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Abstract

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Keywords	Coral reef drowning; Submerged terraces; Deglaciation; Late Pleistocene; Sea-level changes; Hawaii; Meltwater Pulse-1A; Geomorphology, coastal

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New evidence of Hawaiian coral reef drowning in response to Meltwater Pulse-1A

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ABSTRACT

Fossil coral reefs are valuable recorders of glacio-eustatic sea-level changes, as they provide key temporal information on deglacial meltwater pulses (MWPs). The timing, rate, magnitude, and meltwater source of these sea-level episodes remain controversial, despite their importance for understanding ocean-ice sheet dynamics during periods of abrupt climatic change. This study revisits the west coast of the Big Island of Hawaii to investigate the timing of the -150 m H1d terrace drowning off Kawaihae in response to MWP-1A. We present eight new calibrated ^{14}C-AMS ages, which constrain the timing of terrace drowning to at or after 14.75 +0.33/-0.42 ka, coeval with the age of reef drowning at Kealakekua Bay (U-Th age 14.72 ± 0.10 ka), 70 kms south along the west coast. Integrating the chronology with high-resolution bathymetry and backscatter data, detailed sedimentological analysis, and paleoenvironmental interpretation, we conclude the H1d terrace drowned at the same time along the west coast of Hawaii in response to MWP-1A. The timing of H1d reef drowning is within the reported uncertainty of the timing of MWP-1A interpreted from the IODP Expedition 310 Tahitian reef record.

KEYWORDS

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1. INTRODUCTION

Fossil coral reefs are used to investigate paleoenvironmental change and constrain glacio-eustatic sea-level fluctuations during the Quaternary due to their high geologic preservation potential, narrow depth range within which they can grow, and suitability for radiometric dating (e.g. Hopley, 1986; Buddemeier and Smith, 1988; Fairbanks, 1989; Montaggioni et al., 1997). Submerged reefs on rapidly subsiding margins such as Hawaii (Webster et al., 2009) and the Huon Gulf in Papua New Guinea (Galewsky et al., 1996) provide unique settings to investigate sea-level history, as coral reef growth into continually created accommodation space results in expanded stratigraphic sections. These reefs are more sensitive to sea-level rise than are reefs on static or uplifting margins, and their stratigraphy can preserve a sedimentary drowning signature that can be precisely dated (Moore and Clague, 1992; Webster et al., 2009). The volcanic Big Island of Hawaii (henceforth referred to as “Hawaii”) in particular experiences predictable and well-constrained subsidence due to its location on an intra-oceanic plate subjected to volcanic loading, making it an ideal location to study sea-level rise (Webster et al., 2009; Huppert et al., 2015).

Although dependent on regional conditions, evidence from the geological record suggests the maximum vertical accretion rate of shallow-water coral reefs is ~10 mm/yr (Neumann and Macintyre, 1985; Buddemeier and Smith, 1988; Hubbard, 1997; Montaggioni et al., 1997). When relative sea-level (RSL) rise outpaces the vertical accretion of reefs, the reef may ‘give-up’ or drown, at which point neritic carbonate production ceases and deeper water conditions are established, characterized by a distinct sedimentary signature (Schlager, 1981; Campbell, 1984; Davies and Montaggioni, 1985; Neumann and Macintyre, 1985; Grigg and Epp, 1989; Webster et al., 2009). Drowned reef crests represent an important record of accelerated deglacial sea-level rise events, as these mark the times at which reef growth was outpaced by sea-level rise (Blanchon and Shaw, 1995; Galewsky et al., 1996; Hubbard, 1997; Webster et al., 2009).

Models of reef growth on Hawaii involve initiation during sea-level highstands, continuing growth during the subsequent regression, and drowning during early deglaciation from the combined effects of subsidence and global sea-level rise (Moore and Fornari, 1984; Moore and Campbell, 1987; Ludwig et al., 1991; Webster et al., 2007); this process repeats with glacial cycles to form a series of backstepping reef fronts and broad platforms. A refined model suggests that deglacial meltwater pulses (MWP) play a key role in causing reef drowning (Webster et al., 2004), with later stages of reef development forming backstepping reef terraces and sub-terraces (Hubbard, 1997; Blanchon et al., 2002; Cabioch et al., 2008; Webster et al., 2009; Blanchon, 2011).

Several studies of RSL at sites around the globe have suggested that glacio-eustatic sea-level rise following the Last Glacial Maximum was characterized by short, high-amplitude glacial discharge events, the most extreme of which is MWP-1A, which has been studied at several locations, including Barbados (Fairbanks, 1989; Bard et al., 1990; Fairbanks et al., 2005; Peltier and Fairbanks, 2006), Tahiti (Bard et al., 1996; 2010; Deschamps et al., 2012), Papua New Guinea (Chappell and Polach, 1991; Edwards et al., 1993; Cutler et al., 2003), Sunda Shelf (Hanebuth et al., 2000), Vanuatu (Cabioch et al., 2003), and the Marquesas (Cabioch et al., 2008). However, there is still debate on the timing, magnitude, rate, and meltwater source of this abrupt sea-level rise event, despite how critical these data are for understanding the dynamics between climate, global ice-sheet melting, ocean circulation, and global mean sea level (Weaver et al., 2003; Deschamps et al., 2012; Lambeck et al., 2014; Liu et al., 2016). It remains unclear how and if MWP-1A, the Bølling warming, and a potential intensification of the Atlantic Meridional Overturning Circulation are related temporally and mechanistically; specifically, if an Antarctic meltwater source could result in a causal relationship between MWP-1A and the Bølling warming, or if the climatic mechanisms are incompatible with a MWP synchronous with climatic warming (Weaver et al., 2003; Stanford et al., 2006; Deschamps et al., 2012; Golledge et al., 2014; Gregoire et al., 2016; Ivanovic et al., 2017).

MWP-1A was first identified based on the age and stratigraphy of *Acropora palmata* samples from submerged reefs off Barbados (Fairbanks, 1989; Blanchon and Shaw, 1995; Fairbanks et al., 2005; Peltier and Fairbanks, 2006) and was constrained to between 14.08 ± 0.06 and 13.63 ± 0.03 ka (ages updated by Deschamps et al., 2012). Further evidence from Tahiti placed the timing of MWP-1A 500 years earlier, between 14.65 ± 0.02 and 14.31 ± 0.04 ka (Deschamps et al., 2012) coeval with the start of the Bølling-Allerød interstadial (Rasmussen et al., 1998) and within the reported uncertainty of the 14.72 ± 0.10 ka drowning age of the -150 m reef in Kealakekua Bay, Hawaii (Webster et al., 2004), as well as the

MWP-1A initiation timing from the Sunda Shelf sediment core record (Hanebuth et al., 2000) of 14.64 ± 0.87 ka (ages updated by Stanford et al., 2011).

Previous studies have examined the drowning of the -150 m H1d deglacial reef terrace on the west coast of Hawaii using samples collected by submersibles and island-wide bathymetry data (Moore and Fornari, 1984; Webster et al., 2004; 2009). Later work off Hilo on the east coast did not recover any shallow-water (<20 m paleowater depth) corals (Puga-Bernabéu et al., 2016). While H1d has been mapped discontinuously around the island and drowning signatures identified in several locations, temporal constraints of H1d drowning from Hawaii based on U-Th ages come from a single site off Kealakekua Bay (Webster et al., 2004). The purpose of this study is to develop a more comprehensive understanding of reef drowning on the island of Hawaii by sampling Kawaihae, another location 70 kms south along the west coast, which allows us to evaluate if the Kealakekua Bay drowning might have been a local effect. By investigating if H1d reef drowning occurred synchronously along the coast, reef drowning in response to a deglacial meltwater pulse can be supported. This study integrates new and existing geomorphic, sedimentary and chronological data from the drowned terrace and develops paleoenvironmental interpretations using the distribution of modern reef-building and associated biota to examine the history of reef drowning. We report eight new radiocarbon ages, and consider 15 published U-Th and radiocarbon ages from Hawaii. This suite of sedimentary and chronological data is analyzed in context to investigate the timing of island-wide drowning of the -150 m reef terrace and the initiation of MWP-1A.

2. GEOLOGICAL AND BIOLOGICAL SETTING

Hawaii is located at the southeastern end of the Hawaiian-Emperor Seamount Chain (Fig. 1), and is currently positioned over the Hawaiian hotspot; the associated volcanism has resulted in the chain of shield volcanoes that are the Hawaiian Islands. Hawaii's development on this bathymetric high has been shaped by the evolution of its five subaerial and two submarine volcanoes, and it has grown at an average rate of 0.02 km^2/yr for the past 600 kyr (Moore and Clague, 1992). As an intra-oceanic volcanic island, rapid and constant subsidence on Hawaii is almost entirely caused by flexure of the lithosphere due to volcanic loading; this is controlled by the thickness of the oceanic lithosphere and rheology of the underlying mantle, which remain constant over millennial timescales (Moore, 1970; Moore, 1987; Ludwig et al., 1991; Zhong and Watts, 2002; Huppert et al., 2015). The massive addition of lava as the volcanoes grow on the aging oceanic crust is the primary mechanism for the island's vertical motion (Huppert et al., 2015). Potential departures from this rapid subsidence include unloading from giant landslides, which would lead to short-term uplift of the island and exposure of the coral reefs, or large-scale slump movement, which is limited to the active flanks of the volcanoes, such as Kilauea (Moore et al., 1989; Smith and Wessel, 2000; Day et al., 2005). Due to the location and sedimentary evidence, these rapid subsidence events would not be pertinent to the drowning of the -150 m reef.

Based on paleoshoreline data from west Hawaii, a long-term subsidence rate of 2.5 to 2.6 mm/yr over 475 to 500 kyr has been calculated (Ludwig, 1991), which is also appropriate for the past 15 kyr (Moore, 1970; Moore and Campbell, 1987; Webster et al., 2004; 2007). Similar rates were found based on age-depth relationships of the Mauna Kea submarine transition (2.7 ± 0.7 mm/yr over 400 kyr; Sharp and Renne, 2005) as well as the carbonate platforms off the east coast of Hawaii (2.80 ± 0.36 mm/yr over 150 kyr; Puga-Bernabéu et al., 2016). However, there are conflicting measurements of shorter timescale subsidence rates based on static global positioning system (GPS) measurements, which are associated with high uncertainties because they are short time-series. The difference in vertical velocities between the presumably stable tide gauge at Honolulu, Oahu and one at Hilo, Hawaii over 16 years (1996–2002), indicates Hawaiian subsidence of 0.4 ± 0.5 mm/yr (Caccamise et al., 2005), whereas another 9 year GPS record from Mauna Kea, indicates that Hawaii is subsiding 2.21 ± 1.55 mm/yr relative to Honolulu (Bouin and Woppelmann, 2010). The subsidence rate of 2.5 mm/yr will be applied in this study based on its suitability for the timescale and for comparison to previous studies.

This continual subsidence has contributed to the submergence of fringing reefs flanking Hawaii, which, combined with eustatic sea-level change, is responsible for the formation of the reef terraces. Previous studies have identified up to 12 submerged terrace features down to -1500 m, with high-resolution bathymetric mapping revealing a series of four well-preserved backstepping sub-terraces between -50 and -150 m (Moore and Clague, 1992; Webster et al., 2009). This study focuses on the -150 m submerged terrace, or reef H1d (as defined here), previously referred to as Reef 1 (Webster et al., 2004) and the –150 m terrace H1c (Webster et al., 2009).

Interpretation of paleo-reef communities requires an understanding of the modern zonation of reef-building photosynthetic species, which are generally found in specific wave energy regimes and over a narrow vertical depth range due to the attenuation of light with depth. Modern Hawaiian reefs are dominated by reef-building *Porites* spp. (particularly *Porites lobata* and *Porites compressa*), *Montipora* spp., and *Pocillopora* spp. on the reef crest and upper slope at <20 m water depth, although mesophotic corals may occur much deeper (Dollar, 1982; Engels et al., 2004; Luck et al., 2013). Modern zonation work in Molokai, Hawaii by Engels et al. (2004), found branching or columnar *P. compressa* is particularly dominant in lower-energy reef environments. In mid to high-energy communities, *Pocillopora meandrina* and *Montipora* sp. are particularly abundant in shallow (<10 m) higher-energy settings, while massive and encrusting *P. lobata* dominate from 10-25 m, though also occur shallower (<10 m), encrusting in high-energy assemblages. Percent living coral cover generally increases with depth within this shallow (<25 m) environment. As energy increases, percentage coralline algae coverage is higher, particularly in shallow (<5 m) waters (Engels et al., 2004).

Coralline algae form important parts of the reef systems and commonly encrust coral skeletons, with *Porolithon onkodes* as the most abundant shallow-water species from the intertidal zone to 10 m water depth, although it may grow up to 20 m water depth (Adey et al., 1982). Associated biota, including vermetid gastropods, which are abundant in the intertidal zone and most frequently occur <5 m, are often preserved in fossilized material (Hadfield et al., 1972). Figure 2 outlines the depth range of common Hawaiian reef builders and associated biota with importance for paleoenvironmental interpretations.

3. METHODOLOGY

3.1 Sample recovery

A joint field campaign between the University of Sydney, Monterey Bay Aquarium Research Institute (MBARI), and the Association for Marine Exploration was conducted in 2013 off Kawaihae, Hawaii to collect samples from the reef crests of drowned terraces between depths of 50–150 m. Twenty-nine samples were collected from the submerged terraces using mixed-gas technical SCUBA (Fig. 3B). Large coral samples were chosen by the divers at depth, pried from the bottom using a hammer and chisel, and brought to the surface with aid of a float bag. This study focuses on ten of these samples collected from the H1d terrace at approximately -144 m.

3.2 Geomorphic context

High-resolution 2D and 3D bathymetric and backscatter mapping data were integrated to analyze the context of the larger-scale reef system response to deglacial sea-level rise, and to examine evidence of reef drowning along the entire western Hawaiian coast. New and published MBARI (2000) bathymetric and backscatter grids at 3 m (Kawaihae Bay) to 30 m (west coast regional map) resolution were imported into Arc Map 10.2 and QPS Fledermaus 7 for analysis, where Digital Elevation Models (DEM), slope maps and bathymetric profiles were generated. Terrace boundaries were defined and traced based on a suite of criteria established from previous studies (Webster et al., 2004; Faichney et al., 2011; Puga-Bernabéu et al., 2016), including steep slope break, high backscatter response near the margin, as well as visual confirmation based on available underwater photographs and submersible surveys. Additionally, underwater images of the precise locations of the sample locations taken by the human divers were incorporated to elucidate the sample context and analyze local reef features (e.g., Fig. 3A, B).

3.3 Sedimentary analysis

The samples (e.g. Fig. 3C, D) from the H1d reef were examined in hand sample and petrographic thin section to determine lithofacies, coral taxonomy and morphology, algae taxonomy and thickness, associated biota and abundance, and the composition of muds and cements. Established methods were utilized to determine if samples were recovered *in situ*, including 1) the presence of sediment geopetals in cavities, 2) encrusting coralline algae growth on upper surface, and 3) the upwards orientation of coral growth form or corallites (Cabioch et al., 1999; Camoin et al., 2007). The carbonate deposits were classified using primary reef framework and reef detritus descriptors (Camoin et al., 2007; Webster et al., 2011) and samples were categorized into five fossil lithofacies with specified paleowater depth ranges. The water depth distribution of modern calcifying reef biota was used to interpret the sedimentary record (Fig. 2).

3.4 Radiometric dating of H1d

3.4.1. Sample preservation

The best-preserved top one to two growth bands of five *Porites* spp. samples were subsampled and cleaned in an ultrasonic bath prior to dating. An initial round of bulk radiocarbon dating was carried out; however, the samples were found to be highly heterogeneous, with areas exhibiting visible diagenetic alteration based on petrographic thin section microscopy. Following established methods for identifying diagenetic textures of fossil corals in thin section (McGregor and Gagan, 2003; Allison et al., 2007; McGregor and Abram, 2008), intensive petrographic analysis of the dated material and areas directly adjacent was undertaken (Fig. 4A). Post-depositional alteration including extensive infilling of the coral skeletal pore space with cements (secondary aragonite precipitation) and muds, micritic rim development, dissolution of original aragonite, and dissolved centers of calcification were found in areas of the samples (Fig. 4A, B). Based on the prevalence of diagenesis, sections of each sample were categorized on a four-point scale, and only material meeting the criteria of minimal (level 1) diagenesis (i.e., with dark and clearly visible centers of calcification, and lacking visible micrite, cements or secondary mineral growth) were classified as “vetted” and used for a second round of targeted radiocarbon dating, and included in the reef chronology.

3.4.2 Radiocarbon dating

The powdered *Porites* samples (1-2 mg) were prepared using the small-volume graphitization vacuum line and measured by accelerator mass spectrometry (AMS) at the Analytical Center for Environmental Science, Atmosphere and Ocean Research Institute, University of Tokyo, Japan (Yokoyama et al., 2010; Hirabayashi et al., 2017). All coral ^{14}C ages (including all incorporated published ^{14}C ages) were calibrated to age BP (ka) with 2σ

errors using CALIB.7 using the Marine13 2013 international calibration datasets (Reimer et al., 2013) with a mean ocean reservoir local variation (ΔR) correction of -38 ± 3 ^{14}C years (Druffel et al., 2001).

3.4.3 U-Th records

To provide additional chronological context for these samples, we combined recalculated ages from Hibbert et al. (2016) based on previously published U-Th data from other deglacial coral records (Edwards et al., 1993; Cutler et al., 2003; Fairbanks et al., 2005; Bard et al., 2010; Deschamps et al., 2012) as well as additional U-Th age data (Webster et al., 2004; Fairbanks et al., 2005) that we have recalculated following the methodology from Hibbert et al. (2016). All ages (including recalculated published ages) are presented as age BP (ka) with 2σ errors. Age recalculations used the decay constants of Cheng et al. (2013) for ^{230}Th and ^{234}U, and Jaffey et al. (1971) for ^{238}U.

4. RESULTS

4.1 Geomorphology of the H1d terrace

H1d is a well-defined terrace feature off Kawaihae, which is mapped continuously from the northern tip of the island to just south of Kealakekua Bay from the high-resolution DEMs (Fig. 1A). It lies in a series of submerged terraces that have been described down to -1500 m (Webster et al., 2009; Puga-Bernabéu et al., 2016). Off Kawaihae, it runs roughly parallel and close (<5 km) to the modern coast (Fig. 1B). It displays fringing reef morphologies with a raised rim and gentle seaward slope at the top, and minor spur and groove features above a steeply descending seaward slope (Fig. 5). Diver photos and backscatter data reveal a smooth and dense coralgal pavement with overlying patchy mixed sand (Fig. 3A, B, Fig. 1C). The new samples from Kawaihae were collected from the uppermost H1d reef crest, at approximately -144 m. In some areas to the south of the study site, the morphology of H1d is modified by lava flows that overlie and underlie the reef (Moore and Clague, 1987). Off Kealakekua Bay, the terrace is slightly narrower, with the slope break approximately 2 km offshore (Fig. 1D). The seaward slope has a higher gradient than in the north, predominantly >60º. The previously collected ROV *Tiburon* T291 samples from this area that are reanalyzed in this study were recovered from 150 m deep and are generally consistent with the Kawaihae H1d reef crest lithology. The slightly greater depth of the H1d terrace off Kealakekua Bay may be attributed to differential tilting due to volcanic loading (Moore and Campbell, 1987).

4.2 Description of observed lithofacies and paleoenvironmental interpretation

Due to their importance for paleoenvironmental reconstructions, the five sedimentary facies identified in the H1d samples are described, with paleowater depth ranges assigned from modern analogues of the ecological assemblages, following existing facies classification schemes (Webster et al., 2009; Faichney et al., 2011; Puga-Bernabéu et al., 2016) (Fig. 6).

4.2.1. Facies 1: Shallow coral framestone (<-10 or <-20 m)

This facies is represented by *in situ* encrusting, submassive and robust branching *Porites* spp. framework (Fig. 6A, B). The coral reef-builders are predominantly robust branching *P. compressa* and submassive *P. lobata,* along with *Pocillopora* spp. and *Montipora* spp. with associated coralline algae overgrowth in thin to medium (up to 5 cm) crusts or sandwiched between coral. Algae assemblages include *Porolithon onkodes*, '*Pneophyllum' conicum* and *Lithophyllum* gr. *prototypum*. Bioerosion is abundant, including sponge and mollusk borings.

The presence of *Porolithon onkodes* and vermetid gastropods indicate that this facies represents a paleoenvironmental setting of <-10 m (Fig. 7). Samples with minor amounts of or lacking these very shallow water indicators, can be constrained to <-20 m based on the depth range of *Porites* spp. and other shallow-water algae taxa (Adey et al., 1982; Braga and Aguirre, 2004; Webster et al., 2009; Dechnik et al., 2017). Skeletal pore space of the corals may be filled by sediment or cements characteristic of later stage, deeper facies.

4.2.2 Facies 2: Intermediate coralgal bindstone (-20 to -60 m)

This facies framework is predominantly coral-coralline algal bindstone with associated *Porites* spp. and *Montipora* spp. (Fig. 6C, D). Intermediate-water encrusting algal species include fruticose *Lithothamnion prolifer*, *Lithophyllum* gr. *prototypum*, *Lithophyllum insipidum*, '*Pneophyllum' conicum*, and *Harveylithon* gr. *munitum* (Adey et al., 1982; Braga and Aguirre, 2004; Webster et al., 2009; Dechnik et al., 2017). Bioerosion by mollusks, serpulids, and sponges is common and encrusting foraminifera are abundant. Hemipelagic and peloidal muds frequently infill pore space. This facies was relatively common in the sample suite, and is constrained to -20 to -60 m based on the intermediate depth range of algal taxa.

4.2.3 Facies 3: Deep coralline algal crust (-60 to -120 m)

Below the common depth range of shallow-water coral growth, this facies is defined by thin (<1 cm) crusts of deep-water coralline algae and Peyssonnelaceans. Observed taxa include *Lithothamnion* spp., *Mesophyllum* spp., *Sporolithon episoredion*, and *Peyssonnelia* sp., all with thin laminar thalli. The algae crusts are often heavily bioeroded, and have abundant encrusting foraminifera and hemipelagic sediment infilling (Fig. 6E, F). This deep-water facies generally encrusts shallower facies in a subsiding environment. Based on comparison with modern deep fore-reef slope settings, this facies is loosely constrained to -

60 to -120 m paleowater depth (Webster et al., 2009); living coralline algae may occur below -120 m as very thin (mm scale) crusts, but lack reproductive structures, as evident from crusts on volcanic samples collected by submersibles along the west coast of Hawaii (Braga et al., 2005). This facies was relatively uncommon in the sample suite.

4.2.4 Facies 4: Deep-water peloidal sediment (-120 to -150 m)

This facies is characterized by microbial carbonate deposition with peloidal/clotted microfabrics, occurring in deep-water environments, below the zone of active reef-building coral and coralline algae growth. It is not commonly observed in the H1d samples, and primarily occurs as fine scale (<1 mm) peloidal sediments that infill the cavities of shallower facies (Fig. 6G, H). Based on stratigraphic evidence, this facies postdates Facies 3, and thus has been deposited at greater than -120 m off Kawaihae (Webster et al., 2009).

4.2.5 Facies 5: Hemipelagic/pelagic sediment (>-20 m)

The hemipelagic/pelagic micrite facies commonly infills pore spaces of shallower facies (Fig. 6I, J). It is dominated by planktic and small benthic foraminifera, with minor mixed volcanic sediments and other minor bioclasts. This sediment is often deposited as a geopetal, a key indication of *in situ* preservation of reef structure, as it infills cavities or borings. This facies does not have a well constrained depth range, but based on stratigraphic relationship, is likely deeper than the shallow-water coral and coralline algal growth, at >-20 m (Webster et al., 2009).

4.3 Chronological data

The eight new radiocarbon ages from vetted and mostly *in situ* H1d *Porites* samples recovered from -144 m have calibrated mean ages and 2σ uncertainties ranging from 14.75

+0.33/-0.42 ka to 16.01 +0.23/-0.25 ka (Table 1 and Fig. 8). The non-vetted bulk samples, with dates spanning from 6.22 +0.06/-0.07 to 13.40 +0.13/-0.12 ka, are not included in this chronology due to issues with sample preservation.

5. DISCUSSION

5.1 Geomorphology, structure and composition of H1d

New high-resolution bathymetry data confirms the H1d terrace is a relatively continuous and extensive feature at approximately -150 m along the west coast of the Big Island until just south of Kealakekua Bay, consistent with previous mapping work (Webster et al., 2004). Evidence from Hilo, on the east coast, suggests the presence of a sub-terrace at approximately -150 m that likely drowned between 14 and 15 ka based on its stratigraphy and coralline algae ages. There, the reef was likely inhibited from backstepping by the influence of overlying volcanic flows (Puga-Bernabéu et al., 2016). Likewise, the morphology of H1d on the west coast is partially controlled by the presence of lava flows that overlie and underlie the terrace along the coast (Moore and Clague, 1987).

The underwater images, collected samples, and backscatter data in this study show that terrace H1d off Kawaihae is a clearly defined feature composed of coralgal reef material, implying it experienced substantial growth while reef-building corals could keep pace with island subsidence and sea-level changes. The reef crest is well-developed and composed of shallow reef facies including *Porites* spp. framestone. From the paleowater depth interpretation of the five described facies and the observed internal stratigraphy of the samples (Fig. 6), the later-stage deeper facies encrust and/or infill the shallow reef facies as the terrace subsided and sea level rose to the current position. From this, we interpret a complete sedimentary record of the drowning event occurring after the deposition of the shallow reef crest facies, marked by the subsequent occurrence of deeper material.

Several shallower sub-terraces are apparent shoreward of H1d (Fig. 5). Although coral material from the overlying H1c at approximately -125 m was not recovered nor dated, it may represent a backstepped sub-terrace marking a later sea-level stand (Webster et al., 2004). This backstepping response to episodes of sea-level rise is likely further observed in the low-relief substrate off Kawaihae from the sequential shallower sub-terraces H1b and H1a (Fig. 1B; Fig. 5), which are developed to varying degrees, and less clearly defined than H1d. Backstepping is not observed further south off Kealakekua Bay. This may be because of the much steeper antecedent substrate preventing reef growth from reinitiating in this region (Fornari et al., 1980; Webster et al., 2009), or incomplete high-resolution mapping.

5.2 Timing of H1d reef growth and drowning along the west coast

The timing of platform inception cannot be determined without the availability of deep core material, which allows for sampling beneath the outcrops recovered by this diving campaign. Previous numerical modeling work on Hawaii has demonstrated that reef platform development likely started during stable sea-level highstands, with the H1 terrace initiating during early MIS 5 (~126 ka) and developing episodically over a period of 90 kyr (Webster et al., 2007). This model is consistent with a complex growth history in response to high-frequency suborbital sea-level fluctuations, with multiple subaerial exposures and successions of growth and brief drowning periods (<5–10 kyr) prior to the final last deglacial drowning (Webster et al., 2007). From the oldest Kawaihae ^{14}C ages, there is evidence for shallow-water reef growth for 1.26 +0.66/-0.57 kyr, from 16.01 +0.23/-0.25 ka (Fig. 8), consistent with a ^{14}C age from H1d off Kealakekua Bay (15.92 ± 0.18 ka; Moore and Fornari, 1984).

The sedimentary evidence suggests that H1d maintained shallow-water (Facies 1) reef growth during global averaged post-glacial sea-level rise of ~12 mm/yr between ~16.5–15 ka (Lambeck et al., 2014), with an additional 2.5 mm/yr of regional Hawaiian subsidence (Fig. 9). After prolonged resilience to this high RSL rise, the final drowning occurred at ~14.75 ka at both Kawaihae (14.75 +0.33/-0.42 ka) and Kealakekua Bay (14.72 ± 0.10 ka), based on the youngest dated *Porites* reef crest samples (Fig. 8). Following this time, shallow coral reef growth ceased and there was a stratigraphic transition to deeper facies, evident by intermediate to deep algae crusts (Facies 2 and 3), and the presence of deep peloidal (Facies 4) and hemipelagic (Facies 5) sediments that infill coral pore space. Although intermediate to deep algal overgrowth could not be dated in the Kawaihae samples due to preservation issues, similar material from Kealakekua Bay (sample T291-R8) yielded a calibrated age of 14.44 +0.34/-0.30 ka.

The consistency of the new ages with previously published ages confirms that shallow-water reef drowning took place at or shortly after ~14.75 ka, in two locations along the west coast of Hawaii. When reef drowning of H1d initiated, the dated corals in Kawaihae and Kealakekua Bay would have been submerged <10 m deep, based on the presence of associated shallow-water algae (*Porolithon onkodes*) and vermetid gastropods. Considering island subsidence (2.5 mm/yr) and the paleowater depth of the samples, sea-level position at the time of reef drowning and the initiation of MWP-1A, would have been between 95 to 105 m below present sea level (Fig. 8)

While the conditions required to drown a coral reef remain unclear, it is evident that sea-level rise associated with MWP-1A (global averaged rise of >40 mm/yr; Lambeck et al., 2014), in addition to the high local subsidence, greatly outpaced the ~10 mm/yr limit of vertical accretion of shallow reefs in Hawaii (Fig. 8, 9). Similarly, shallow-water *Acropora palmata* reef growth in Barbados is reported to have drowned as a direct result of MWP-1A, evident from the distinct breaks in reef framework and backstepping reef growth, where the lower diversity and smaller depth range of corals (compared to the Indo-Pacific) may have been a contributing factor (Fairbanks, 1989; Blanchon and Shaw, 1995; Blanchon, 2011). However, similar signatures of reef drowning are not observed in other reef systems experiencing lower subsidence rates. Tahitian deglacial reefs, for example, did not drown as a direct result of MWP-1A. In several Tahiti cores, a shift to the more turbidity-tolerant massive *Porites* coral assemblage is evident prior to the meltwater pulse, between 15.23 ± 0.03 ka to 14.72 ± 0.03 ka (Abbey et al., 2011; Camoin et al., 2012), and a transition to a less dense framework of fast-growing branching *Porites* and *Pocillopora* coral assemblages during the ~350 yr period of MWP-1A (14.65–14.31 ka) (Abbey et al., 2011; Camoin et al., 2012; Deschamps et al., 2012). In addition to the lower rates of RSL rise experienced in Tahiti due to lower subsidence rates (published rates based on difference reference levels include 0.15 mm/yr, Pirazzoli and Montaggioni, 1988; 0.25 mm/yr, Deschamps et al., 2012; 0.5-0.6 mm/yr, Blanchon et al., 2014) the higher diversity of coralgal taxa present in Tahitian reefs may have allowed for continual coral growth and made it more resistant to drowning compared to its Hawaiian counterpart.

5.3 Timing of MWP-1A

The oldest possible timing of the H1d shallow-water reef drowning from both Kawaihae (^{14}C age 14.75 +0.33/-0.42 ka) and Kealakekua Bay (U-Th age 14.72 ± 0.10 ka) in Hawaii is consistent, within reported analytical uncertainties, with the timing of MWP-1A initiation based on the IODP Exp. 310 Tahiti record (14.65 ± 0.02 ka; Deschamps et al., 2012) (Fig. 9). This places the timing of MWP-1A coeval with the onset of the Bølling warming (~14.6 ka; Rasmussen et al., 1998; Lambeck et al., 2014) and thus with intensifying thermohaline circulation (Kienast et al., 2003), suggesting a possible causative coupling between the two events. Although the conditions required to drown a coral reef remain uncertain, this rapid RSL rise and associated climatic shift resulted in conditions in which shallow-water reef growth could not be sustained in Hawaii. This rapid rate of rise would have increased paleowater depths above the depth range of Facies 1 shallow coral growth, causing a rapid shift to intermediate and deeper facies growth.

6. CONCLUSIONS

Our results support the drowning of the H1d coral reef terrace on the west coast of Hawaii as a result of MWP-1A, based on the timing constrained by samples from Kawaihae (^{14}C age 14.75 +0.33/-0.42 ka) and Kealakekua Bay (U-Th age 14.72 ± 0.10 ka). These dates are consistent with the timing of the initiation from the IODP Exp. 310 Tahiti reef record (14.65 ± 0.02 ka; Deschamps et al., 2012). The near-identical timing of reef drowning in both locations in Hawaii is supported by high-resolution bathymetric mapping, from which H1d is interpreted as a continuous feature along the west coast. At the time of drowning, H1d shallow reef growth is constrained to <10 m water depth based on sedimentary paleoenvironmental indicators, placing sea-level position at between 95 to 105 m below present sea level, considering a local subsidence rate of 2.5 mm/yr. After this time, shallow facies coral reef growth ceased and intermediate to deep facies were subsequently deposited. On a geomorphic scale, the terrace exhibits apparent backstepping upslope of reef H1d, consistent with episodic rapid sea-level rise events with intervening conditions favorable to coral growth. These results support MWP-1A and associated climatic changes causing deglacial reef drowning of H1d at or after ~14.75 ka.

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Conflicts of interest: none

Figure Captions

Figure 1. Hawaii regional shaded nearshore bathymetric map showing the location of the study area off the west coast of Hawaii. (A) H1d terrace traced down the west coast of Hawaii, including the location of the samples analyzed in this study (10 m bathymetric grid). (B) The mapped sub-terraces of the Kawaihae region at approximately - 150 m (H1d), -125 m (H1c), -110 m (H1b), - 70 (H1a) and -50 m (modern reef), with the location of the new samples (3 m bathymetric grid). (C) Corresponding backscatter for Kawaihae (3 m resolution). (D) The H1d terrace mapped in Kealakekua Bay (10 m bathymetric grid; all maps GCS WGS1984; MBARI Mapping Team, 2000).

Figure 2. Predominant depth range (solid bar) and less frequent deeper extent (dashed line) for modern Hawaiian reef-building *Porites* coral (Maragos, 1977; Dollar, 1982; Engels et al., 2004; Storlazzi et al., 2005; Grigg, 2006) encrusting coralline algae growth (Adey et al., 1982; Braga and Aguirre, 2004) and associated vermetid gastropods (Hadfield et al., 1972) with importance for paleoenvironmental interpretation.

Figure 3. (A-B) Deep diver photographs of sample recovery on H1d. (C-D) Examples of split H1d *Porites* samples recovered from the location show in A/B, with the location of encrusting coralline algae (CCA) and vermetid gastropods (V) annotated. Images courtesy of Association for Marine Exploration and Monterey Bay Aquarium Research Institute.

Figure 4. (A) Petrographic images of pristine and diagenetic textures observed in cross-polarized light in 4x and 10x magnification, including cement or sediment infilling, preservation of centers of calcification, micritic rims, and secondary botryoidal aragonite needles infilling pore space. (B) Example of a sample map identifying vetted (outlined in

blue) and substantially altered (outlined in brown) areas used in the vetting of samples for geochemical analysis.

Figure 5. Location (top) of slope profile A-A′ (bottom) off Kawaihae (in QPS Fledermaus 7). The recovery location of the new sample suites is shown in blue (3 m bathymetric grid; GCS WGS1984).

Figure 6. Examples of the five classified facies in hand sample (left column), thin section (center column, with red boxes indicating approximate thin section location), and a schematic showing their representative stratigraphic order (right column). (A/B) Shallow-water algae encrusting *Porites* coral framestone. (C/D) Encrusting intermediate-water algae *Lithophyllum* gr. *prototypum*. (E/F) Infilled deep-water algae. (G/H) Deep-water peloidal sediment infilling. (I/J) Hemipelagic sediment infilling in cavity. Note the schematic illustrations are not to scale.

Figure 7. Characteristics of H1d Facies 1 features defining a <-10 m paleowater depth, including (A) *Porolithon onkodes* encrusting coralline algae, (B) *Porites* framework and (C) vermetid gastropods, all key shallow-water indicators (scale is same for all images).

Figure 8. Summary of chronological data from Kawaihae (blue symbols) and Kealakekua Bay (green symbols) including the new ^{14}C dated corals, published ages from Kealakekua Bay, and a RSL curve model for Hawaii based on an Earth-Ice sheet glacial isostatic adjustment (GIA) model (Bassett et al., 2005). Vertical error bars represent paleowater depth of the coral or algae samples, and horizontal errors denote 2σ age range. The transition from shallow (yellow) to deep (blue) facies growth is shown with shading.

Figure 9. New Hawaii shallow-water ages (orange, this study) and previously published ages from Hawaii (grey, Webster et al., 2004) plotted at depth of recovery, with a global averaged sea-level curve (black line, Lambeck et al., 2014). Plotted below are global published sea-level records, including Tahiti (pink, Bard et al., 2010; blue, Deschamps et al., 2012), Barbados (green, ages from Fairbanks et al., 2005 and depths from Peltier and Fairbanks, 2006), Huon Peninsula, Papua New Guinea (teal, Edwards et al., 1993; red, Cutler et al., 2003), and the Sunda shelf (purple, Hanebuth et al., 2000; ages updated by Stanford et al., 2011). All U-Th ages plotted are those recalculated by Hibbert et al. (2016), or following this methodology. The vertical bands indicate timing of MWP-1A based on the Tahiti (blue band, 14.31–14.65 ka; Deschamps et al., 2012) and Barbados (green band, 13.61–14.08 ka; Fairbanks, 1989) records. Horizontal errors denote 2σ age range. For the purposes of this figure, the RSL depths are stacked and the vertical depths are not the focus.

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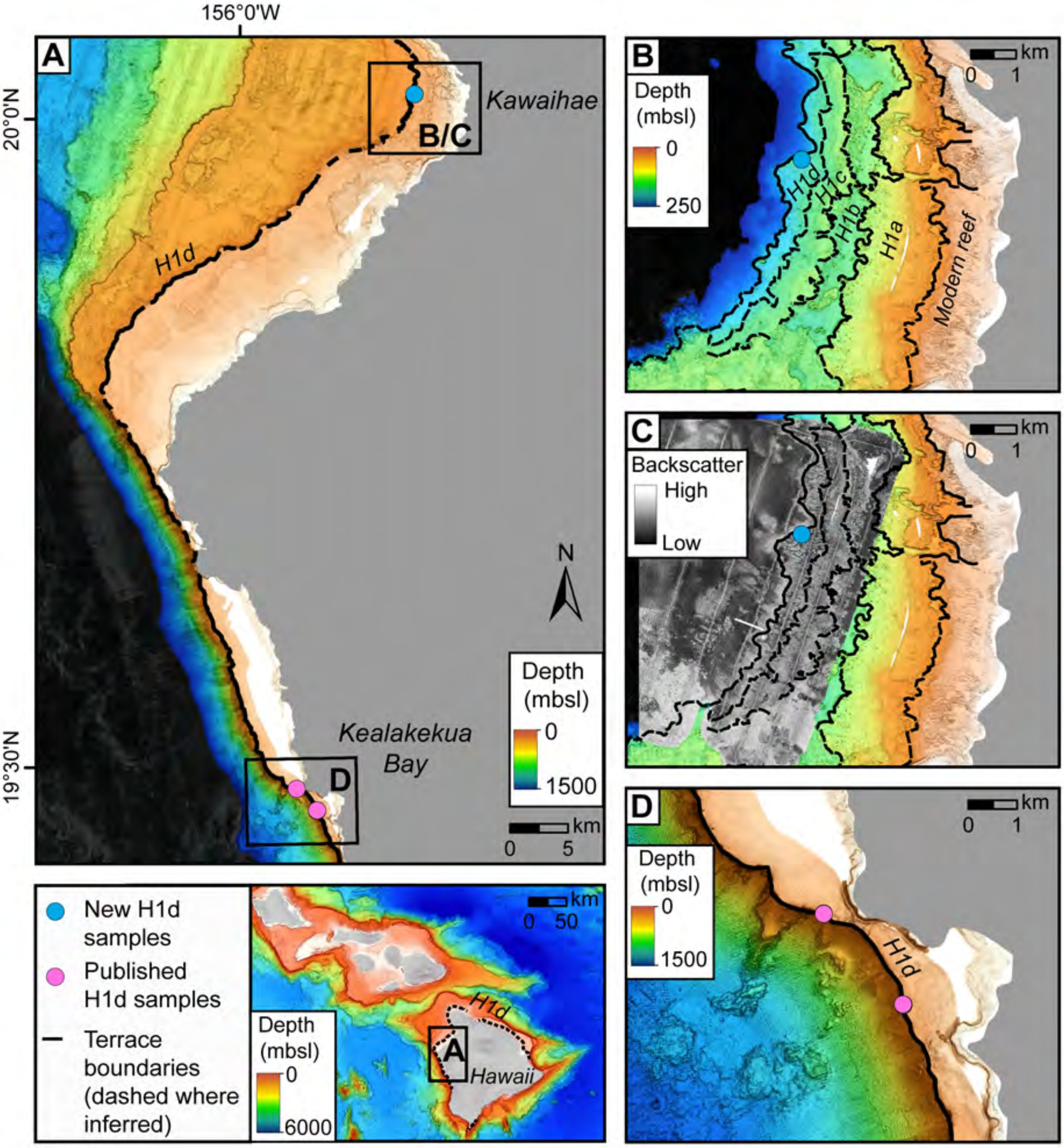

156°0'W
A
20°0'N
19°30'N
Kawaihae
B/C
H1d
N
Kealakekua
Bay
D
Depth
(mbsl)
0
1500
km
0 5
B
Depth
(mbsl)
0
250
km
0 1
H1d
H1c
H1b
H1a
Modern reef
C
Backscatter
High
Low
km
0 1
D
Depth
(mbsl)
0
1500
km
0 1
H1d
New H1d samples
Published H1d samples
Terrace boundaries (dashed where inferred)
Depth
(mbsl)
0
6000
km
0 50
H1d
A
Hawaii

Fig. 1

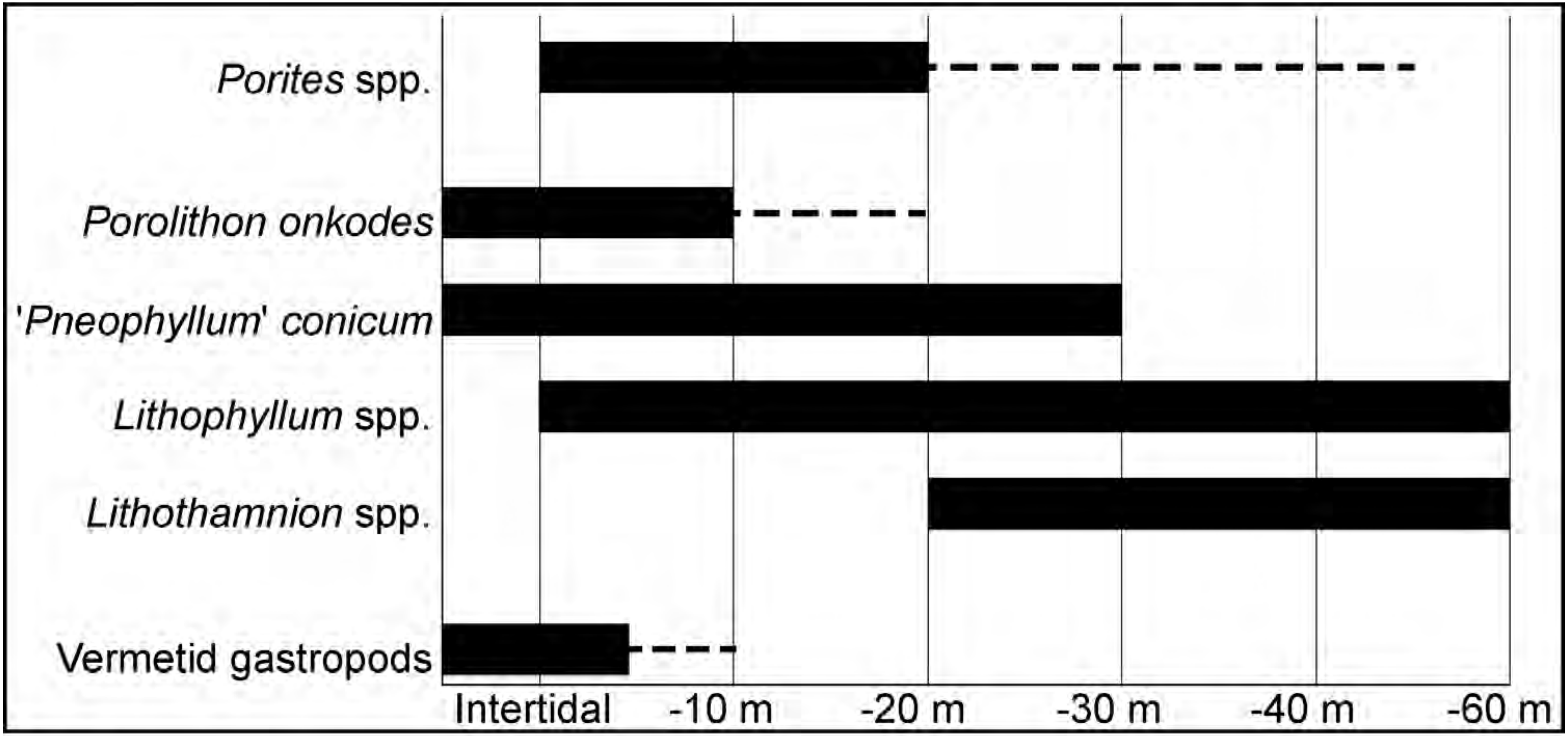

Porites spp.
Porolithon onkodes
'Pneophyllum' conicum
Lithophyllum spp.
Lithothamnion spp.
Vermetid gastropods
Intertidal
-10 m
-20 m
-30 m
-40 m
-60 m

Fig. 2

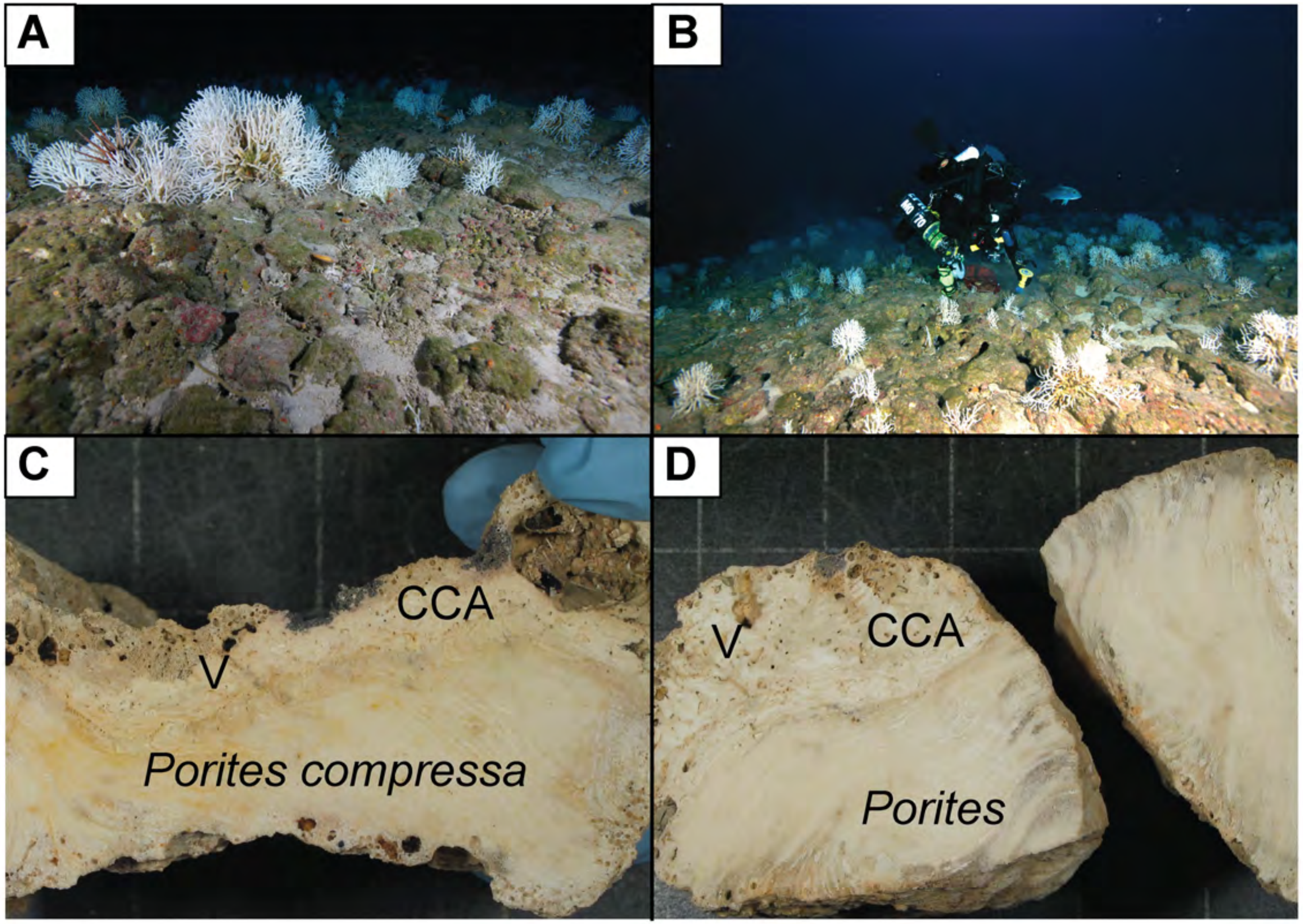
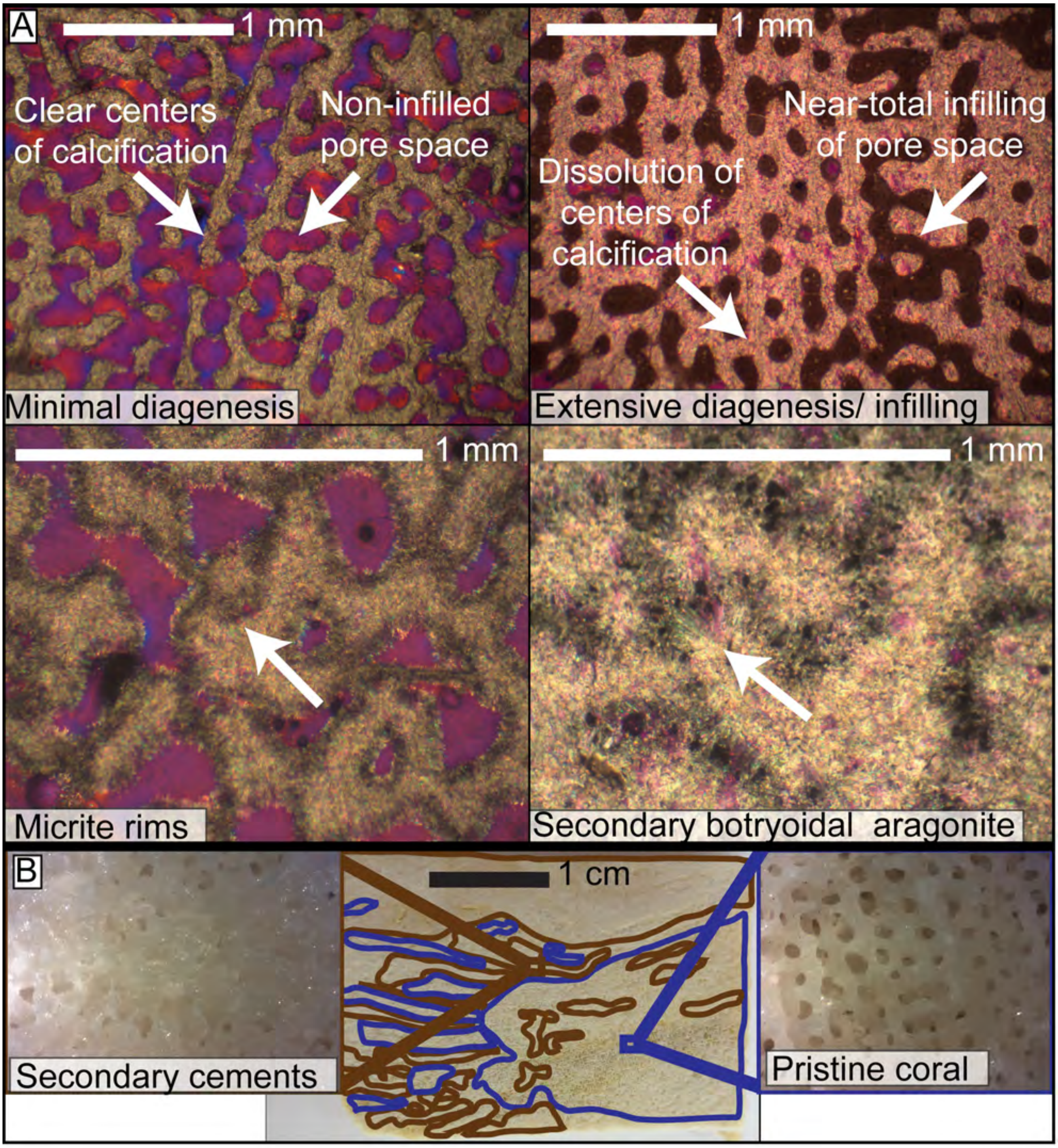


Fig. 3



A
1 mm
Clear centers of calcification
Non-infilled pore space
Minimal diagenesis
1 mm
Near-total infilling of pore space
Dissolution of centers of calcification
Extensive diagenesis/ infilling
1 mm
Micrite rims
1 mm
Secondary botryoidal aragonite
B
1 cm
Secondary cements
Pristine coral

Fig. 4

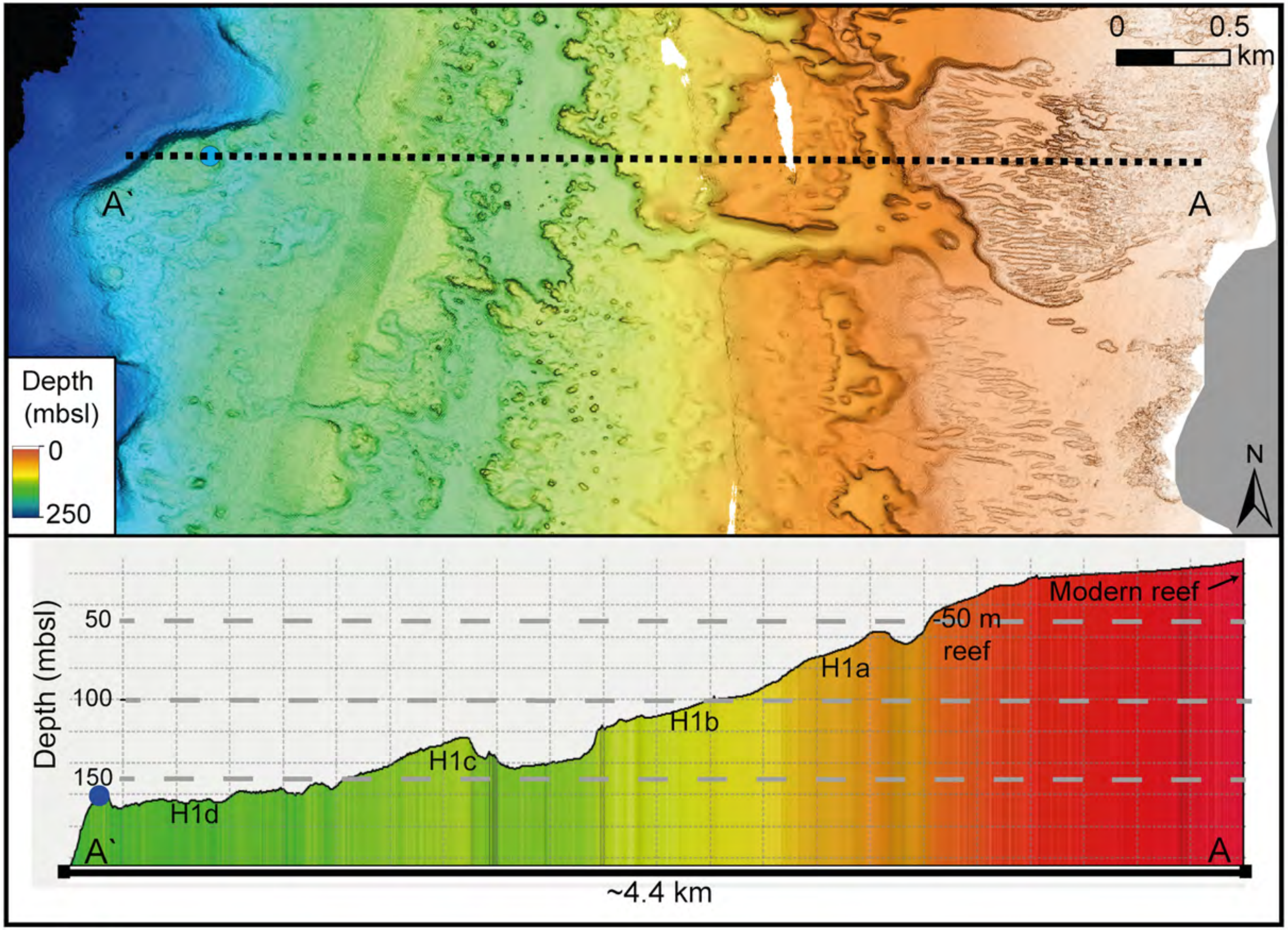

0
0.5
km
A`
A
Depth
(mbsl)
0
250
N
Depth (mbsl)
50
100
150
Modern reef
-50 m
reef
H1a
H1b
H1c
H1d
A`
A
~4.4 km

Fig. 5

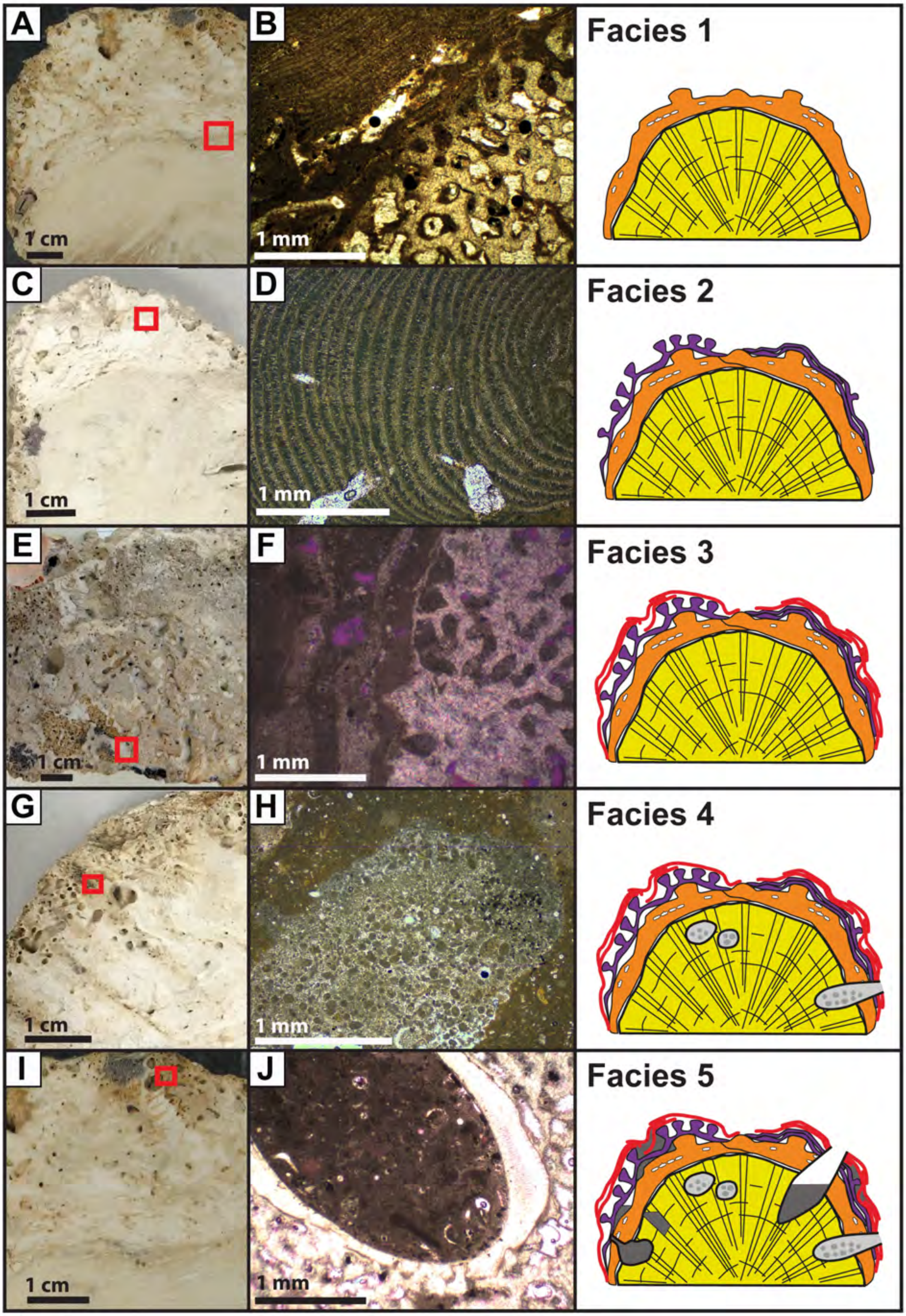

A
1 cm
B
1 mm
Facies 1
C
1 cm
D
1 mm
Facies 2
E
1 cm
F
1 mm
Facies 3
G
1 cm
H
1 mm
Facies 4
I
1 cm
J
1 mm
Facies 5

Fig. 6

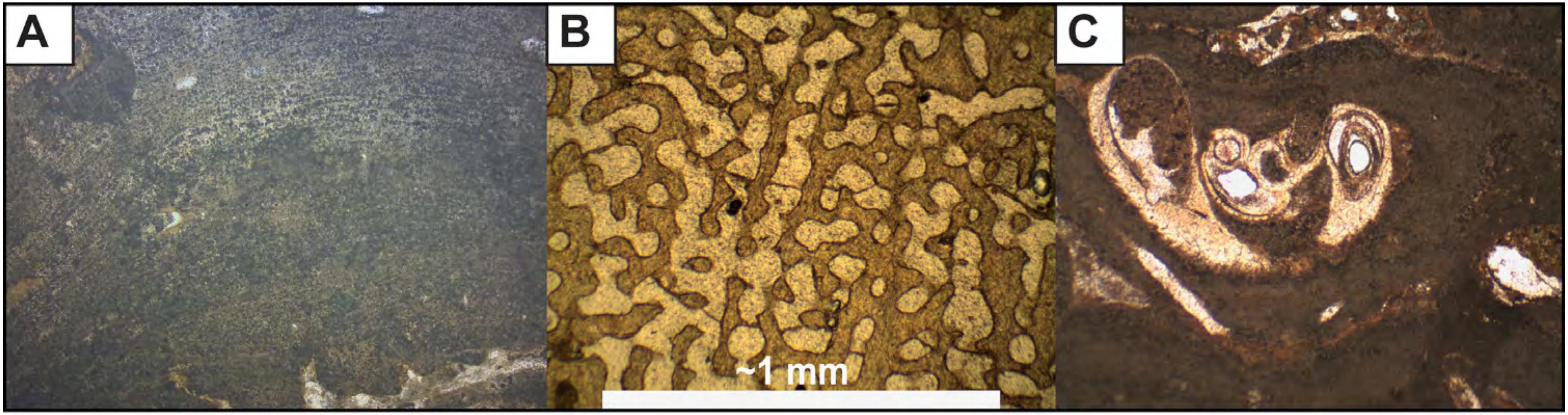
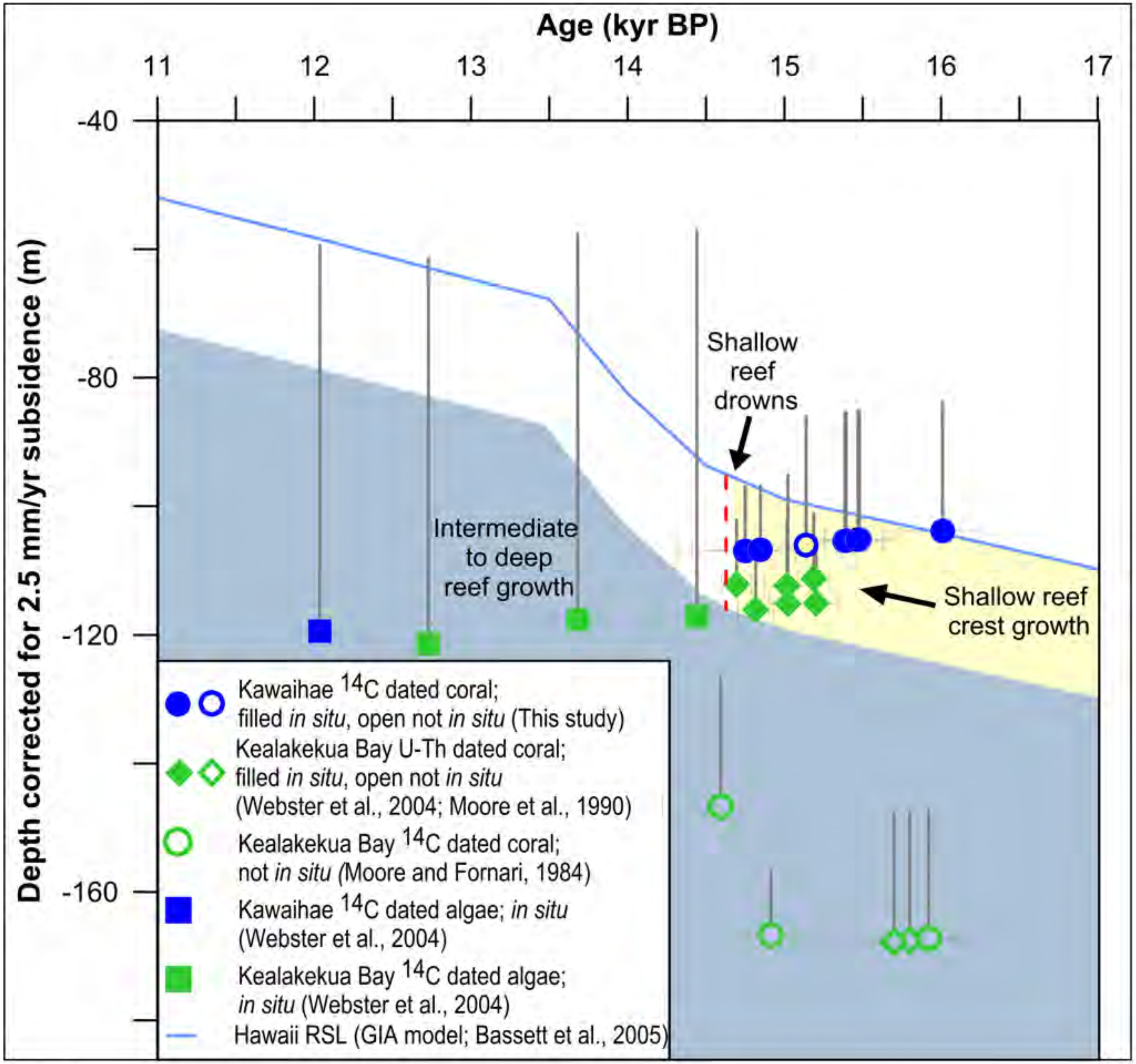
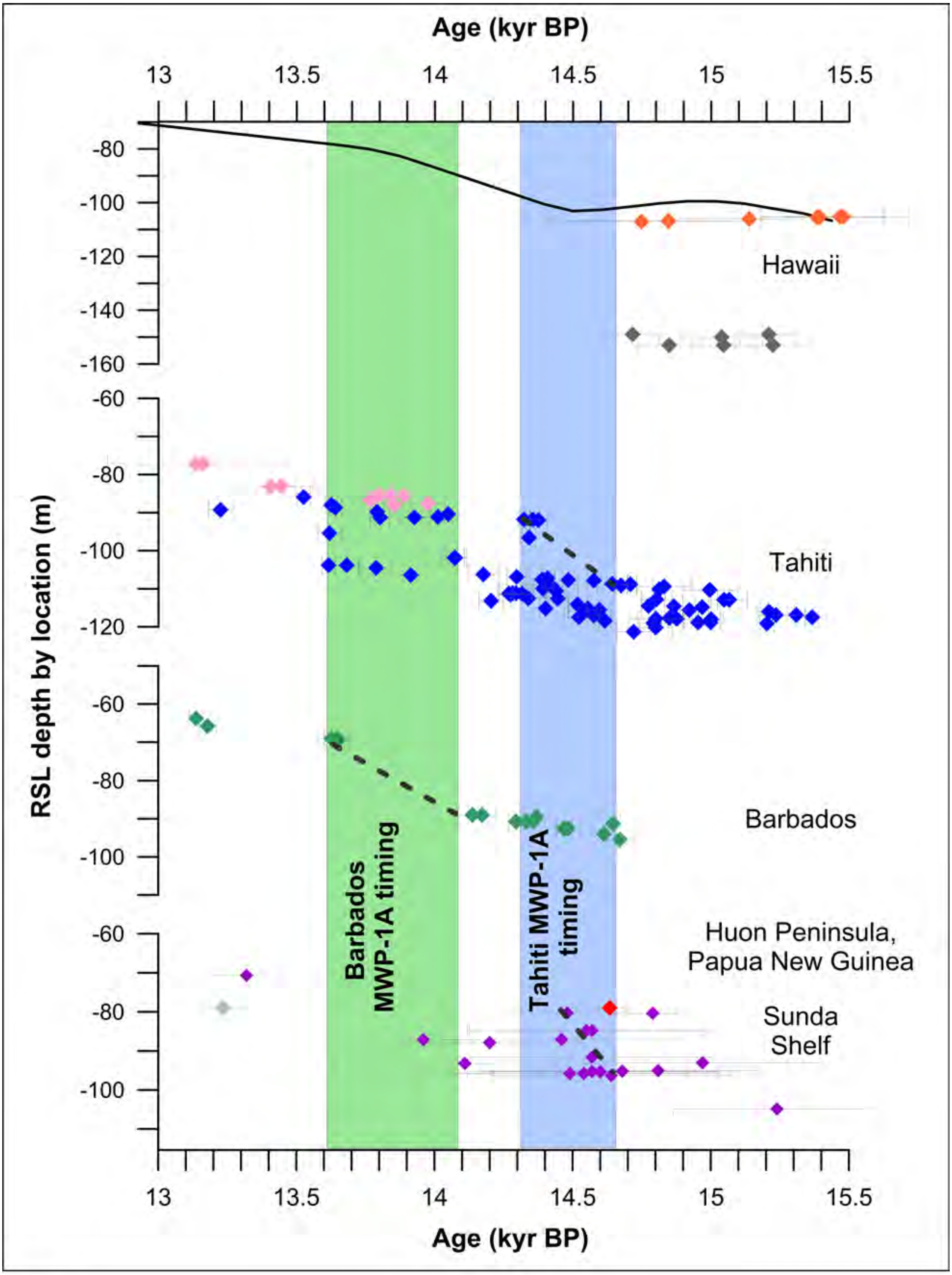


Fig. 7



Age (kyr BP)
11
12
13
14
15
16
17
-40
-80
-120
-160
Depth corrected for 2.5 mm/yr subsidence (m)
Shallow reef drowns
Intermediate to deep reef growth
Shallow reef crest growth
Kawaihae 14C dated coral; filled in situ, open not in situ (This study)
Kealakekua Bay U-Th dated coral; filled in situ, open not in situ (Webster et al., 2004; Moore et al., 1990)
Kealakekua Bay 14C dated coral; not in situ (Moore and Fornari, 1984)
Kawaihae 14C dated algae; in situ (Webster et al., 2004)
Kealakekua Bay 14C dated algae; in situ (Webster et al., 2004)
Hawaii RSL (GIA model; Bassett et al., 2005)

Fig. 8



Age (kyr BP)
13
13.5
14
14.5
15
15.5
RSL depth by location (m)
-80
-100
-120
-140
-160
-60
-80
-100
-120
-60
-80
-100
-60
-80
-100
Hawaii
Tahiti
Barbados
Huon Peninsula, Papua New Guinea
Sunda Shelf
Barbados MWP-1A timing
Tahiti MWP-1A timing
13
13.5
14
14.5
15
15.5
Age (kyr BP)

Fig. 9

Table 1. Hawaiian H1d sample data table

Sample Suite	Location	Sample code	Recovered depth (m)*	Latitude (□N)*	Longitude (□W)*	*In situ*?	Lithology	Radio-carbon age (^{14}C ka)	Calibrated median probability (kyr BP)	U/Th age (kyr BP) [†]	2σ calibrated age range (kyr BP) [†]	Source
New Vetted Sample Dating	Kawaihae	KAW1-472-A-1	-144	20.019	-155.865	Yes	Robust branching *Porites compressa?*	12.915± 0.055	14.750	n/a	14.326-15.076	This study
	Kawaihae	KAW1-472-A1	-144	20.019	-155.865	Yes	Robust branching *Porites compressa?*	12.944± 0.061	14.847	n/a	14.410-15.138	This study
	Kawaihae	KAW1-472-B-1	-144	20.019	-155.865	Yes	Robust branching *Porites compressa?*	13354± 0.056	15.479	n/a	15.262-15.716	This study
	Kawaihae	KAW1-472-B-3	-144	20.019	-155.865	Yes	Robust branching *Porites compressa?*	13.296± 0.056	15.385	n/a	15.179-15.625	This study
	Kawaihae	KAW1-472-B1-1	-144	20.019	-155.865	Yes	Robust branching *Porites compressa?*	13.698± 0.078	16.010	n/a	15.764-16.244	This study
	Kawaihae	KAW1-472-B1-4	-144	20.019	-155.865	Yes	Robust branching *Porites compressa?*	13.299± 0.056	15.394	n/a	15.185-15.633	This study
	Kawaihae	KAW1-472-D1	-144	20.019	-155.865	Yes	Submassive *Porites lobata?*	13.356± 0.056	15.469	n/a	15.254-15.707	This study
	Kawaihae	KAW1-472-E1	-144	20.019	-155.865	Unclear	Robust branching *Porites compressa?*	13.103± 0.062	15.139	n/a	14.851-15.332	This study
Tiburon	Kawaihae	T276-R5	-150	20.018	-155.866	Yes	Coralline algae (*Lithothamnion prolifer*)	10.635± 0.045	12.036	n/a	11.816-12.296	Webster et al., 2004
Makali'i	Kealakekua Bay	M-162-3	-204	19.471	-155.943	No	*Porites*	12.940± 0.050	14.914	n/a	14.600-15.160	Moore and Fornari, 1984
	Kealakekua Bay	M-169-1	-183	19.468	-155.943	Unclear	*Porites*	12.820± 0.060	14.594	n/a	14.223-14.991	Moore and Fornari, 1984
	Kealakekua Bay	M-170-5A	-207	19.478	-156.101	No	*Porites*	n/a	n/a	15.8	15.300-16.300	Moore et al., 1990
	Kealakekua Bay	M-170-5B	-207	19.478	-156.101	No	*Porites*	n/a	n/a	15.7	15.200-16.200	Moore et al., 1990

Sample Suite	Location	Sample code	Recovered depth (m)*	Latitude (□N)*	Longitude (□W)*	*In situ*?	Lithology	Radio-carbon age (^{14}C ka)	Calibrated median probability (kyr BP)	U/Th age (kyr BP) †	2σ calibrated age range (kyr BP) †	Source
Makali'i	Kealakekua Bay	M-170-5C	-207	19.478	-156.101	No	*Porites*	13.610± 0.050	15.920	n/a	15.732-16.104	Moore and Fornari, 1984
	Kealakekua Bay	T291-R12D	-152	19.466	-155.94	Yes	Coralline Algae (*Lithophyllum* sp.?)	12.185± 0.045	13.681	n/a	13.511-13.827	Webster et al., 2004
	Kealakekua Bay	T291-R16	-149	19.483	-155.956	Yes	*Porites*	n/a	n/a	14.718	14.813- 14.622	Webster et al., 2004
Tiburon	Kealakekua Bay	T291-R17A	-150	19.483	-155.956	Yes	*Porites*	n/a	n/a	15.039	15.186- 14.892	Webster et al., 2004
	Kealakekua Bay	T291-R4	-149	19.466	-155.94	Yes	*Porites*	n/a	n/a	15.210	15.315- 15.105	Webster et al., 2004
	Kealakekua Bay	T291-R7	-153	19.466	-155.94	Yes	*Porites*	n/a	n/a	15.225	15.363- 15.088	Webster et al., 2004
	Kealakekua Bay	T291-R8	-153	19.466	-155.94	Yes	Coralline Algae (*Lithophyllum* sp.?)	12.755± 0.050	14.442	n/a	14.143-14.782	Webster et al., 2004
	Kealakekua Bay	T291-R8A	-153	19.466	-155.94	Yes	*Porites*	n/a	n/a	14.849	14.967- 14.732	Webster et al., 2004
	Kealakekua Bay	T291-R8B	-153	19.466	-155.94	Yes	Coralline Algae (*Lithothamnion* sp., *Sporolithon* sp.)	11.216± 0.056	12.729	n/a	12.615-12.869	Webster et al., 2004
	Kealakekua Bay	T291-R9	-152	19.466	-155.94	Yes	*Porites*	n/a	n/a	15.047	15.1631- 14.930	Webster et al., 2004
Bulk Sample Dating	Kawaihae	KAW1-472-A	-144	20.019	-155.865	Yes	*Porites compressa?*	7.199± 0.030	7.697	n/a	7.618-7.782	This study
	Kawaihae	KAW1-472-D	-144	20.019	-155.865	Yes	*Porites lobata?*	7.340± 0.031	7.847	n/a	7.760-7.926	This study
	Kawaihae	KAW1-472-E	-144	20.019	-155.865	Unclear	*Porites compressa?*	5.749± 0.028	6.218	n/a	6.145-6.281	This study
	Kawaihae	KAW1-472-H	-144	20.019	-155.865	Yes	*Porites*	7.838± 0.032	8.345	n/a	8.268-8.412	This study
	Kawaihae	KAW1-472-D-1	-144	20.019	-155.865	Yes	*Porites lobata?*	11.952± 0.055	13.403	n/a	13.280-13.532	This study

*All depth information for new Kawaihae samples was obtained from dive computers at time of recovery and location was determined from GPS units at the surface.

†U-Th data recalculated following methodology of Hibbert et al. (2016).