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Revised Postglacial Sea-Level Rise and Meltwater Pulses from Barbados

RESEARCH PAPER

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ABSTRACT

Reconstructions of postglacial sea-level rise have provided key insight into the rapid disintegration of ice-sheets and the discharge of large meltwater pulses during the last deglaciation. The most complete reconstruction is from Barbados where thick, back-stepping sequences of the reef-crest coral *Acropora palmata* have been recovered in cores from the insular shelf and slope off the Island's south coast. Differences in the depth, timing, and magnitude of meltwater pulses between the Barbados reconstruction and other reefal records, however, has led to significant uncertainty in their origin, and the consequent timing of ice-sheet collapse. Here we re-analyse the published sedimentary, stratigraphic, and chronological data from Barbados, and find evidence for *ex-situ* data which indicates that reefal sequences contain coral clasts generated during hurricanes. By adjusting for biases caused by these *ex-situ* data, we provide a revised sea-level reconstruction which shows that MWP-1b was an 8–11 m rise from –53 m in ~250 years starting at 11.3 ka, which is 5 m smaller, and 150 years younger than previous estimates. It also shows that the onset of MWP-1a cannot be determined at Barbados because the downslope core sequences are not reef-crest deposits due to their association with deeper coral assemblages and lack of depositional relief. The end of this meltwater pulse can however be determined from the upslope reef, and occurred at a similar time and depth to that documented from Tahiti.

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1. INTRODUCTION

Postglacial reconstructions of sea level (SL) derived from submerged sequences of drowned coral-reefs have provided key insight into the timing and nature of ice-loss during the last glacial termination (Fairbanks 1989; Bard et al. 1990; Blanchon and Shaw 1995; Bard et al. 2010; Deschamps et al. 2012; Abdul et al. 2016). The first major advance was made by Fairbanks (1989), who recovered cores from postglacial reefs off the south coast of Barbados composed of thick sequences of the reef-crest coral *Acropora palmata* (Ap). Using only the age-depth data from these corals, and correcting them for tectonic uplift, he reconstructed SL rise during the last deglaciation and identified two "exceedingly rapid" rise events separated by a period of reduced melting. He suggested that the rapid-rises corresponded to intense pulses of seasonal melt-water discharge during the disintegration of Northern Hemisphere ice-sheets, and termed them Meltwater Pulses (MWP). Subsequent stratigraphic analysis showed that each MWP coincided with metre-scale gaps between core sequences, which represented episodes of reef-crest drowning and back-stepping on Barbados and other Caribbean islands (Blanchon and Shaw 1995). Coral ages in Ap units above and below these gaps indicated that the first pulse, MWP-1a, was a 19 m jump from –93 m in 450 years starting at 14.1 ka, and the second, MWP-1b, was a 14 m jump from –56 m in 300 years starting at 11.4 ka (Bard et al. 1990; Peltier and Fairbanks 2006). Subsequent drilling and further sampling of the existing cores has recently supported the timing and magnitude of MWP-1b on Barbados (Abdul et al. 2016).

Drilling of postglacial reef sequences elsewhere has also found evidence for meltwater-pulse induced jumps in SL, but have differed in depth, timing and magnitude to those on Barbados. On Papua New Guinea, a 52 m core from the rapidly uplifting reef terraces of the Huon Peninsula showed evidence that the onset of MWP-1b occurred at ~11 ka from a depth of 59 m, some 350 years later than on Barbados (Chappell and Polach 1991; Edwards et al. 1993). However, the Huon sequence is condensed due to the high-uplift rates, and the corals have larger depth ranges, thereby producing a less precise and lower resolution reconstruction than on Barbados. By contrast, a higher-resolution reconstruction based on cores from the modern barrier reef at Tahiti, which recovered a thicker 90 m sequence back to 13.8 ka, failed to register any SL jump during the same time interval as MWP-1b on Barbados (Bard et al. 1996; 2010). Furthermore, cores drilled in the fore-reef at Tahiti during IODP Expedition 310, found that MWP-1a was a 14–18 m jump from a depth of 105.2 m in 340 years, starting at 14.65 ka (Deschamps et al. 2012). This is 12 m deeper and 450 years earlier than on Barbados. This earlier timing (but not depth) is supported by non-reefal data from the Sunda Shelf, Indonesia, which registered MWP-1a as a 16 m jump from a depth of 96 m in 300 years starting at ~14.64 ka (Hanebuth et al. 2000).

Attempts to account for these differences in depth and timing between the Barbados and other reconstructions have considered the geophysical response to the balance between ice-mass and global SL but have yet to reach consensus on its importance (e.g., Bard et al. 2016; Mortlock et al. 2016). Some geophysical models show that the Barbados reconstruction closely reflects a eustatic or global average SL record with deviations of only 3–4 m at the last glacial maximum (Peltier and Fairbanks 2006; Peltier et al. 2015), whereas other models suggest a maximum deviation of 7 ±1 m (Austermann et al. 2013). Coupled with these deviations are the uncertainties of reconstructing SL from coral assemblages themselves which can also produce metre-scale uncertainty. Reef-crest corals in the Caribbean, for example, are thought to be restricted to a 5 m depth window based on the modern ecology, but drilling has shown that hurricanes destroy and redistribute the skeletal remains of these corals into waters as deep as 10 m (Blanchon and Perry 2004). Examining both geophysical and ecological assumptions is therefore required to better quantify differences between reconstructions.

Uncertainty in the depth, timing, and magnitude of meltwater pulses between reconstructions causes uncertainty in their origin, which has implications for the timing and nature of ice-sheet collapse and climate change during deglaciation. Originally, MWP-1a at Barbados was interpreted to coincide with the Older-Dryas cooling seen in Greenland ice-core records between 13.8–13.9 ka, and was postulated to cause instability in North Atlantic circulation that eventually led to the Younger Dryas cold interval (Bard et al. 1996; Bard et al. 2010). But the earlier timing of MWP-1a found at Tahiti and the Sunda Shelf led Deschamps et al (2012) to propose that it coincided instead with rapid warming at the onset of the Bølling-Allerod at 14.65 ka seen in Greenland ice-cores, and therefore pointed to a significant contribution of meltwater from the Antarctic ice sheet. Reconstructing the precise timing and magnitude of these meltwater pulses has therefore been central in identifying both leads and lags in deglacial climate change, and their magnitudes have provided important boundary conditions for glacio-isostatic and ice-sheet modelling (e.g. Peltier et al. 2015; Stokes et al. 2016).

Although the SL reconstructions from Tahiti and the Sunda Shelf each have their own set of problems (e.g. Blanchon 1998), they collectively show that the timing of MWP-1a on Barbados is anomalously late, and this in-turn raises uncertainty about the timing and magnitude of MWP-1b (Bard et al. 2016; Mortlock et al. 2016). Here we attempt to reduce the coral-derived uncertainty and reassess the Barbados SL reconstruction based on a detailed re-analysis of the published sedimentary and stratigraphic data, which to-date has received little attention. By comparing these data with that from modern Caribbean reefs, as well as fossil reef sequences from the last Interglacial, we report evidence which indicates that the postglacial sequences on Barbados are affected by the transport of coral clasts during hurricanes, and that this biases the SL record and the timing and magnitude of the two meltwater pulses. Assessing these biases, we provide a revised SL reconstruction which better estimates the magnitude and timing of both meltwater pulses. This revision helps reconcile some of the differences between Barbados and other postglacial SL reconstructions.

2. MATERIAL AND METHODS

On the south coast of Barbados, at Oistins Bay, two drilling expeditions recovered 14 cores with thick Ap sequences between the 10 and 80 m isobaths (***Figure 1***). From these cores more than 100 coral samples have recently been dated and re-dated (Abdul et al. 2016), providing a complete data set that extends back to 30 ka and makes earlier measurements redundant (e.g., Bard et al 1990). We use these age-elevation data to analyse reef development and accretion between 14.6 and 9.0 ka, covering the postglacial to early Holocene interval when meltwater pulses and reef drowning have been previously reported (Blanchon and Shaw 1995; Sanborn et al. 2017).

The ages of Ap coral samples and their recovered depths (uncorrected for subsidence) from all cores except RGF-9 and 15 were taken from Abdul et al (2016), who reported 106 Thorium-230 ages over a combined core interval of 79 m from 90 Ap corals (including 16 replicate ages). This gives an average sample interval of 0.87 m. Age-depth data (uncorrected for subsidence) for Ap units in RGF-9 and 15 were taken from Peltier and Fairbanks (2006), who reported 18 Th-230 ages over a combined core interval of 17.2 m giving an average sample interval of 0.96 m. Stratigraphic age reversals in these age data are defined as those exceeding the mean 2-sigma analytical uncertainty and use the mean age of replicates where these are involved. Although minor differences exist in the way ages are calculated between studies, they do not affect the analysis of stratigraphic reversals within each core.

Using the age-depth data from these sources, we also construct reef accretion curves to test the stratigraphic consistency of Ap units and their degree of taphonomic bias. For each Ap unit, transient vertical accretion that occurs between consecutive ages is measured, where

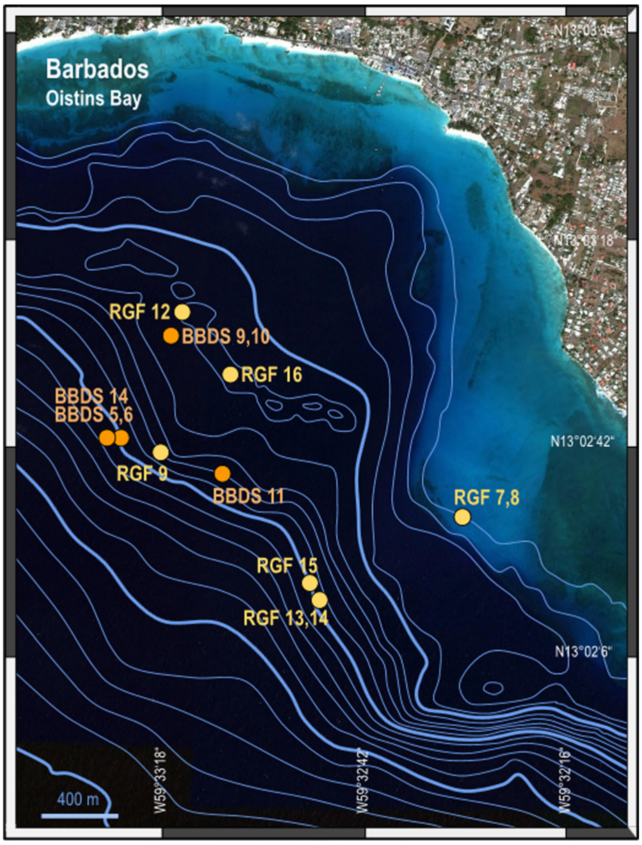

Figure 1 Bathymetry and location of reef cores drilled in Oistins Bay, off the south coast of Barbados (modified after Bard et al 2010 and Abdul 2017). All drill sites are shown for the sake of completeness, but sites RGF-16 and BBDS-9 had limited recovery, and sites RGF-13 and 14 had limited Ap data. Core data from sites BBDS-5, 6, 11 and 14 are yet to be reported.

these ages are from different corals and with an age difference greater than the mean analytical dating uncertainty (reported by Abdul et al. 2016 as ~30 years or 0.25% of age). For a vertical sequence of *in-situ* corals, the transient accretion trend should always be higher-and-younger, as new corals grow on top of older ones. But if accretion is the result of clast accumulation and *ex-situ* corals are present, then this trend can reverse, producing higher-and-older excursions due to the transport of coral clasts both up and downslope. Transient accretion thus represents the time-limited variation in reef accretion due to either rapid coral growth and/or coral-clast accumulation.

In addition to transient accretion, the horizontal and vertical range of corals can also help determine the degree of taphonomic bias in the Ap sequences. The vertical distribution of coeval corals, defined as those which plot within the same 100 year interval, determines the depth range over which coral samples occur, and can be used to assess either the consistency of habitat range for *in-situ* corals or the depth range of coral clast deposition. In the Caribbean, modern reefs with crests exposed to open-ocean conditions are dominated by monospecific thickets of *in-situ* Ap that have a habitat range up to a maximum of 5 m deep (Goreau 1959; Adey and Burke 1976; Geister 1977; Lighty et al. 1982). However these shallow thickets are commonly destroyed by hurricanes and their skeletal clasts can accumulate over a larger depth range (Woodley et al. 1981; Blanchon et al. 1997; Blanchon and Perry 2004). *In-situ* Ap corals can also grow as isolated colonies in waters deeper than 5 m (e.g. Goreau and Wells 1967), but do not form monospecific thickets and instead are mixed with other corals (Lighty et al. 1982). As a consequence, taphonomic bias in the vertical distribution of dated corals can only be determined from monospecific Ap sequences.

Similarly, the horizontal distribution of coral samples at any given 1 m elevation interval provides a measure of either cohort age of *in-situ* corals that occupied the same horizon at different points in time (Edinger et al. 2007), or the degree to which older or younger coral clasts have been transported up or downslope. In the case of *in-situ* corals, horizontal transects of dated corals in Holocene reefs from the Huon Peninsula have a cohort age of ~500 years if large, long-lived head-corals are excluded, and ~1000 year if included (Edinger et al. 2007). Although no similar data exists for the Caribbean, we assume that a 500 year range is also applicable to sequences of monospecific Ap composed of *in-situ* colonies. Therefore ranges exceeding 500 years, when accompanied by stratigraphic age reversals, provide an additional criteria supporting the presence of *ex-situ* corals.

In addition to these taphonomic data, we also use sequence boundaries and facies associations reported in Fairbanks (1989) and Abdul et al (2016) to re-assess the depth, timing and magnitude of meltwater pulses. Blanchon and Shaw (1995) reported that meltwater-pulse induced jumps in SL exceeded the accretion rate of Caribbean reefs causing them to drown and back-step upslope during deglaciation. These back-stepping events produced metre-scale gaps in the monospecific Ap sequences between cores that represent the interval over which the rate of SL rise exceeded the maximum reef-accretion rate. Measuring the differences in age and elevation between the top of the downslope (drowned) Ap unit, and the base of the upslope (backstepped) unit is therefore used to constrain the onset depth, timing and magnitude of meltwater pulses, which were previously estimated only from the age and depth of coral samples themselves (Fairbanks 1989; Bard et al. 1990; Abdul et al. 2016).

Finally we use these taphonomic and stratigraphic data to revise the Barbados SL reconstruction, but make two methodological changes compared to previous reconstructions. First, instead of correcting each individual dated sample for the tectonic uplift of Barbados, as was done previously, we correct Ap units in each core for the average uplift that has occurred during the formation interval using the same 0.34 m/ka uplift rate used in Abdul et al (2016) and discussed by Mortlock et al (2016). This alleviates the problem of changes in relative sample elevation caused by true-age variation and/or age inversions, which are common in Ap units dated on a sub-metre resolution (Blanchon and Perry 2004). Second, the previous reconstruction of Abdul et al (2016) drew a best-fit curve through the uplift-corrected samples, assuming that all corals were *in-situ* and the highest samples grew at sea level. They estimated this curve had a +2 m uncertainty by assuming that the deepest corals grew at a depth of 5 m, at the base of ecological habitat of Ap. Instead of relying on these subjective assumptions, we reconstruct SL position by first measuring the maximum vertical spread of data points in cores from the same interval, where data points include both coeval corals and the tops and bases of Ap units. Vertical tie-lines with this maximum vertical spread are then centred on clusters of coeval data with a minimum of 3 data points (including the tops and bases of the Ap units which serve as a limit for the tie-lines). Connecting tie-lines thus provides an upper limit for SL and an envelope within which all data plots, and therefore avoids assumptions based on the unknown *in-situ*/*ex-situ* status of the sample or its depth distribution.

3. RESULTS

FACIES ASSOCIATIONS

Stratigraphy of the Barbados cores, originally reported in Fairbanks (1989) and Abdul et al (2016), is summarized in ***Figure 2***, and shows several metre-thick units composed of monospecific Ap. These units were claimed to consist entirely of *in-situ* colonies, and yet no fabric or taphonomic

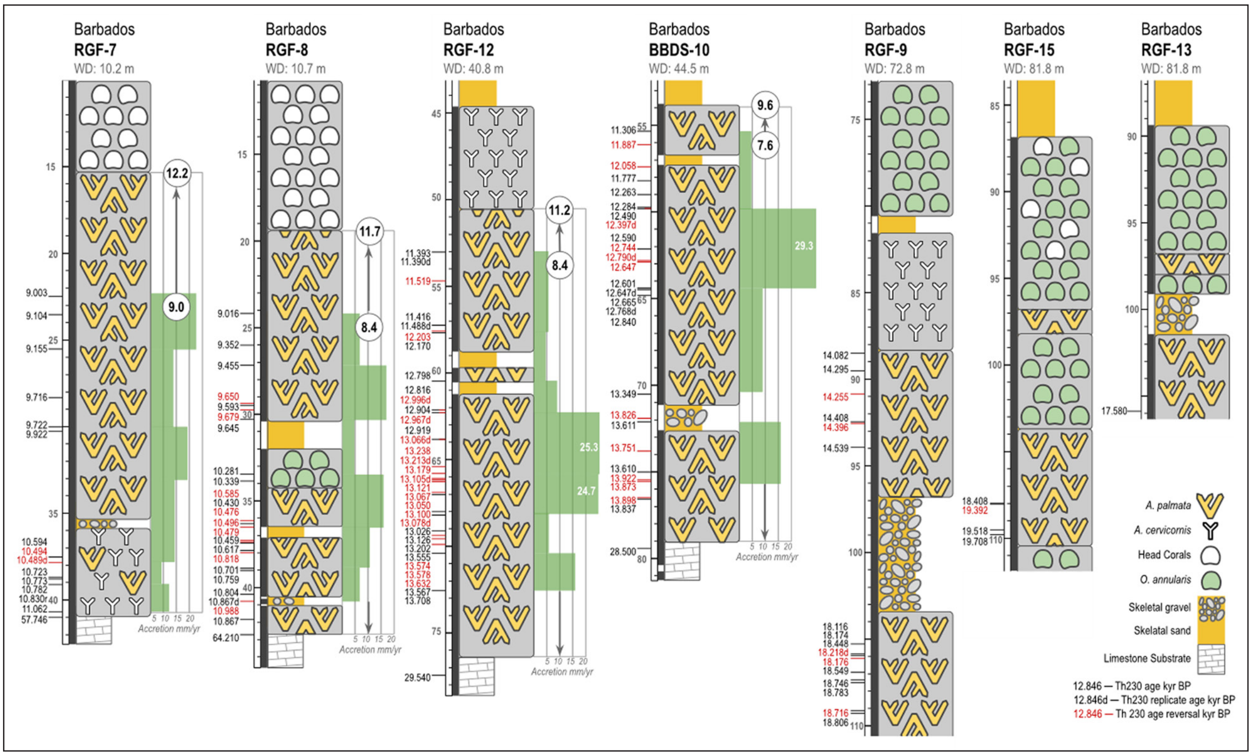

Figure 2 Postglacial reef development at Barbados. Core logs show stratigraphy (m below SL), chronology (Th-230 ages in ka BP), and accretion rates (mm/yr) of reef-crest units containing *A. palmata* (Ap). Transient accretion rates are shown between stratigraphically-consistent ages, including maximum rates that exceed 20 mm/yr. Also shown is the average accretion rate of the dated interval, as well as the complete unit interval. Stratigraphy and chronology modified from Fairbanks (1989) and Abdul et al. (2016).

data was published to support these interpretations, making a reef-crest origin uncertain (Blanchon and Perry 2004). Nevertheless, in the shallow shelf cores from sites RGF-7, 8, 12, and BBDS-10, these taphonomically undifferentiated Ap units commonly lie directly on or close to the underlying substrate and are topped by units with corals typical of deeper-living assemblages, thus forming a deepening-up sequence (***Figure 2***). This is a common postglacial facies sequence and implies that the Ap units developed at the shore in shallow water and are consistent with reef-crest deposits. The thickness of these units (7 to 20 m) exceeds the 5 m depth habitat of Ap, implying that vertical accretion of the crest kept pace with postglacial SL rise. During later stages crest units become capped by deeper coral assemblages, implying that either the rate of SL rise outpaced their accretion (causing deepening), or that the axis of reef accretion was inclined (Blanchon and Blakeway 2003).

A similar deepening-up sequence, however, is absent in cores from sites RGF-9, 15 and 13, that were drilled on the insular slope directly below the shallow cores. Instead these slope cores recovered thinner Ap units (5–9 m) that are underlain either by undifferentiated skeletal detritus or corals with deeper habitat ranges. In some cases the units are sandwiched between deeper corals (such as in RGF-13 and 15; ***Figure 2***). Such irregular facies associations imply that the Ap units in the slope cores are not shallow-water crest assemblages but formed in deeper water. Also, unlike the thick Ap-crest units in the shelf cores which form a peripheral ridge, the Ap units in the slope cores developed at the same level as the slope itself and therefore lack any significant depositional relief. Together, these differences imply that Ap units in the slope cores are inconsistent with *in-situ* reef-crests, but instead formed alongside deeper coral assemblages.

STRATIGRAPHY AND ACCRETION

The sub-meter sample density of the Th-230 age-depth data reported in Abdul et al (2016) and Peltier and Fairbanks (2006) allows for an analysis of stratigraphic consistency in the Ap units. In terms of analytical error, the 106 Th-230 ages from Ap corals reported by Abdul et al. (2016) have a 2-sigma error between 10–112 years with a mean of 45.2 years. However the 16 replicates show a true-age variation of 3–180 years, with a mean of 64.6 years, and are thus greater than the analytical error. The age uncertainty revealed by the true-age variation can be compared with the magnitude of the 14 age reversals reported by Abdul et al (2016) in order to verify stratigraphic inversions. The reversals range from 57–500 years with a mean of 156.6 years, and occur over intervals ranging from 0.1–3.1 m (***Figure 2***). Of the 14 reversals, 11 exceed both the mean analytical error and mean true-age variation, and are statistically different from the true-age variation, implying that they represent valid stratigraphic inversions (see **Supplementary Information**). As illustrated by deviations in the transient accretion curves in ***Figure 3***, these age reversals

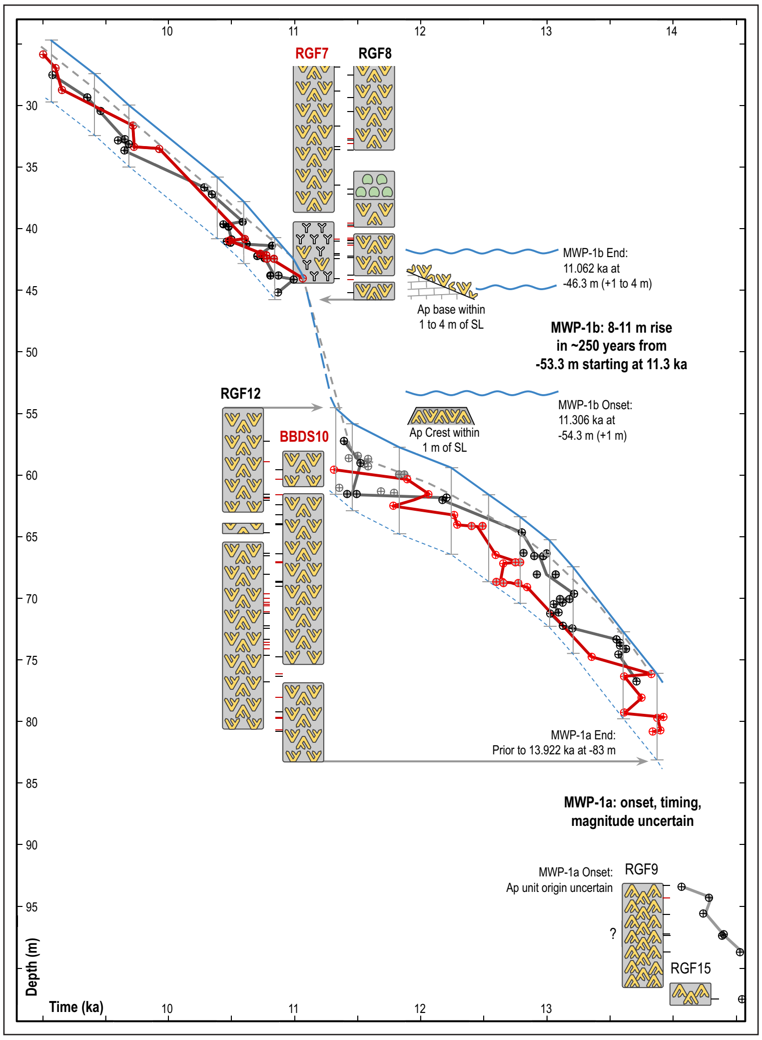

Figure 3 Revised postglacial sea-level (SL) reconstruction for Barbados, showing colour-coded transient accretion trends in individual cores, SL tie-lines, and position, timing, and magnitude of meltwater pulses (uplift corrected). Replicate ages are shown as grey-filled circles and the accretion trend shows mean age. Grey circles are Ap samples from short cores RGF-16 and BBDS-9. Note that all age-data points (circles) have a diameter that is equivalent to the mean analytical error (~50 years). The SL tie-lines show the maximum vertical data range in overlapping cores, and are centred over clusters of coeval ages and sequence tops and bases to produce an upper SL limit (solid blue line), and an envelope of maximum data distribution (dashed blue line). Ap units (not individual samples) in each core are corrected for their mean uplift by assuming a constant uplift rate of 0.34 m/kyr. Also shown are positions of Th-230 ages (inversions in red), and the top and base of the Ap sequence for each backstepping interval. Dashed grey line is the SL reconstruction of Abdul et al. (2016).

are common in all Ap units dated at a sub-metre resolution and therefore demonstrate that they contain stratigraphic inversions consistent with the presence of *ex-situ* coral clasts. As a consequence the Ap units cannot be composed of 100% *in-situ* Ap framework as previously claimed (Fairbanks 1989, Peltier and Fairbanks 2006, Abdul et al. 2016, Mortlock et al. 2016).

In addition to stratigraphic inversions, another indicator of taphonomic bias in the Ap units is the vertical and horizontal spread of the age-depth data. In the shallow-shelf cores (RGF-7 and 8) vertical spread of coeval corals is between 3–4 m which is within the habitat range of Ap. But in the shelf cores further downslope (RGF-12 and BBDS-10) the spread almost doubles to 6 m and, if the top and base of the units are considered, extends to 7 m (***Figure 3***). This spread implies that either *in-situ* coral thickets lived 2 m deeper than the habitat range, or that their skeletal clasts were transported downslope and accumulated in deeper water. The fact that the vertical spread is consistent with the habitat range in the shallow-shelf cores, implies the latter. This downslope transport is also supported by the horizontal spread of ages which shows a similar trend, being <400 years in the shallow-shelf cores, but more than doubling to ~900 years in the downslope shelf cores (***Figure 3***).

Although these taphonomic data do not allow the proportions of clasts to *in-situ* colonies to be quantified, both contribute to the vertical accretion of Ap units and thus determine their potential to keep-pace with SL rise. As shown in ***Figure 2***, rates of transient accretion measured between stratigraphically consistent ages within Ap units attain ~15 mm/yr in all cores, and peak at 25–29 mm/yr in cores RGF-12 and BBDS-10 respectively. However, mean accretion rates for the dated Ap intervals in each core are between 7.6 to 10.3 mm/yr, which are considered minimum values given that they do not include the entire Ap sequence. If the entire core sequence is considered, then average accretion rates increase to between 9.6 to 12.2 mm/yr (***Figure 2***). As a consequence, the sustained vertical accretion potential is likely to be 10-15 mm/yr, which is consistent with estimates from Ap units in other areas (Hubbard, 2009).

SEA-LEVEL RECONSTRUCTION AND MELTWATER PULSES

In addition to identifying *ex-situ* corals, the vertical spread of coeval corals is also useful in reconstructing SL position through time. In sequences dominated by *in-situ* Ap, coeval corals plot within a 0-5 m depth habitat, but may extend below this range when combined with data from *ex-situ* clasts. As a consequence, we use the maximum depth-range of coeval corals as a more objective way to constrain SL position, as opposed to previous reconstructions which only considered the depth habitat. For the shallow-shelf cores (RGF-7 and 8) coeval corals plot within a maximum vertical depth-range of 4 m, which is consistent with the depth habitat of Ap. Whereas in the deeper shelf cores (RGF-12 and BBDS-10) this range increases to 7 m, which likely reflects more downslope movement of clasts. As illustrated in the SL reconstruction in ***Figure 3***, this maximum coeval-coral range is represented by vertical tie-lines that delineate the depth envelope in which all data plot. In the shallow-shelf cores, the top of the 4-m tie-lines show a SL position similar to that interpreted by Abdul et al (2016). However, the 7 m tie-lines in the deeper-shelf cores show a SL position as much as 3 m above the previous reconstruction.

The other main consideration in SL reconstruction for Barbados is correcting for the assumed average uplift rate of 0.34 mm/yr (Fairbanks 1989; Abdul et al. 2016). Correcting each dated coral for uplift (as was done previously) introduces bias in sequences that contain *ex-situ* data because age reversals alter the relative positions of adjacent corals. This can be avoided if complete Ap core sections are instead corrected for the average uplift during their interval of development. In the case of RGF-7, for example, the Ap unit has an age range of 11,062 to 8,934 years, which produces uplift corrections of 3.8 to 3.0 m respectively. Using the 3.4 m average of this uplift to correct the dated corals in the entire sequence only results in a maximum difference of 40 cm.

Using this revised method of correcting for uplift coupled with coeval-coral tie-lines results in the revised SL reconstruction seen in ***Figure 3***. The metre-scale gaps between the Ap core sequences represent MWP-1a and 1b, when the rate of SL rise exceeded the reef accretion rate causing drowning and backstepping (Blanchon and Shaw 1995). The onset of each MWP is consequently defined using the age and depth of the drowned reef, which is represented by the youngest Ap sample (the presumed last survivor) and the top of the highest Ap unit (the presumed reef crest). The end of each MWP is similarly defined using the age and depth of the backstepped reef, represented by the oldest Ap sample (the presumed first colonizer) and the level of the unit base (the presumed reef-crest base). The position of SL at the onset of each MWP is therefore estimated by adding the presumed water depth over the drowned reef crest (in modern reef crests this is usually 1 m or less). And the position of SL at the end of the MWP is estimated by adding the vertical depth range of coeval corals to the base of the Ap unit (***Figure 3***).

In the case of MWP-1b, the uplifted-corrected depth of the drowned reef-crest in RGF-12 is 54.3 m below SL, and the youngest (last surviving) coral is 11,306 years. Whereas the oldest (first colonizing) coral in the backstepped reef at RGF-8 is 11,062, and the unit base is –46.3 m (***Figure 3***). Assuming a 1 m water depth over the drowned crest, and a 1 to 4 m depth range for corals in the backstepped reef (found in RGF7 and 8), these data show that MWP-1b was an 8–11 m rise in SL from –53 m in 244 (±32) years starting at 11.3 ka.

In the case of MWP-1a, however, the data are insufficient to calculate the timing or magnitude of the jump. As alluded to above, this stems from the uncertain origin of the Ap units in RGF-9 and 15, which have no depositional relief and are associated with deeper-water coral assemblages and so are unlikely to be reef-crest units. All that can be determined is the end of MWP-1a, from the timing and depth of the backstepped reef, which occurs at –83 m prior to 13,922 years, as the basal 3 m of BBDS-10 is undated (***Figure 3***). Assuming an accretion rate of 10–15 mm/yr gives an estimate of 200–300 years for this undated section and puts the end of MWP-1a around ~14.2 ka.

4. DISCUSSION

The accuracy of reef-based reconstructions of postglacial SL rise at Barbados (and elsewhere) rests upon the fundamental assumption that the ecological zonation on modern reef-crests is representative of the geological reef deposit in the subsurface. In other words, that reef accretion occurs by the simple upward growth of coralgal assemblages through time, and that taphonomic processes which bias the record, such as tropical storms and cyclones, have no impact on the resulting geological sequence. In the Caribbean, where Ap dominates modern reef-crests, subsurface drilling has shown that this assumption is invalid for reefs in hurricane-prone areas (Blanchon et al. 1997; Blanchon and Perry 2004; Blanchon et al. 2017). On the Campeche Bank, for example, Blanchon and Perry (2004) reported that cores from the reef-front (–2 to –10 m), the reef-crest (0 to –2 m), and rubble cay zones (0 to +1 m), are underlain by a compositionally homogeneous deposit of Ap clasts, and that dating on a sub-metre scale showed age reversals of up to 450 years (Blanchon and Perry 2004). As a consequence, they concluded that SL reconstructions based on the identification of *in-situ* Ap assemblages in reef-core sequences should be viewed with caution until the shallow-water facies have been differentiated using taphonomic criteria.

Data from the undifferentiated Ap units in the Barbados cores also show evidence consistent with hurricane impact. Common age inversions in the accretion curves, as well as expanded horizontal and vertical age distributions are inconsistent with modern *in-situ* coral assemblages. In the shallow shelf cores (RGF-7 and 8) age inversions suggest that the Ap sequences are mixtures of *in-situ* and *ex-situ* corals, but their limited horizontal and vertical age distributions imply that they accumulated in the normal reef-crest habitat-range of Ap (≤5 m). However, in the steeper gradients around the downslope cores (RGF-12 and BBDS-10), the inversions coupled with expanded horizontal and vertical age distributions suggest that hurricanes transported Ap clasts further downslope. The facies associated with the Ap units in the deepest cores (RGF-9 and 15), which are located on the steepest gradients on the slope, suggests this process led to significant downslope transport into waters occupied by deeper-coral communities.

The impact of hurricanes on Barbados reef development has also been reported from the uplifted Ap sequences deposited during the Last Interglacial (Blanchon and Eisenhauer 2001; Perry 2001). For example Perry (2001) found that reef-crest deposits in 'First High Cliff' on the northeast coast were composed of metre-thick sequences of clast-dominated Ap units with a sciaphilic to photophilic transition in secondary encrusters indicative of hurricane-induced destruction and deposition. Whereas on the west and south coasts, Blanchon and Eisenhauer (2001) reported that fabric analyses of reef-crest sections indicated that they were also dominated by Ap clasts and that the proportion of *in-situ* corals seldom exceeded 30% and was as low as 17% in some exposures. Furthermore, several analyses of the benthic substrate of modern and Holocene reefs, shows that shallow reef crests around Barbados consist of a high proportion of skeletal Ap fragments (Lewis 1984; Macintyre et al. 2007). Collectively, these studies provide independent evidence that reef-crest deposits on Barbados are mixtures of *in-situ* and *ex-situ* corals

Previous SL reconstructions based on the Barbados data have either ignored evidence of *ex-situ* data in the Ap sequences, such as age reversals, or even claimed they were stratigraphically consistent (Peltier and Fairbanks 2006; Abdul et al. 2016; Mortlock et al. 2016). Using these arguments, Abdul et al. (2016) claimed that the thick sequences of Ap in offshore cores "unambiguously represent the shallow water interlocking framework of the reef crest facies" (Abdul et al. 2016; p334). This was contested by Bard et al. (2016) who noted a discrepancy in the depth habitat of Ap between cores RGF-9 and 15 implying growth in deeper water between 14.5 and 14.0 ka ago. Following Toscano and Macintyre (2003), they suggested this was the result of Ap colonies surviving at deeper depths (10–15 m) during rapid SL changes, and led them to conclude that Ap may not be as good for SL reconstruction as previously claimed. The depth discrepancy, however, was resolved by Mortlock et al. (2016) who reported an error in the drilling depth of RGF-15 (75.4 m was changed to 81.8 m). As a consequence they rejected the idea that Ap lived deeper, and downplayed the potential of coral fragmentation to bias the SL record at Barbados. Yet there is clear evidence from both the offshore and onshore Ap sequences that shallow reef accretion on Barbados and elsewhere does not involve the simple upward growth of corals, but results from the cyclic destruction and regeneration of Ap assemblages through time producing thick sequences of hurricane-generated detritus (Blanchon et al. 1997; Blanchon and Esienhauer 2001; Perry 2001; Blanchon et al. 2017). As a consequence, the use of these sequences for SL reconstruction is more complicated and must address the presence of *ex-situ* data.

By ignoring age reversals and assuming that the uppermost corals grew at SL, the reconstruction of Abdul et al. (2016) placed the curve to intersect with the uppermost data points, suggesting an uncertainty of +2 m above the curve. In the SL reconstruction in ***Figure 3***, we assume that data are centred within the maximum depth range of coeval corals measured in the Ap sequence (vertical tie lines), and therefore explicitly include *ex-situ* data. For the shallow-shelf cores (RGF-7 and 8), the difference between reconstructions is minimal because the coeval depth ranges are the same (<5 m), but for the deeper-shelf cores (RGF-12 and BBDS10), the maximum coeval depth range is 7 m and this produces a curve that lies up to 3 m above that of Abdul et al. (2016), (***Figure 3***).

Although the inclusion of *ex-situ* data does not produce differences greater than 3 m in shallow parts of the reconstructions, it does make a significant difference in deeper parts and in assessing the rate, magnitude and timing of meltwater pulses. For example, Abdul et al. (2016) calculated that MWP-1b was a 14 ±2 m jump from –58 m in 350 years starting at 11.45 ka. This estimate assumes that the onset of the meltwater pulse is defined by the youngest samples in RGF-12 (RGF12-5-2 at 56.9 m and RGF12-6-7.3 at 58.6 m), but ignores ages as young as 11.3 in BBDS10 (BBDS10-8-3 at 59.1) and RGF-9 (RGF9-8-2 at 60.6 m). It also ignores the top of the Ap unit in RGF-12 at –54 m which represents the crest of the drowned Ap reef and therefore a –53 m SL position at the onset of MWP-1b. By including these data, the reconstruction in ***Figure 3*** shows that MWP-1b was an 8–11 m jump from –53 m in ~250 years starting at 11.3 ka, which is 5 m smaller and shallower, and 150 years later than the Abdul et al. (2016) reconstruction. The revised rate of SL rise during this jump is 32–44 mm/yr which exceeds even the highest transient-accretion rates recorded in the Ap sequences (~30 mm/yr) and would have caused reef-crest drowning and backstepping on Barbados and across the Caribbean (Blanchon and Shaw 1995). However, in open-ocean Indo-Pacific reefs, like those around Tahiti, a smaller 8–11 m jump may not have displaced reef-crests into waters with deeper communities, making MWP-1b more difficult to identify (Blanchon 1998).

Previous estimates for MWP-1a at Barbados are more problematic. By U/Th dating the radiocarbon-dated samples reported by Fairbanks (1989), Bard et al. (1990) estimated MWP-1a was a 19 m jump from 93.5 m in 450 years starting at 14.1 ka (updated with ages in Peltier and Fairbanks 2006). However, the uncertain origin of the Ap units in RGF-9 and 15, which have no depositional relief and are associated with deeper-water facies (and so are unlikely to be reef-crest units), means that the onset of MWP-1a cannot be reliably estimated at Barbados. Instead the data from RGF-9 and 15 maybe contaminated by downslope transport of clasts from reefs which are a mere 500 m away on the shelf above (RGF-12 and BBDS10). The termination of this meltwater pulse, however, is represented by the resumption of Ap reef accretion in BBDS10 and likely occurred around 14.2 ka, which is consistent with the timing on Tahiti (Deschamps et al. 2012).

5. SUMMARY AND CONCLUSIONS

Our re-analysis of the published stratigraphy and facies data in Ap sequences from the Barbados cores shows that stratigraphically inverted ages are common in all Ap units dated at a sub-metre resolution, these ages have a vertical and horizontal spread that is inconsistent with those of *in-situ* assemblages, and Ap units in cores from the slope have no depositional relief and are associated with deeper coral assemblages. These findings imply that the Ap sequences did not form from the simple vertical accretion of *in-situ* reef-crest corals, but include *ex-situ* corals generated by colony fragmentation and transport during hurricanes.

The age inversions and expanded vertical and horizontal age distributions produced by this *ex-situ* data have biased previous reconstructions of SL rise and Meltwater Pulses at Barbados. This bias is minimal in cores from the shallow shelf, due to the low gradients and limited vertical displacement of clasts by hurricanes, but increases downslope as gradients increase and clasts are transported into deeper water and out of the normal reef-crest habitat of monospecific Ap. The bias is greatest in the deepest slope cores where Ap units are interlayered with skeletal gravel and deeper-coral communities. This transport has two important consequences for measuring the depth, timing and magnitude of meltwater pulses: First, it means that the onset date of MWP-1a cannot be reliably determined at Barbados but, like Tahiti, it finished ~14.2 ka ago at a depth of 83 m; and second, that MWP-1b was 5 m smaller and shallower, and 150 years younger than claimed previously, and is estimated here to be an 8-11 m rise from –53 m in ~250 years, starting 11.3 ka ago.

This revised SL reconstruction and meltwater-pulse estimates from Barbados underlines the importance of assessing the taphonomic bias inherent in reef accretion and not simply assuming that ecological assemblages on modern reefs are perfectly preserved into the subsurface (cf. Pandolfi and Minchin 1996). They also illustrate the potential difficulty of identifying the depth, magnitude and timing of meltwater pulses from different reefs, with different communities and taphonomic filters, in different areas. For example, the more diverse and resilient ecology of Indo-Pacific reefs, like those around Tahiti, make it more difficult to identify meltwater pulses (Blanchon 1998). Indeed, their response might not involve a simple reef drowning and backstepping of modern-like crest assemblages, but a more complex submergence and recovery (Camoin et al. 2012), with transitions into and out of assemblages that may be unrepresented by their modern counterparts (Blanchon et al. 2014). As a consequence, other approaches may be needed to track SL and identify meltwater pulses from the more complex reef sequences of the Indo-Pacific.

ADDITIONAL FILES

The additional files for this article can be found as follows:

- **Lay Summary.** Revised reconstruction of postglacial sea level rise and meltwater pulses from drowned reef-crest cores off Barbados. DOI: *https://doi.org/10.5334/oq.87.s1*
- **Supplementary Information.** Statistical analysis of age reversals in reef-crest cores off Barbados. DOI: *https://doi.org/10.5334/oq.87.s2*

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Co-author FDH was one of the two anonymous referees invited to review the original and revised manuscript versions. Following its final revision, FDH was invited by PB (via the handling Editoral Board member) to become a co-author in recognition of their intellectual contributions made during the review. The addition of FDH as a post-review co-author is approved by the Publisher, Lead Editor and handling Editorial Board member.

AUTHOR CONTRIBUTIONS

PB designed the study, analysed the data and wrote the manuscript; AMV ran the statistical analysis; FDH and AMV edited and approved the final version of the manuscript for publication.

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