA, ELU, XWA) or mildly to moderately uplifted (OHU, LZI, NSA, BUK?), these sites document this event in most global ocean basins.

Stratigraphy, diagenesis, and dating

The early Pleistocene is recognizable in many subtropical Quaternary coastal records by the advanced state of recrystallization of limestone outcrops and by the presence of a massive red soil (Vacher et al., 1989; Hearty and Vacher, 1994; Hearty et al., 2005a,b; Olson et al. 2005). The +20 m deposits are stratigraphically younger, and preserve much of their original mineralogy. In deep-sea $\delta^{18}O$ records, MIS 11 is recognized as one of the warmer and longer interglacials of the past million years, while previous (MIS 13 and 15) and subsequent (MIS 9) interglacials are relatively less intense (Lisiecki and Raymo, 2005). Amino acid racemization (AAR) geochronology and U/Th TIMS ages from flowstones and corals corroborate stratigraphic and isotopic records in placing the +20 m sea level in MIS 11 around 400 kyr (Hearty et al., 1999).

Terrace geomorphology, bedded and sorted sediments, and sedimentary structures

Erosional and constructional terraces are found at BDA, ELU, OHU, XWA, NSA, LZI, and BUK, but are most elegantly preserved in ELU where 10-20 m wide erosional benches at two locations are mantled by low-angle bedding in fine grained, sorted oolite, filled with intertidal fenestral porosity or "beach bubbles" at +18 to +22 m (Fig. 1A-C). Graded and sorted marine sand and conglomerate partially fill caves between +18 and +21 m in Bermuda, and formerly mantled an "erosional nip at 70 feet" (+21.3 m) (F. Mackenzie, pers comm., 2007) in the same Government Quarry (Land et al., 1967; Hearty et al., 1999; Kindler and Hearty, 2000) but have since been destroyed. Marine conglomerate,

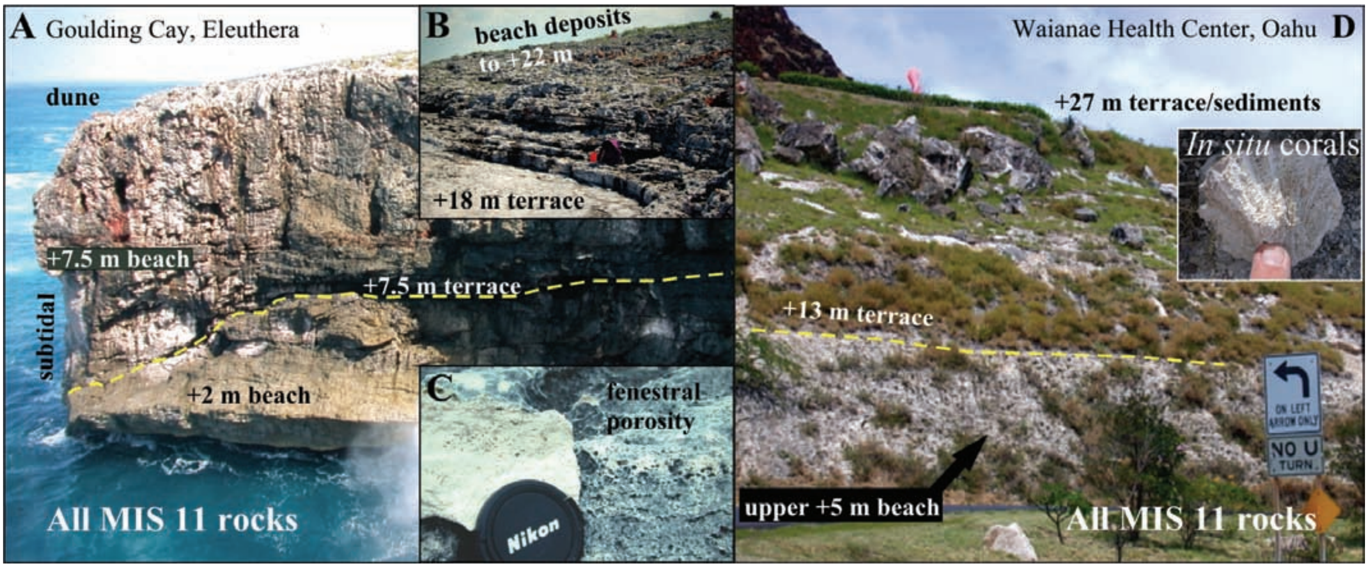

*Figure 1: **A**) Vertical stratigraphic sequence at Goulding Cay, Eleuthera (ELU) showing the stepping up of sea level from +2 m to +7.5 m. The eroded terrace surface at +7.5 m extends over 40 m horizontally, and required several thousands of years to form; **B**) The last sea-level step at ELU showing a narrow eroded terrace in the lower dune, mantled with beach sediments filled with fenestral porosity; **C**) between +18 to +22 m; **D**) Isopachous fibrous "rim" cements (Fig. 2) document early diagenesis in a marine environment at all sites. A stratigraphic sequence in western Oahu (OHU) exposes almost an identical "stepping up" sequence of sea levels. A broad eroded terrace surface at +13 m at OHU corresponds with the +7.5 m level at ELU. The highest OHU level at +28 ± 2 m correlates with the +20 m level in stable locations and contains coral heads in growth position (inset).*

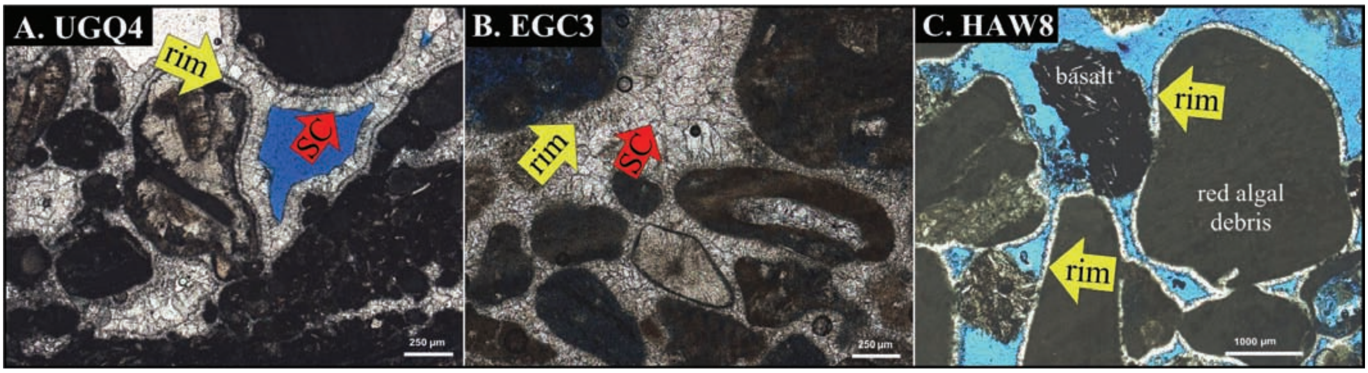

Figure 2: Cements in +20 m (Bermuda and Bahamas) and +30 m (Hawaiian Islands) shore deposits: ***A****) Bermuda cave UGQ4 filled with marine sands cemented initially by isopachous "rim" cements indicating early diagenesis in a marine environment, and subsequent diagenesis under vadose conditions indicated by sparry calcite (SC);* ***B****) Eleuthera, Bahamas +20 m marine limestone showing delicate textures of early and late generations of rim and sparry calcite cements;* ***C****) Kaena Point, west Oahu (HAW8) at +26 to +30 m (calculated uplift at 2 m/100 kyr) with isopachous rim and lacking later generation of sparry calcite, possibly due to very arid, rain shadow conditions on leeward Oahu. MIS 11 marine deposits retain much of their primary mineralogy (A-C) in contrast to early Pleistocene limestones, which are most often totally recrystallized. Thin section images and interpretation courtesy of P. Kindler (U. Geneva).*

bedded sand and in situ coral heads occur on a succession of erosional and constructional terraces at two sites in western OHU (Fig. 1D). Corrected for uplift of ~2 m/100 kyr (based on U/Th dated MIS 5e deposits), the OHU evidence also points to a +20 m "Kaena" highstand during the mP (Hearty, 2001). A "give up" reef terrace complex at XWA reflects the rise of sea level well above +13 m. Bowen (1999) deduced a MIS 11 highstand at +19.8 to +23.2 m at BUK, while Kaufman and Brigham-Grette (1993) attributed a mP beach ridge, exposed for tens of kilometers at several locations along the Arctic Ocean and Bering Strait, to a +20 m stand of MIS 11 sea level.

Sustained marine submergence confirmed by marine cements and organisms

In addition to the preceding documentation of a +20 m highstand, one of the most unassailable pieces of physical evidence is the presence of isopachous cements at each of three study areas of BDA, ELU, and OHU (Fig. 2ABC). This distinct, early generation of isopachous fibrous "rim" cement indicates initial aragonite precipitation around sand grains in marine waters, while a successive generation of sparry calcite (SC) indicates subsequent diagenesis in a vadose environment. Growth position corals among +20 m deposits at OHU and +13 m reef complex at XWA also confirm sustained submarine conditions.

Sea level oscillations during a mid-Brunhes interglacial

The intra-interglacial structure of sea level is revealed in the coastal stratigraphy at numerous locations. Limestone rocks and erosional surfaces at BDA, ELU, and OHU reflect the same sea-level changes culminating in the terminal +20 m rise. ELU is most representative, instructive, and explicit in detail (Fig. 1A-C). An early MIS 11 sea level stabilized at +2 m, followed by a rapid rise to +7.5 m, where a broad (>40 m) marine platform was eroded and mantled by sub-, inter-, and supratidal (dune) bedding. After prolonged stability at +7.5 m, sea level rose to a peak around +20 m, where it etched a small terrace in the underlying dune, and remained for perhaps 1-2 kyr. In OHU (Fig. 1D), three similar levels are documented at +5, +13, and +26 m (uncorrected for uplift), approximating those from ELU and BDA, as well as differences between levels. At +20 m, there was sufficient time to erode a narrow bench, generate sediments, and grow coral heads, but not enough to carve an extensive platform or develop a reef terrace (which likely "gave up" at XWA as a result of a rapid ~12 m deepening).

MIS 11 extinctions?

Extinction of the last remaining species of albatross in the North Atlantic has been directly tied to the +20 m highstand in Bermuda (Olson and Hearty, 2003), and such a highstand would have had a profound negative effect on thousands of populations of seabirds as well as causing massive extinctions of terrestrial organisms on low-lying islands (Olson et al., 2005; 2006) and isolated continental lowlands.

Conclusions

1) In situ rocks are the most direct and reliable form of scientific evidence that documents the "smoking gun" of an extreme mP +20 ± 2 m highstand.

2) A MIS 11 correlation, rather than preceding (MIS 15 or 13) or subsequent (MIS 9 or 7) highstands, is suggested by many deep-sea isotope records, while TIMS ages constrain the age of the event in BDA between about 400 and 550 kyr. Stratigraphy, diagenesis, and AAR data further exclude the possibility of this being a Plio-Pleistocene sea-level event.

3) The geographic range and the ample time required to develop a complex stratigraphy (even along the northeastern coast of Alaska) unequivocally eliminate emplacement of + 20 m deposits by tsunami (e.g., McMurtry et al., 2007) or storm waves. The convergence of several independent lines of physical evidence can be parsimoniously justified by the punctuated "stepping up" of sea level to a maximum of +20 m during MIS 11, caused by the collapse and draw down of major ice sheets.

Acknowledgments

S.L. Olson, (Smithsonian Institution), P. Kinder (University of Geneva) and R.L.Edwards and H. Cheng, (University of Minnesota) have contributed significantly to this project. This communication is an outgrowth of a MIS 11 workshop sponsored by Woods Hole Oceanographic Institute, INQUA, and the Morss Foundation (J. McManus and C. Tzedakis, organizers).

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