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Sea level 400 000 years ago (MIS 11): analogue for present and future sea-level

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Abstract

Comparison of sea-levels today and 400 000 years ago (MIS 11), when the Earth's orbital characteristics were similar, may provide indications of future sea-level during the present interglacial. Evidence for former sea-levels occur on uplifting coastlines where shorelines are preserved. The sea-level term and the uplift term may be separated with an "uplift uplift correction" formula. This discovers the original sea-level at which the uplifted shoreline was fashioned. Estimates are based on average uplift rates of the "last interglacial" sea-level (MIS 5.5) using a range estimates for sea-level and age at that time and at different locations. These, with varying secular tectonic regimes in different ocean basins, provide a band of estimates for MIS 11. They show the MIS 11 sea-level was close to its present level and Greenland and West Antarctic ice volumes were similar to present.

1 Introduction

The importance of estimating the sea-level of oxygen isotope stage 11 (MIS 11) at ∼400 ka is because it may be an analogue for present and future sea-level. Then, and now, orbital eccentricity was low and precession dampened (Berger and Loutre, 2002). Previous proposals of the MIS 11 sea-level at the land-ocean interface occur in two groups. A sea-level between 0 to 5 to m (Bender et al., 1979; Schellmann and Radtke, 2004a, b; Bowen, 2003b, c) which compares with inferences from oxygen isotope stratigraphy of a band between ∼0 m (McManus et al., 2003) and ∼6 m (Waelbroeck, 2002). And a higher group of about +20 m (Pirrazoli et al., 1993; Howard, 1997; Hearty; 2002; Hearty et al., 1999; Olson and Hearty, 2009; Rohling et al., 1998). Given the potential analogue of MIS 11 sea-level for present and future ones it is desirable to resolve this difference.

An entirely new way of looking at past sea-level variability stemmed from the oxygen isotope analysis of marine foraminifera by Emiliani (1955) who made correlations between oxygen isotope variability and classical continental stratigraphy. Subsequently, Fairbridge (1961) proposed correlations between sea-levels, marine oxygen isotope and solar variability. Whereas Emiliani (1955) placed greater emphasis on the temperature term in the partitioning of ^{16}O and ^{18}O (δ^{18}O), Shackleton (1967) argued that benthic foraminifera inhabited deep water where little if any temperature change occurred thus eliminating the temperature term in the δ^{18}O signal and leaving a continental ice volume signal as a surrogate for sea level. Shackleton and Opdyke (1973) explored this further when they suggested that 0.1‰ of δ^{18}O change was equivalent to a 100 m of sea-level change: thus 0.01‰ corresponded with 10 m of sea-level change. This is no longer the case because ocean bottom water temperatures changed in the past and regional hydrological variability was also a factor in the partitioning of the oxygen isotope signal (e.g. Lea et al., 2002). Many clever attempts have been made to convert oxygen isotope variability to its sea-level equivalent by: for example, Chappell (1974), Shackleton and Chappell (1986), Shackleton (1987), Waelbroeck et al. (2002) and McManus et al. (2003). Presently it is generally believed that ocean core SITE 849 from the NE Pacific may provide the closest approximation for sea levels (Mix et al., 1995).

Evidence for former sea-levels is provided by: marine terraces, shoreline angles, erosional and bioerosional notches, littoral and beach sediments, back-barrier deposits, fossil corals, and other marine organisms that indicate past water levels. Others include a potential range of water levels: for example, corals grow up to mean low water mark and may show variability up to 5 m water depth and with rising sea level some reefs are “keep up” (Barbados), “catch up” (Bermuda) or “give up” (Muhs et al., 2002). The most reliable indicators of former sea-levels these are shoreline angles, notches and back barrier deposits and these are addressed at different locations (Table 1).

2 Method

Estimating the MIS 11 sea-level is based on an “uplift correction” procedure to estimate average (not constant) tectonic rates of uplift from the uplifted MIS 5.5 shoreline

(Chappell, 1974). The "uplift correction" formula used in this study is based on Pillans et al. (1998):

$$S = H - Ut, \text{ with } U = (H^* - S^*)/t^* \tag{1}$$

where S is sea-level at time t relative to present sea-level, H is the elevation of the marine deposit with age t, and where U is the average tectonic uplift rate at a location. U is calculated from the height H^* of a reference marine deposit of age t^*.

Relatively few age estimates are available from the MIS 11 (11.3) shoreline although some locations are dated by ESR, AAR, TL. Time t, however, is taken as event 11.3 (406 ka) on the Bassinott et al. (1994) timescale. It receives strong support from the ^{40}Ar/^{39}Ar ages of 416±11 and 407±11 on tephra within estuarine sediments downstream from Rome (Karner and Marra, 2003). Time t* is used for estimating uplift age for uplift correction but there is no universal agreement for its precise age or elevation of its sea-level. Ages for MIS 5.5 range from ~132 to 116 ka and indicate a longer interglacial than predicted by orbital theory (Muhs, 2002; Muhs and Sabot, 1994; Muhs et al., 2002; Stein et al., 1993). The global complexity of the climate system has resulted in a long sea-level response for the last interglacial (Muhs et al., 2002) and different responses to earlier ones (Siddall et al., 2007). During the ~16 kyrs of the last interglacial (MIS 5.5) some variability in sea-level occurred, on the one hand as inferred by Oppo et al. (2006) from ODP 980 west of Ireland; and on the other hand from the detailed geomorphological mapping and ESR ages on reefs and terraces in Barbados (Schellmann and Radtke, 2004a, b). It has been suggested that the highest MIS 5.5 sea-level occurred late and precipitously during the interglacial and was caused by a catastrophic collapse of the West Antarctic ice sheet (Neumann and Hearty, 1996; Hearty et al., 2007), but this has received little support (Carew, 1997; Mylroie, 1997).

The elevation of the last interglacial MIS 5.5 sea level (H^*) has been commonly taken as +6 m above sea-level. But after a review of the literature Murray-Wallace and Belperio (1991) concluded that: "the concept of a reference level of +6 m for the elevation of the MIS 5.5 sea-level is based on the observations of Veeh (1960) that fossil corals throughout the Pacific and Indian Oceans are found consistently between +2 m and + m. Broecker et al. (1968); Chappell, (1974); Bloom et al. (1974) and many others have since used a +6 m reference as a de facto global eustatic sea-level for the last interglaciation" (Murray-Wallace and Belperio, 1991). They proposed that the Gawler craton coastline in South Australia was a better MIS 5.5 sea-level datum because its shoreline runs for some 150 km at 2 m. Similarly a stable area of West Australia has proposed as an informal type area for the MIS 5.5 sea-level where TIMS ages of 128±1 to 116±1 on corals lie at about 3 m above sea-level (Stirling, et al. 1998).

Because of the range of ages and sea-level elevation for MIS 5.5 in the literature, a range of values is used to explore possible uplift rates and calculations of the MIS 11 sea-level (Appendix, Table 2 and Fig. 1). Calculations based on the uplift rate for the MIS 5.5 sea-level at different locations are made with that sea-level at 2 m, 3 m and 6 m for ages of 116 ka, 124 ka and 132 ka which represent the earliest, latest, and median ages of MIS 5.5. An Appendix presents the raw data from which outliers, defined at or greater than two standard deviations, have been removed and rounded up (Appendix, Table 2 and Fig. 1).

Viscoelastic Earth models have investigated glacio-hydro-isostatic processes that caused spatial and temporal variability in sea-level for Termination 1 at the MIS 2/1 transition (e.g. Peltier, 2004) and Termination 2 at the MIS 6/5.5 (Lambeck and Nakada, 1992; Potter and Lambeck, 2003;). Such models, however, require verification by field geology and a powerful argument against the glacio-hydro-isostatic model for T2 is the observation that MIS 5.5 marine deposits on apparently stable intermediate-field localities such as Bahamas, Bermuda, California and Baja California are: "not significantly higher than those of MIS 5.5 age in far-field apparently stable localities such as Western Australia" (Muhs et al., 2002). This may indicate that glacio-hydro-isostatic recovery is rapid and that it is not yet possible to model the T 2 event. Potter and Lambeck (2003) have also suggested that MIS 5.1 marine deposits above sea-level on the US Atlantic Coastal Plain (Wehmiller et al., 2004) result from glacio-hydro-isostasy. Yet

Muhs et al. (2002) suggest that such a high sea level should be expected given complete deglaciation of the Laurentide Ice Sheet at a time when Baffin Island was warmer than the Holocene (Miller et al., 1999; Wolfe et al., 2000). Summer temperatures higher than present in northern Fennoscandia during MIS 5.1 also suggest complete deglaciation of the Fennoscandian ice sheet (Valiranta et al., 2009). Thus not only could the MIS 5.1 sea level have been close to present, its effect on soft sediment coasts may have been significant and could account for the MIS 5.1 sea level at Gomez Pit, Virginia (Mirecki et al., 1995). For Termination V at the MIS 12/11 transition it is unlikely that that secular tectonic average has been overprinted by glacio-hydro-isostatasy.

3 Location

The locations are discussed in ascending order of average uplift rates (Table 1). The appendix, Table 2 and Fig. 1 show the estimated elevations for the MIS 11 shoreline based on different initial assumptions for the selected locations. Much importance is attached to age estimates and elevation of the MIS 5.5 sea-level on which the extrapolated average uplift rate is calculated.

3.1 Charleston, South Carolina, USA

The Atlantic Coastal Plain between the Fall Line and the edge of the Continental Shelf is the inner edge of a passive continental margin and its marine sediments range from Miocene to Holocene (Cronin, 1981). Their study has been characterised by two approaches one geomorphic the other palaeontological. While the former recognised gently inclined marine terraces with shoreline features it became evident that the terraces do not correspond to lithostratigraphical units although (Colquhoun, 1965; Colquhoun et al., 1991) combined both. Six Quaternary marine lithostratigraphical units run north-east broadly in parallel with the modern shoreline (McCartan et al., 1984; McCartan, 1988). In each one several lithofacies tend to grade into each other and consist of burrowed, fine to medium-grained sand with interbedded mud and shells; well-sorted fine to medium-grained sand and back-barrier muddy fine to medium-grained sand, mud and shells as well as fluvial lithofacies. By comparison with modern and Holocene (Unit Q1) deposits McCartan (1988) believed that "The highest back-barrier deposits mark approximately the highest relative sea-level for each period of deposition". Back-barrier deposits up to 8 m occur in Unit Q2 (Wando Formation) and its late Pleistocene (5.5) age is based on U-series alpha ages on corals between 90 and 120 ka (McCartan et al., 1980; Szabo, 1985) and AAR as well as relatively fresh minerals (McCartan et al., 1982). The Ladson Formation (Unit Q4) of Malde (1959) has back-barrier deposits up to 15 m. It is correlated with the Canepatch Formation at Myrtle Beach (SC) by a U-series alpha age of about 450 ka and by mollusc and ostracode faunas (Cronin in McCartan, 1988). The occurrence of the coccolith *Gephyrocapsa* supports an age ascribed to MIS 11 (Cronin et al., 1984). Uplift rates calculated from event MIS 5.5 back-barrier deposits do not differ greatly from those of Cronin (1981) who used shoreline datums that he related to lithospheric flexure of the Coastal Plain-offshore Carolina platform and Carolina Trough.

3.2 The Coorong Coastal Plain (SE South Australia)

SE South Australia has an uplifted Plio-Pleistocene record of back-barrier deposits (Murray-Wallace, 2002). Back-barrier lagoon and estuarine deposits are preserved in inter-dune corridors where largely unsorted facies with articulated inertial fauna are used for determining sea-levels (Murray-Wallace, 2002). These are dated by U-series, amino acid racemization (AAR), ESR ages of molluscs and corals and TL dating of quartz sand from aeolianites on a transect from Robe to Naracoorte (Murray-Wallace, 2002). The MIS 5.5 sea-level is represented by the Woakwine barrier deposits at 1 m with a TL age of 132±9 ka. The higher East Avenue 11.3 barrier sea-level lies at 2 m with a T L age of 414±29 (Murray-Wallace, 2002). Based on an uplift rate from an MIS 5.5 sea-level of 2 m, Murray Wallace (2002) estimated the MIS 11 sea level to have been – m at 42 ka.

3.3 Curacao (Netherlands Antilles)

The island of Curacao consists of off-lapping carbonate units forming marine terraces on a volcanic basement. Using TIMS age estimates Lundberg and McFarlane (2002) identified sea-levels related to the MIS 5.5 and MIS 11 events. The former has a well-preserved notch at 10.5 m with a TIMS age of 123.65±0.35 ka on coral. A TIMS age of 412±14 ka on coral was obtained from "the base of the MIS 11 terrace" at 21 m whereas the notch at the rear of the terrace is at 37 m.

4 Oahu (Hawaii)

The Waimanalo Formation, mapped by Stearns in 1939 (Stearns, 1966), was later remapped east of Kaena Point (Muhs and Szabo, 1994). TIMS age estimates on the Waimanalo Formation confirm its MIS 5.5 age (Muhs et al., 2002). Along the west and northwest coasts of Oahu between Kaena Point and Waianae lie well exposed reefs and shoreline deposits between 0 and 28 m (Hearty, 2002). Those up to 12 m are believed to represent event MIS 5.5 as suggested by TIMS ages at Kahe Point (Muhs and Szabo, 1994).

At higher elevations (∼30 m) Stearns (1978) mapped the Kaena high stand of sea-level for which Veeh estimated an age of 600±100 ka from infinitely aged alpha samples (Stearns, 1978). Muhs and Szabo (1994) who commented that the sedimentology of the deposits was not characteristic of a giant wave (unlike McMurtey et al., 2007) confirmed their general elevation. Those at 28 m have been ascribed to MIS 11 age (Hearty, 2002) which is close to an ESR age of 468±136 (Jones, 1993). Hearty described a section 2 km south-east of Kaena Point where a beach conglomerate, correlated with MIS 5.5 lies in a shoreline angle at ∼11 m (Hearty, 2002). Above it at 29 m is a similar deposit with amino acid ratios correlated with MIS 11. Similar field relations between the MIS 5.5 and MIS 11 sea level indicators also occur at the Waianae Health Center (Hearty, 2002). Uplift rates for Oahu range between 0.03 to 0.005 m/ka (Muhs

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and Szabo, 1994) and 0.06 m/ka (Grigg and Jones, 1997).

4.1 The Nome Coastal Plain (Alaska)

Six high stands of sea-level are found on the Nome Arctic Coastal Plain and consist of shorelines and superimposed shelf sequences with fossil evidence for climate that was as warm as or warmer than present. Beaches, barrier islands and spits of the Pelukian marine transgression 12 m (Brigham-Grette and Hopkins, 1995) and are correlated with event MIS 5.5 (Brigham-Grette, 1999). At 23 m above sea level lie shelf, beach and lagoonal sediments of the Karmuk Member of the Gubik Formation that is correlated with the Anvillian marine deposits of the Alaskan Coastal Plain (Kaufman, 1992; Kaufman and Brigham-Grette, 1993). This has a U-series trend age of 540±60 ka (Brigham, 1985), AAR age estimates of about 475 ka. The deposits have been correlated with the middle of the *Rhizosolenia barboi* diatom zone between 430 and 360 ka Pushgar et al. (1999).

4.2 San Paulo Formation, Rome

Downstream from Rome fluviodeltaic sediments include the San Paulo Formation, silty sand that includes ostracodes, foraminifera as well as *Cerastoderma* and *Tellina* that indicate a brackish water environment (Karner and Marra, 1998). Its upper surface lies at 63 m (Karner and Marra, 1998; Karner and Renne, 1998; Karner and Marra, 2003) and ^{40}Ar/^{39}Ar ages of 416±11 and 407±11 on tephra are part of the formation (Karner and Marra, 2003). Downstream the 5.5 terrace with a shoreline angle 20 m (Giordana et al., 2003) allows the calculation of uplift rates and the 11.3 sea-level.

4.3 Oceanside, San Diego County, California

Other than for clearly defined stretches coast, for example, around the Rose Canyon Fault north of San Diego city and minor deformation adjacent to faults, the coastal hinterland between north of Point Loma, San Diego and Newport Beach, consists of "gently warped beach ridges and terraces" that show "long-term vertical structural stability" (Lajoie et al., 1979). Some have age estimates provided by U-series and AAR. The most widespread terraces are related to the Nestor Terrace ~120 ka and the Bird Rock Terrace ~80 ka that both run northwards along the coast (Lajoie et al., 1991; Kern and Rockwell, 1992). Several marine terraces show lateral continuity up to 10 km, but shoreline angles are frequently masked by varying thicknesses of colluvium that increases for higher and older terraces. Using uplift rates calculated from the elevation of the Nestor Terrace Kern and Rockwell (1992) predicted the ages of higher terraces. With a sea-level of 6 m, for the Nestor Terrace (5.5) uplift rates varied between 0.13 and 0.14 ka and they predicted that the Parry Grove Terrace at an average elevation of 55 m was 413 ka (MIS 11) in age.

4.4 Barbados

Barbados has long been the testing field for U-series ages (Alpha to TIMS using ^{230}Th and ^{231}Pa/^{235}Th ages) on coral terraces (Bender et al., 1979; Broecker et al., 1968; Mesolella et al., 1969; Edwards et al., 1997). ESR ages on coral samples from sites determined by detailed geomorphological field mapping of former sea cliffs, erosional notches, reef crests, and wave cut terraces to an accuracy of 1 m demonstrated 18 separate stands of sea-level compared with only 11 previously recognised (Schellmann and Radtke, 2004a, b). The highest MIS 5.5 elevation is 39 m with an ESR age of 132 ka. Estimated elevations for the MIS 11 shoreline are shown on Table 1, Appendix and Fig. 1. The preferred estimate for the MIS 5.5 sea-level is 2 m which subject to uplift rate determination gives sea-level elevations for 398 ka (Terrace T-12) of −2 m and for 410 ka (Terrace T-13) of 5 m (Schellmann and Radtke, 2004a, b).

4.5 Westport, South Island New Zealand

Seawards of the Paparoa Range and south of Westport in the northwest of South Island New Zealand lies a staircase of wide marine terraces. These run from north to south by way of Westport and Greymouth to Hokitika and are gently warped by a series of west to east folds that run more or less normal to the coastline. Suggate (1992) used traverses across the terraces, a 5.5 sea-level of +6 m, and uplift correction to propose the elevation of sea-levels from events 5.1 to 14. The terrace identified as 400 ka in age was ascribed to a sea-level of 0 m compared with the present (Suggate, 1992).

4.6 Sumba Island, Indonesia

Jouannic et al. (1988) mapped a flight of marine terraces at Cape Laundi on the northern side of Sumba Island Indonesia (map in Bard et al., 1996), the oldest of which was correlated with MIS 27 (Pirazzoli et al., 1993). ESR ages on corals correlated with MIS 15 and MIS 9 showed an "uplift trend" of 0.49 m/ka (Pirazzoli et al., 1993). Bard et al. (1996) used TIMS and AMS ages that identified the 5.1, 5.3, 5.5 (between 119 and 132 ka) and MIS 9 (~305 ka). They suggested that the average uplift rate lies between 0.2 to 0.5 m/ka, but the data of Pirazzoli et al. (1993, Fig. 9) provide an uplift rate of 0.49 m/ka. The 5.5 sea-level lies at 60 m.

4.7 Autaro Island, Indonesia

Chappell and Veeh (1978) who established an uplift rate of 0.47 m/ka based on the inner margins of the terraces mapped well-preserved marine terraces at Berau in southern Autaro Island. Alpha U-series ages suggest that reef 2 marks the 5.5 sea level. Its inner margin of reef 2 lies at 63 m.

4.8 Chala Bay, Southern Peru

Goy et al. (1992) mapped a staircase of some 27 regularly spaced marine terraces between sea-level and 275 m. The geomorphology of the regularly spaced and uplifted marine terraces allows relative ages to be estimated (Ortlieb, et al., 2003) and an average uplift rate of 0.4 m/ka was proposed for the last 500 ka. Some AAR and ESR ages exist but greater promise may ensue from ^{10}Be ages on the terraces, for example:

Hall et al., 2008). Goy et al. (1992) identified the highest 5.5 terrace (III) at 68 m and the 11.3 terrace at 200 m.

5 Bermuda and the Bahamas

High MIS 11 sea-levels have been proposed for the apparently stable carbonate platforms of Bermuda (21 m) and Eluthera Island in The Bahamas (18 m) (Hearty, 1998, 2002; Hearty and Kaufman, 2000; Hearty et al., 1999; Kindler and Hearty, 2000; Olson and Hearty, 2009). These have been widely adopted in the literature (e.g. Howard, 1997; Rohling et al., 1998).

5.1 Bermuda

Fossiliferous deposits described as typical of a foreshore assemblage lie in within karstic features in Government Quarry at 21 m (Hearty, 1998, 2002; Hearty and Kaufman, 2000; Hearty et al., 1999; Kindler and Hearty, 2000; Olson and Hearty, 2009). At the Calonectris Quarry (Government Quarry) at 21.3 m they consist of a conglomerate with rounded and flattened cobbles of limestone overlain by poorly sorted calcarenite with marine and terrestrial shells, coral fragments and an extensive avifauna. (Olsson and Hearty, 2009). TIMS ages on a "flowstone" of 312±30 and 360±30 ka and from its base 364±24, 405±28 and 409±15 ka. The mean age of these ages is 399±11 ka (McMurty et al., 2007; Olson and Hearty, 2009). McMurty et al. (2007), howver, attributed the deposits to a mega tsumani. In describing the "foreshore" assemblage of fossiliferous deposits from the fissure at Calonectris Quarry at 21.3 m Olsson and Hearty (2009) dismissed their empacement as the result of tectonic uplift or by tsunami waves. An alternative is a "hurricane-phreatic" hypothesis. Hurricane winds can transport materials, including sediments and fauna, to higher elevations: for example, the 2004 effects of Hurricane Ivan produced severe wave effects up to 27 m above sea-level (Stone et al., 2005). Sediments and fauna thus may have a landward provenance for emplacement in a phreatic system. The present position of the Calonectris quarry, some distance landwards from the Holocene shoreline because of quarrying operations, lends support to this “hurricane-phreatic” hypothesis

Other marine and aeolian deposits for former sea-levels lie in a zone within only a few meters of present sea-level with an MIS 5.5 sea-level of about 6 m. The definitive paper of Land et al. (1967) provided the stratigraphical scheme subsequently modified by Vacher (1981). Alpa U-series age estimates (Harmon et al., 1983) clustered into two groups: 228 to 220 ka from the Belmont and 134±8 to 118±+6 ka with a mean age of 125±4 ka from the Devonshire Formation (Rocky Bay Formation). Muhs et al. (2002) provided TIMS ages: two of 200 and 198 ka for the Belmont Formation; six further ages between 125 and 113 ka for the Rocky Bay (5.5) Formation; and seventeen for the Southampton Formation at Fort St. Catherine of ∼80 ka.

5.2 The Bahamas

Eluthera lies in the path of the NE trade winds and consists of carbonate aeolianite blown onshore during times of low sea-levels (Carew and Mylroie, 1995, 1999); the aeolianite is subdivided by palaeosols that formed during warmer times (Mylroie, 2008). It has been claimed that MIS 11 marine sands with ooids and fenestral structures in sands on Eluthera lie at ∼18 m (Hearty, 1998; Hearty et al., 1999). No geochronological ages are available despite some textual ambiguity in Hearty et al. (1999). Mylroie (2008) however showed that at the proposed MIS 11 site on the east coast of Eluthera consists of the infilling of a small bench in an older aeolianite by modern Holocene sands with a fenestral porosity characteristic of many such Holocene deposits that look like such beaches although they are less than one year old and were emplaced during storm events at present sea-level (Mylroie, 2008).

Raised marine deposits in situ only occur up to 3 m (Mylroie, 2008) represent the MIS 5.5 event with TIMS ages of 131 to 119 ka (Chen et al., 1991). Because there is evidence long term subsidence of the islands sea-level may have been higher as indicated by bio-erosional notches (Mylroie, 2008). It has been suggested that the

5.5 peak sea-level occurred late in the interglacial (Neumann and Hearty, 1996; Hearty et al., 2007) but field geologists on the islands (Carew, 1997; Mylroie, 1997; Carew and Mylroie, 1999) do not support this.

Evidence for high MIS sea-levels at ~20 m in Bermuda and The Bahamas is controversial (McMurty et al., 2007; Mylroie, 2008) and is not supported by evidence from uplifted global shorelines (Appendix, Table 2, Fig. 1). Both islands lie within the hurricane belt and both have phreatic drainage systems within the calcareous aeoliante deposits that, in the case of Bermuda, may have been influential in simulating evidence for marine deposits in situ.

6 Discussion

Figure 1 shows the range of possible sea-levels for MIS 11.3 from uplift correction calculations based on different assumptions (Appendix, Table 2, and Fig. 1). Also included in Fig. 1 are estimates from Barbados and The Coorong Coastal Plain. The preferred calculation of Schellmann and Radtke (2004a, b) is 1.5 m (average of 5 m for Terrace T 13 at 410 ka and −2 m sea-level for Terrace T 12 at 398 ka) based on uplift correction using an MIS 5.5 sea-level at 2 m. The Coorong Coastal Plain calculation of −3 m sea-level at 420 ka is also based on a 2 m sea-level for MIS 5.5 (Murray-Wallace, 2002). The mean value of these is 0±4 m. Because of their detailed geomorphology and geochronological age estimates these are arguably the most important locations under consideration. Both lie within a band defined by 2 m±7 from the raw data from uplift correction and in particular close to the 124 ka at 2 m sea-level of 1 (−0.8)±2 m (Appendix, Table 2). Schellmann and Radtke (2004a, b) found that the Barbados data best fitted with the MIS 5.5 sea-level of 2 from the Gawler Craton (above) of Murray-Wallace and Belperio (1991) and not with estimates based on an MIS 5.5 sea-level of 6 m (see also Appendix). Estimates of the MIS 11 sea-level based on uplift correction from a MIS 5.5 sea-level at 6 m tend to lie on the higher side (Bowen, 2003b, c) although none exceed ~10 m.

If the MIS 11 sea-level was at ~20 m then the sea-level rise from the MIS 12 low stand of – 140 m (Rohling et al., 1998) saw it rise 160 m which compares with only 130 m at the MIS 2/1 sea-level rise. Where did the extra 30 m of sea-level come from? What melted? Could it happen again (Chappell, 1998)? Hearty et al. (1999) suggested that the melting of Antarctic ice caused the MIS 11 high sea-level although the potential to raise present sea-levels with contributions of meltwater from the Greenland and Antarctic ice sheets is dominated by uncertainties (Alley, et al., 2005).

An MIS 11 sea-level at or close to present does not require melting of the West Antarctic and Greenland ice sheets because only 140 m of sea-level rise is required. This is only 10 m more than the MIS 2/1 (Termination I) rise in sea-level, a quantity readily accounted for by the melting of mid-latitude northern hemisphere ice sheets that were at their greatest extent of the last 0.5 Ma in MIS 12 (Sibrava et al., 1986). Indeed the survival of MIS 7 ice in Greenland precludes complete melting even during MIS 5.5 (Suwa et al., 2006). It is also pertinent to note that Chappell (1974) calculated the 400 000 sea- level close to 0 m on the Huon Peninsula, New Guinea.

7 Conclusions

The sea-level of MIS 11 was close to present. There is no need to invoke additional melting of the West Antarctic and Greenland ice sheets for the rise in sea-level from the MIS 12 low stand at 140 m. The melting of northern hemisphere mid-latitude ice-sheets at their greatest extent during MIS 12 yielded the greatest transfer of continental ice volume to the oceans of the last 0.5 Ma.

An MIS 11 sea-level close to present concurs with inferences drawn from benthic oxygen isotope stratigraphy (McManus et al., 2003) and lies well within the band of sea-levels estimated by Waelbroeck (2002).

Data from uplifted shorelines and inferences from benthic oxygen isotope stratigraphy suggest that sea-level and global ice volume were similar to those of the present. These independent data support the notion that the MIS 11 sea-level is a plausible analogue for the present and future of the current interglacial. Neither of these data sets supports the notion of an MIS 11 sea-level at ~20 m.

As proposed by Berger and Loutre (2002) the MIS 11 interglacial was the longest of the last 0.5 Ma and they believed it was an analogue for the present interglacial. The implication for future sea-level is that any changes will be forced by natural variability caused by millennial and orbital forcing.

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Table 1. Locations arranged in order of increasing uplift rates (example for an MIS 5.5 sea-level at 2 m), evidence for MIS 5.5 and MIS 11 shorelines and tectonic style of locations.

Location	Uplift m/ka	MIS 5.5	MIS 11	Tectonic
Charleston S Carolina	0.03	back-barrier	back-barrier	intra plate
Coorong CP Aust	0.07	back-barrier	back-barrier	intra plate
Curacao, Antilles	0.07	notch	notch	island arc
Oahu Hawaii	0.07	shoreline angle	shoreline angle	volcanic
Nome CO Alaska	0.08	shoreline angle	shoreline angle	intra plate
Rome CP Italy	0.15	shoreline angle	estuarine	active margin
Oceanside California	0.16	shoreline angle	shoreline angle	active margin
Barbados	0.3	shoreline angle	shoreline angle	island arc
Westport NZ	0.39	shoreline angle	shoreline angle	active margin
Sumba I Indonesia	0.47	shoreline angle	shoreline angle	island arc
Autaro I Indonesia	0.5	shoreline angle	shoreline angle	island arc
Chala Bay S Peru	0.5	shoreline angle	shoreline angle	active margin

Table 2. Sea-levels calculated from different MIS 5.5 ages and sea-level at those times for uplift correction (see Appendix for detail). Sea-level calculations are based on the removal of outliers (bold) identified at or beyond two standard deviations. Calculated MIS 11 sea-levels are rounded up.

Age (ka)	116 ka			124 ka			132 ka			S
MIS 5.5. SL	2	4	6	2	4	6	2	4	6	
Charleston	–5	3	7	–5	3	7	–5	3	10	2±6
Coorong CP	–2	6	14	–2	6	**14**	2	6	**14**	4±6
Curacao	5	**13**	–21	**9**	**13**	**21**	9	**17**	**21**	4±6
Oahu, Hawaii	–3	5	13	1	5	13	9	9	**13**	–2±16
Nome CP Alaska	**–14**	5	3	**–9**	5	**13**	3	–1	3	3±6
Rome CP Italy	–2	6	14	2	10	**22**	6	14	**17**	6±6
Oceanside	–1	3	11	3	7	**15**	7	11	**19**	5±5
Barbados	–10	–2	6	–2	6	10	6	10	**19**	3±7
Westport NZ	–8	–4	4	0	8	**16**	12	**16**	**24**	2±7
Sumba I	–13	–5	–1	–1	7	11	11	**19**	**15**	1±9
Autaro I	–3	–5	3	–1	7	**15**	**15**	19	**27**	4±11
Chala Bay	**–31**	–3	–15	–3	–11	–3	–3	–3	9	–4±7
S	–6	1	3	1	4	7	3	6	7	
	±6	±5	±11	±2	±6	±6	±7	±6	±4	

Table A1. Calculations for estimates for the MIS 11.3 sea-level from MIS 5.5 average uplift rates under different assumptions. S (1) is the sealevel for MIS 11.3 from all locations. H: elevation of MIS 11.3 high sealevel; H*: elevation of the MIS 5.5 sea-level on which uplift rate will be based; H*-2 elevation of the MIS 5.5 sea-level minus the estimated elevation of the MIS 5.5 sea-level at that time; uplift rate m/ka; UC: uplift correction elevation; S MIS 11.3 sea-level (UC H).

116 ka 2 m	**H**	**H***	**H*-2**	**uplift m/ka**	**UC**	**S**
Charleston	15	8	6	0.05	20	-5
Coorong	26	10	8	0.07	28	-2
Curacao	37	11	9	0.08	32	5
Nome CP	29	11	9	0.08	32	-3
Oahu	20	12	10	0.09	37	-14
Rome	63	20	18	0.16	65	-2
Oceanside	68	22	20	0.17	69	-1
Barbados	120	39	37	0.32	130	-10
Westport	158	50	48	0.41	166	-8
Sumba I	190	60	58	0.5	203	-13
Autaro I	202	63	61	0.53	215	-13
Chala Bay	200	68	66	0.57	231	**-31**
					mean	-6
					±	6

116 ka 4 m	**H**	**H***	**H*-4**	**uplift m/ka**	**UC**	**S**
Charleston	15	8	4	0.03	12	3
Coorong	26	10	6	0.05	20	6
Curacao	37	11	7	0.06	24	**13**
Nome CP	29	11	7	0.06	24	5
Oahu	20	12	8	0.07	28	-5
Rome	63	20	16	0.14	57	6
Oceanside	68	22	18	0.16	65	-3
Barbados	120	39	35	0.3	122	-2
Westport	158	50	46	0.4	162	-4
Sumba I	190	60	56	0.48	195	-5
Autaro I	202	63	59	0.51	207	-5
Chala Bay	200	68	64	0.55	223	-3
					mean	0.6
					±	5

116 ka 6 m	**H**	**H***	**H*-6**	**uplift m/ka**	**UC**	**S**
Charleston	15	8	2	0.02	8	7
Coorong	26	10	4	0.03	12	14
Curacao	37	11	5	0.04	16	-21
Nome CP	29	11	5	0.04	16	13
Oahu	20	12	6	0.05	20	3
Rome	63	20	14	0.12	49	14
Oceanside	68	22	16	0.14	57	11
Barbados	120	39	33	0.28	114	6
Westport	158	50	44	0.38	154	4
Sumba I	190	60	54	0.47	191	-1
Autaro I	202	63	57	0.49	199	3
Chala Bay	200	68	62	0.53	215	-15
					mean	3
					±	11

124 ka 2 m	**H**	**H***	**H*-2**	**uplift m/ka**	**UC**	**S**
Charleston	15	8	6	0.05	20	-5
Coorong	26	10	8	0.07	28	-2
Curacao	37	11	9	0.07	28	**9**
Nome CP	29	11	9	0.07	28	1
Oahu	20	12	10	0.08	32	**-9**
Rome	63	20	18	0.15	61	2
Oceanside	68	22	20	0.16	65	3
Barbados	120	39	37	0.3	122	-2
Westport	158	50	48	0.39	158	0
Sumba I	190	60	58	0.47	191	-1
Autaro I	202	63	61	0.5	203	-1
Chala Bay	200	68	66	0.5	203	-3
					mean	1
					±	2

124 ka 4 m	**H**	**H***	**H*-4**	**uplift m/ka**	**UC**	**S**
Charleston	15	8	4	0.03	12	3
Coorong	26	10	6	0.05	20	6
Curacao	37	11	7	0.06	24	**13**
Nome CP	29	11	7	0.06	24	5
Oahu	20	12	8	0.07	28	**-5**
Rome	63	20	16	0.13	53	10
Oceanside	68	22	18	0.15	61	7
Barbados	120	39	35	0.28	114	6
Westport	158	50	46	0.3	150	8
Sumba I	190	60	56	0.47	183	7
Autaro I	202	63	59	0.5	195	7
Chala Bay	200	68	64	0.5	211	-11
					mean	4
					±	6

124 ka 6 m	**H**	**H***	**H*-6**	**uplift m/ka**	**UC**	**S**
Charleston	15	8	2	0.02	8	7
Coorong	26	10	4	0.03	12	14
Curacao	37	11	5	0.04	16	**21**
Nome CP	29	11	5	0.04	16	13
Oahu	20	12	6	0.05	20	**3**
Rome	63	20	14	0.1	41	**22**
Oceanside	68	22	16	0.13	53	**15**
Barbados	120	39	33	0.27	110	10
Westport	158	50	44	0.35	142	**16**
Sumba I	190	60	54	0.44	179	11
Autaro I	202	63	57	0.46	187	**15**
Chala Bay	200	68	62	0.5	203	-3
					mean	7
					±	6

Table A1. Continued.

132 ka 2 m	**H**	**H***	**H*-2**	**uplift m/ka**	**UC**	**S**
Charleston	15	8	6	0.05	20	-5
Coorong	26	10	8	0.06	24	2
Curacao	37	11	9	0.07	28	9
Nome CP	29	11	9	0.07	28	1
Oahu	20	12	10	0.08	32	-9
Rome	63	20	18	0.14	57	6
Oceanside	68	22	20	0.15	61	7
Barbados	120	39	37	0.28	114	6
Westport	158	50	48	0.36	146	12
Sumba I	190	60	58	0.44	179	11
Autaro I	202	63	61	0.46	187	**15**
Chala Bay	200	68	66	0.5	203	-3
					mean	3
					±	7

132 ka 4 m	**H**	**H***	**H*-4**	**uplift m/ka**	**UC**	**S**
Charleston	15	8	4	0.03	12	3
Coorong	26	10	6	0.05	20	6
Curacao	37	11	7	0.05	24	**17**
Nome CP	29	11	7	0.05	24	9
Oahu	20	12	8	0.06	28	-1
Rome	63	20	16	0.12	53	14
Oceanside	68	22	18	0.14	61	11
Barbados	120	39	35	0.27	114	10
Westport	158	50	46	0.35	150	**16**
Sumba I	190	60	56	0.42	183	**19**
Autaro I	202	63	59	0.45	195	**19**
Chala Bay	200	68	64	0.5	211	-3
					mean	6
					±	6

132 ka 6 m	**H**	**H***	**H*-6**	**uplift m/ka**	**UC**	**S**
Charleston	15	8	2	0.012	5	10
Coorong	26	10	4	0.03	12	**14**
Curacao	37	11	5	0.04	16	**21**
Nome CP	29	11	5	0.04	16	13
Oahu	20	12	6	0.05	20	**3**
Rome	63	20	14	0.1	46	**17**
Oceanside	68	22	16	0.1	49	**19**
Barbados	120	39	33	0.25	101	**19**
Westport	158	50	44	0.33	134	**24**
Sumba I	190	60	54	0.43	175	**15**
Autaro I	202	63	57	0.43	175	**27**
Chala Bay	200	68	62	0.47	191	9
					mean	7
					±	4

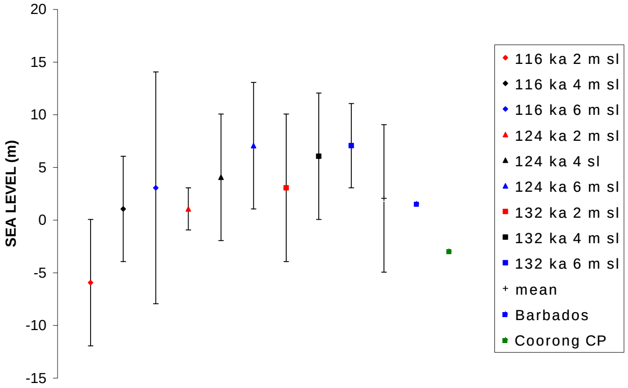

Fig. 1. Calculations of the MIS 11.3 sea-level based on different assumptions (see Results and Discussion) and caption for Table 2.