Drowning of the $-150$ m reef off Hawaii: A casualty of global meltwater pulse 1A?

Jody M. Webster
David A. Clague
Kristin Riker-Coleman
Christina Gallup
Monterey Bay Aquarium Research Institute, Moss Landing, California 95039, USA
Department of Geological Sciences, University of Minnesota Duluth, Duluth, Minnesota 55812, USA
Juan C. Braga
Department de Estratigrafía y Paleontología, Universidad de Granada, Granada, Spain
Donald Potts
Department of Ecology and Evolutionary Biology, University of California, Santa Cruz, California 95064, USA
James G. Moore
U.S. Geological Survey, MS 910, 345 Middlefield Road, Menlo Park, California 94025, USA
Edward L. Winterer
Scripps Institution of Oceanography, University of California, San Diego, California 92093, USA
Charles K. Paull
Monterey Bay Aquarium Research Institute, Moss Landing, California 95039, USA

ABSTRACT

We present evidence that the drowning of the $-150$ m coral reef around Hawaii was caused by rapid sea-level rise associated with meltwater pulse 1A (MWP-1A) during the last deglaciation. New U/Th and $^{14}$C accelerator mass spectrometry dates, combined with reinterpretation of existing radiometric dates, constrain the age of the coral reef to $15.2-14.7$ ka (U/Th age), indicating that reef growth persisted for $4.3$ k.y., following the end of the Last Glacial Maximum at $19$ ka. The drowning of the reef is roughly synchronous with the onset of MWP-1A between $14.7$ and $14.2$ ka. Dates from coralline algal material range from $14$ to $10$ cal ka (calibrated radiocarbon age), $1-4$ k.y. younger than the coral ages. A paleoenvironmental reconstruction incorporating all available radiometric dates, high-resolution bathymetry, dive observations, and coralgal paleobathymetry data indicates a dramatic rise in sea level around Hawaii ca. $14.7$ ka. Paleowater depths over the reef crest increased rapidly above a critical depth (30–40 m), drowning the shallow reef-building Porites corals and causing a shift to deepwater coralline algal growth, preserved as a crust on the drowned reef crest.

Keywords: Hawaii, coral reef drowning, deglaciation, meltwater pulse 1A.

INTRODUCTION

A well-developed series of submerged reefs is preserved around the Island of Hawaii (Moore and Fornari, 1984). They developed in response to rapid subsidence associated with the continued accumulation of volcanic material on the Hawaiian ridge and eustatic sea-level fluctuations over the past 500 k.y. (Ludwig et al., 1991). Moore and Fornari (1984) suggested that the reefs began forming during sea-level falls leading to glacial periods, when the rate of sea-level change was similar to the rate of land subsidence and stable shoreline conditions prevailed. Each reef drowned during the subsequent deglaciations due to the combined effects of rapid sea-level rise and continued subsidence (Moore and Fornari, 1984; Moore and Campbell, 1987). Potentially, the reef tops contain important information about the timing and paleoenvironmental conditions during different deglaciations.

The focus of this paper is the $-150$ m submerged reef off Hawaii. Moore and Fornari (1984) dated this reef as $13.3$ $^{14}$C ka (radiocarbon age), indicating that it drowned during the last deglaciation. A major advance in our understanding of climate dynamics is the recognition that sea-level rise during the last deglaciation was not smooth and continuous, but was characterized by at least two dramatic meltwater pulse events, identified as meltwater pulse 1A (MWP-1A) (14.2–13.8 ka) and MWP-1B (11.5–11.1 ka), based on data from Barbados (Fairbanks, 1989; Bard et al., 1990). Since the subsequent reanalysis of the Barbados sea-level curve (Clark et al., 2002; Weaver et al., 2003) and new results from the Sunda Shelf (Hanebuth et al., 2000), Argentine Shelf (Guilderson et al., 2000), Huon Peninsula (Cutler et al., 2003), and South China Sea (Kienast et al., 2003), debate has continued concerning the precise timing, amplitude, and rate of sea-level rise of MWP-1A. The well-documented $^{14}$C plateau (Edwards et al., 1993) and limited U/Th coral records during this interval have hampered efforts to constrain this important climate event. Despite the controversy, MWP-1A is a real feature of the postglacial eustatic sea-level history (Peltier, 2002), characterized by a very rapid ($40–50$ mm/yr) sea-level rise, beginning between $14.7$ and $14.2$ ka.

Because shallow-water coral reefs cannot accrete vertically faster than $10–20$ mm/yr (Neumann and Macintyre, 1985; Montaggioni et al., 1997), we argue, using new radiometric, bathymetric, and sedimentary data, that the $-150$ m reef off Hawaii drowned as a direct result of unusually rapid sea-level rise associated with MWP-1A, rather than mean sea-level rise during deglaciation, and island subsidence.

NATURE AND EXTENT OF THE $-150$ M REEF

The $-150$ m reef offshore Hawaii forms a consistent break in slope extending $150$ km from the Kohala Peninsula to Kealakekua Bay (Moore and Fornari, 1984) (Fig. 1). Submersible dives and bathymetric surveys (Moore et al., 1990) identified the $-150$ m reef off Ka Lae (South Point). There are few data indicating the presence of the $-150$ m reef off the eastern coast of Hawaii, although a survey by Clague et al. (1998) imaged a prominent reef-like structure off Hilo at $-125$ to $-150$ m that presumably extends northwest along the broad shelf toward Kohala.

Off Kawaihae, the $-150$ m reef is composed of three distinct bathymetric levels (reefs 1–3; Figs. 2A, 2B). Rising steeply from the base of the slope at $-240$ m, the top of the main reef structure (reef 1) is at $-160$ to $-150$ m. The second bathymetric feature (reef 2) is $1$ km landward of the main reef at $-125$ m. A bathymetric depression consistent with lagoon and associated patch-reef morphologies (Campbell, 1984) is landward of reef 2. The third feature (reef 3) is $1.8$ km landward of the main reef at $-105$ m (Figs. 2A, 2B). Bathymetric and backscatter characteristics (Clague et al., 1998) indicate that these two features may also be coral reefs, although, based on the morphology of the seaward edge of the third feature, we cannot exclude the possibility that it is a lava flow.

DIVE OBSERVATIONS AND SEDIMENTARY FACIES

In 2001, ROV dives (Tiburon) were carried out off Kawaihae (T276) and Kealakekua Bay (T291) (Fig. 1). Combined with the previous Makalii and Pisces submersible dives, there are 8 dives, $>20$ h of video, and 60 samples from the $-150$ m reef (reef 1) off Kawaihae, West Hualalai, Kealakekua Bay, and Ka Lae (South Point) (Fig. 1).
Figure 1. Hawaii and offshore bathymetry showing known (solid line) and probable (dashed line) extent of −150 m drowned reef and positions of submersible dives and sampling sites (black arrows). New radiometric dates are from dives T276 and T291. Solid box denotes location of high-resolution EM300 bathymetry and backscatter data off Kawaihae (see Fig. 2). Bathymetry data are after Clague et al. (1998) and Smith et al. (2002).

Dive observations and bathymetric data show that the −150 m reef consists of four morphologic zones (see Data Repository1): (1) fore-reef slope; (2) reef wall; (3) upper reef slope; and (4) reef crest (<−150 m) (Fig. 2B). At Kawaihae and Kealakekua Bay a distinct pavement is exposed as a 20–30-cm-thick crust at the break in slope between the reef crest and the upper reef slope.

Samples from the crust on the reef crest clearly record a deepening sequence (Figs. 3A, 3B). Submassive Porites corals are commonly overgrown by 10 cm crusts of coralline algae formed by thin encrusting thalli and minor warty plants that grew one over the other (Figs. 3A, 3B), and topped by thin crusts (1–2 mm) of living pink coralline algae (Sporolithon and Lithothamnion), bryozoans, and solitary corals. Sandwiched between the algal layers are encrusting foraminifera (Gypsina or Acervulina? sp.), bryozoans, and layers of micrite (Fig. 3C). The main coralline algae genera within the crust are Mesophyllum and Lithothamnion (Fig. 3C), associated with Sporolithon, Lithoporella, and plants of the L. pustulatum species group, and Peyssonnelia sp. In modern reefs around Hawaii, massive Porites grow in depths <50 m but are abundant only in depths <20 m (Maragos, 1977). In contrast, the recorded algal genera are the main components of the deepest (>60 m) present-day coralline algal assemblages in the Hawaiian Islands (Adey et al., 1982). The thin encrusting to warty morphology of the algae also suggests low to moderate energy and deep settings (Bosence, 1983, 1985). Similar algal frameworks form modern buildups in deep fore-reef settings (60–110 m) in the southern Great Barrier Reef (Marshall et al., 1998), Gulf of Mexico (Minnery et al., 1985), and Pleistocene deep-water buildups in the Huon Gulf, Papua New Guinea (Webster et al., 2004). Based on their morphology and species composition, the Hawaiian coralline algal crust limestone developed in deep fore-reef settings (>60–200 m).

Figure 2. A: Color shaded relief map showing −150 m reef off Kawaihae (Clague et al., 1998). B: Bathymetric profile (A–B) shows three distinct reefs at −150 m (reef 1), −125 m (reef 2), and −105 m (reef 3) and likely lagoon and patch-reef features. Following morphologic zones are identified: fore-reef slope (FRS, −250 to −190 m), reef wall (RW, −200 to −170 m), upper-reef slope (URS, −170 to −150 m), and reef crest (RC, <−150 m).

**RADIOMETRIC DATES**

For comparison with the U/Th ages (ka), all radiocarbon ages (14C ka) were converted to calibrated ages (cal ka) using the program CALIB 4.3 (see footnote 1). There are 21 radiometric dates available, 10 from the top of the −150 m reef and 11 from the slope and flanks (Fig. 4). The ages of corals collected in situ from the reef crest range from 15.2 to 14.7 ka, indicating that the −150 m reef stopped growing after this interval.

Coral samples from below the reef crest (i.e., slope and flanks) were collected as loose talus, so their original positions and implications for sea-level reconstructions are uncertain. That they were loose and their reconstructed paleo-water depths too deep (~100–200 m) for coral reef growth (Fig. 4) suggest that these corals were derived from more landward, shallower locations. However, except for two samples, the ages of the loose corals are consistent with the age range defined...
by the in situ corals from the reef crest (Fig. 4). Presumably these corals tumbled down from the −150 m reef crest, whereas the two younger corals (13.9–13.4 ka) were transported from a shallower, younger, landward phase of reef growth.

Another striking pattern is the age difference between the corals and deep-water coralline algal material. The algae are mainly younger than the adjacent coral samples from the reef crest, ranging from 14 to 10 cal ka with an average of 12.3 cal ka. Combined with a cover of similar living corallines, these data indicate that the coralline algae crust formed 1–4 k.y. after the demise of the shallow reef-building corals and has continued forming to the present day.

**TIMING OF REEF DROWNING—SYNCHRONOUS WITH GLOBAL MELTWATER PULSE 1A?**

The drowning history of the −150 m reef during the last deglaciation is summarized in Figure 4. Following the end of the Last Glacial Maximum (LGM) ca. 19 ka, relative sea level rose at 8 mm/yr (5.5 mm/yr eustatic sea-level rise and 2.5 mm/yr subsidence; Fairbanks, 1989; Bard et al., 1990; Moore et al., 1996). Contrary to previous concepts of drowned reef formation (Moore and Fornari, 1984), the −150 m reef was able to keep pace with this initial sea-level rise, approaching within −10 m of sea level prior to MWP-1A (14.7–14.2 ka). During this event paleowater depths increased dramatically to 35 m in <−500 yr. The rate of sea-level rise during MWP-1A was 30–40 mm/yr (Clark et al., 2002; Hanebuth et al., 2000). Five times the maximum vertical accretion rate for modern coral reefs in the Hawaiian Islands (Grigg and Epp, 1989). This rate of sea-level rise, combined with the increase in paleowater depths beyond a critical depth (>30–40 m; Grigg and Epp, 1989), would have drowned the −150 m coral reef within decades to centuries. The coral ages (15.2–14.7 ka) from the reef crest indicate that the cessation of coral reef growth was effectively synchronous with the onset of MWP-1A.

Following reef drowning and the termination of MWP-1A, paleowater depths increased more slowly as sea-level rise and subsidence continued (Fig. 4). By ca. 12 cal ka, depths over the crest were >60 m, well beyond the range of normal coral reef growth. Carbonate accretion shifted to deep-water coralline algal growth, preserved as a thin crust. Algal growth continues today on the drowned reef crest at its present depth of −150 m. Based on previously published vertical accumulation rates for similar crustose coralline algal frameworks (0.04 mm/yr; Reid and Macintyre, 1988), the crust on top of the −150 m reef is unlikely to have accumulated more than 50 cm over the past 12 k.y., consistent with the sample and dive observations.

Less direct evidence for episodic and dramatic sea-level rises during the last deglaciation in the subtropical North Pacific Ocean comes from off Oahu. Fletcher and Sherman (1995) identified four paleoshorelines preserved as submerged intertidal notches at −120, −90, −58, and −24 m (Fig. 4). They interpreted these features as erosional notches formed during periods of slow sea-level rise and preserved by rapid sea-level jumps at 20, 16–14, 13–11, and 9–7 ka. Oxygen isotope data from an adjacent high-resolution sediment core (PC17) record a dramatic decrease (0.6‰) in δ18O between 15–13 14C ka and 12–11 14C ka (Lee and Slowey, 1999). Similar decreases in δ18O at about the time of MWP-1A have been observed in sediment cores from the Gulf of Mexico (Leventer et al., 1982), Bermuda Rise (Keigwin et al. 1991), and corals from the western Indian Ocean (Colonna et al., 1996). Without more data (e.g., independent sea-surface temperature [SST] proxies) and better age control, it is not possible to determine if the Oahu δ18O excursions reflect changes in SST and/or freshwater flux associated with MWP-1A. However, we note the general synchronicity of these data with the drowning age of the −150 m reef, the apparent age of the −90 m paleoshoreline, and the timing of MWP-1A. We also speculate that the two apparent reef structures (reef 2 and 3) landward of and shallower than the −150 m reef off Kawaihae may preserve a
CONCLUSIONS

The new data constrain the drowning age of the −150 m reef off Hawaii to ca. 14.7 ka, indicating (1) that reef growth persisted for 4.3 k.y. after the end of the LGM, and (2) that the drowning age was synchronous with the onset of MWP-1A. During this dramatic paleoclimate event, paleowater depths increased rapidly above a critical depth, drowning the coral reef and causing a shift to deeper coralline algal growth. Our data provide evidence for the occurrence and timing of MWP-1A ca. 14.7 ka in the subtropical North Pacific Ocean, consistent with recent data from the Sunda Shelf, South China Sea, and Huon Peninsula. Furthermore, we propose that the chronologic and paleobathymetric relationships recorded in the −150 m reef may serve as a model for interpreting the drowning history of other older and deeper submerged reefs, which may also have drowned during as-yet unidentified global meltwater pulses.

REFERENCES CITED


