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Shore-line reconstruction around Australia during the Last Glacial Maximum and Late Glacial Stage

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Abstract

Being both relatively tectonically stable and far from formerly glaciated regions, continental Australia is particularly well-suited for the study of sea-level evolution since the Last Glacial Maximum (LGM) and the Late Glacial Stage. Sea-level data from such regions are valuable indicators of ice-volume equivalent sea level since the effects of glacio-hydro-isostatic terms is less significant for far-field sites though still not negligible. In this study, we review published sea-level observations and results of recently developed numerical models for several areas of coastal Australia and produce corresponding palaeogeographic maps of the results of our numerical models. The results suggest that the Australian continental shelf was largely exposed during the LGM and provide detailed predictions of the timing of inundation as a function of position. Temporal and spatial variation of sea level provide important constraints that can in turn be used to improve the accuracy of numerical models, and better determine important rheological response parameters for the mantle and environmental conditions during the Late Glacial. The palaeoshoreline data from the modeling performed in this study indicate several key locations for future palaeo-environmental studies of sea-level change.

Keywords: Sea-level change; Last Glacial Maximum; Late Glacial; Radiocarbon dating; Glacio-hydro-isostasy; Palaeogeographic map

1. Introduction

Records of variation in sea level provide constraints on numerical models related to mass exchange between the oceans and land-based ice-sheets. However, sea-level change is not spatially uniform due to the isostatic response of the earth to variable loading. At sites far from the former ice sheets, such as Australia, sea-level change is less dependent on isostatic factors and is thus less sensitive to mantle rheology and the details of ice-sheet evolution. Sea-level observations from these locations are mainly dependent on changes in ocean volume and provide the best estimates of land-based ice volumes during glacial periods. Particularly important is the sea-level minimum at far-field sites which constrains ice volumes at the time of the Last Glacial Maximum (LGM).

Murray-Wallace and Belperio (1991) investigated sea-level observations from the last inter-glacial around the coast of Australia (Fig. 1) and suggested that the Australian continental margin can be separated into distinct zones of varying tectonic stability. The results of this and other studies (e.g. Schwebel, 1984; Belperio et al., 1995; Marshall and Thom, 1976; Marshall and Davis, 1984) allow tectonic effects to be identified over the last ~130 ka. In general, tectonic effects along the northern and eastern coasts of Australia since the last inter-glacial are found to be small. The majority of the observed uplift in these regions may be attributed to hydro-isostatic effects and the difference in elapsed duration between the present and last inter-glacial periods (Stirling et al., 1995, 1998). Such environments are ideal for observing the position of sea level during Late Glacial time while avoiding the complications introduced by vertical tectonic movement.

In this paper, we review some published sea-level observations, provide a summary of the details of our numerical modeling of glacio-hydro-isostatic effects and

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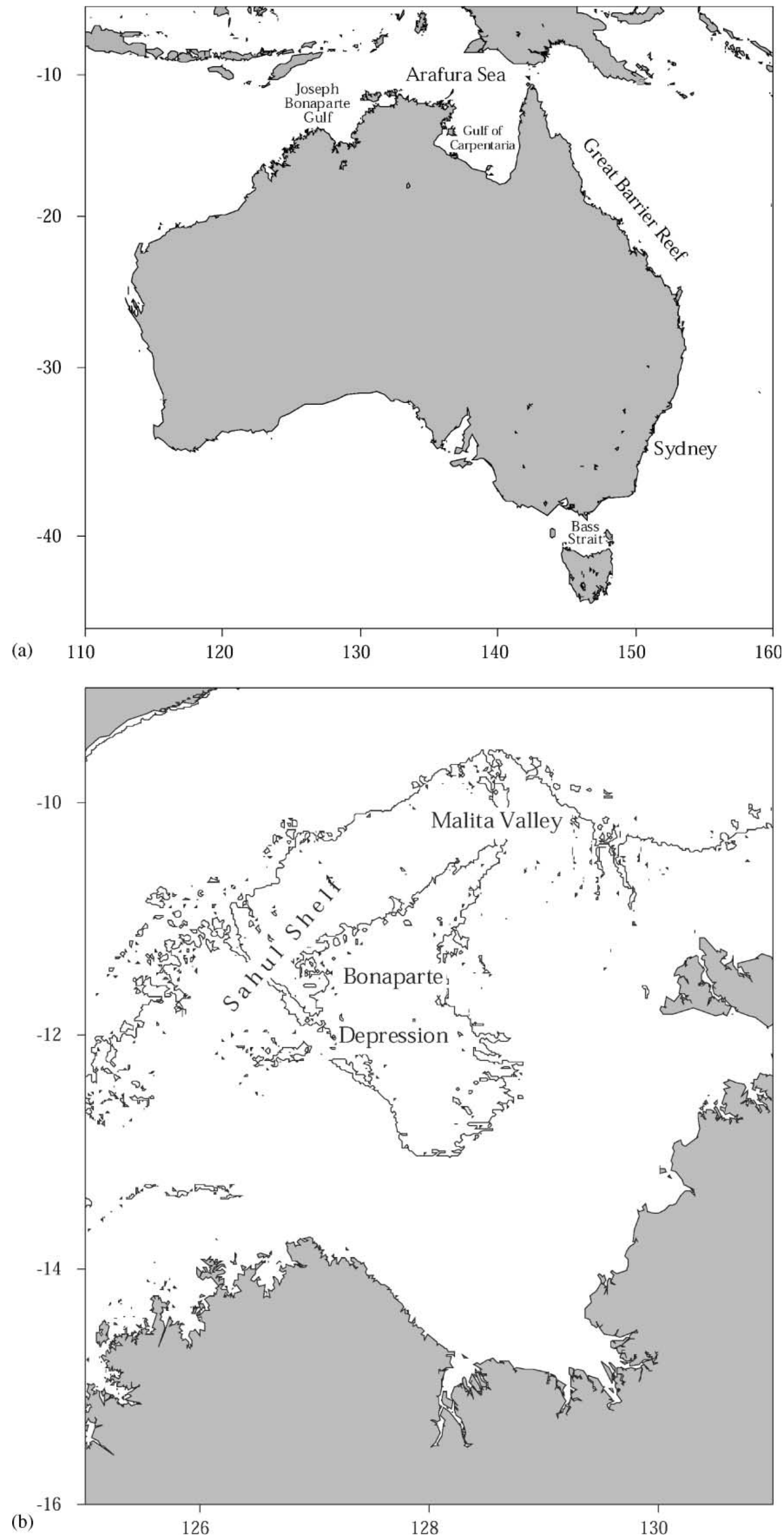

Fig. 1. (a) Map showing locations discussed in this paper. The Northwest Shelf is not marked but consists of the submerged continental shelf area off the Northwestern coast of Australia and includes the Sahul Shelf and the Joseph Bonaparte Gulf. The Malita Valley is a narrow channel that serves as principal outflow of the Bonaparte Depression during sea-level low stands. (b) Detailed map of the Bonaparte Gulf region showing significant features and the 100 m bathymetric contour.

display the results of our modeling in the form of palaeo-shoreline geographic maps for several key areas around Australia. More systematic sea level observations for the areas discussed in this paper would be of great benefit in further refining the history of sea level change since the LGM and the history of deglaciation of the major ice sheets.

2. Sea level observations around Australia during the Last Glacial Maximum and the Late Glacial Stage

Sea level data for the LGM and the Late Glacial Stage are rare because of inundation after the last deglaciation during the late Pleistocene and early Holocene. Around the coast of Australia, a number of isolated data points have been reported but no systematic study has yet been made apart from the northwestern shelf of Australia (Yokoyama et al., 2000a, 2001a,b). Much of this information has come from sediment cores (Table 1) but the majority of the earlier data is subject to uncertainties inherent in the dating techniques used. Most previous radiocarbon dates were obtained using conventional methods and the samples were only minimally etched ($<10\%$ of total weight loss). Samples of such great age are in fact likely to need more severe etching to remove all traces of younger carbon contamination.

Continental shelf areas with shallow sea-floor depressions, better lend themselves to a systematic study of sea-level change. During the LGM, large parts of the Australian continental shelf were exposed, and large, shallow depressions may have acted as pools for the collection and preservation of lagoonal or terrestrial material. The subsequent inundation of these features may then be recorded as transitions from terrestrial or fresh-water conditions to marine conditions in either floral or faunal remains within the sediments. If depressions with different sill heights occur, it becomes possible to map the sea level change through time.

Several localities that merit examination are found off the coast of Australia where most of the continental shelf would have been exposed during the LGM. Examples include: (i) the Gulf of Carpentaria, (ii) areas within the Great Barrier Reef (GBR); (iii) Bass Strait, and (iv) the Bonaparte Depression and the North-western Shelf (Fig. 1).

Northwestern Australia has a very wide continental shelf, in fact one of the widest in the world. Van Andel and Veevers (1967) extensively examined its sedimentary features and concluded that relative sea level in this area was lowered during the Last Glacial Maximum by about 130 m. Yokoyama et al. (2000a, 2001a) investigated sea-level history in this area using sediment cores systematically recovered and radiocarbon dated expressly for this purpose. Palaeo-water depth at each site was determined using micropalaeontological indicators. The LGM sea level at this locality was observed to be 120 m below the present sea level and rose sharply at about 16,500 ^{14}C yr BP. The character of the sea level observations obtained in this study is given in Fig. 2.

The Gulf of Carpentaria was a gigantic basin in Late Glacial time, well separated from the sea by sills in the Arafura Sea (at a depth of 53 m) and in the Torres Strait (at a depth of 12 m). Several studies on palaeo-environmental reconstruction have been conducted in this area (Torgersen et al., 1985, 1988; Chivas et al., 1986; De Deckker et al., 1988) and the character of sea-level change is reasonably well understood. The isolated depression allowed the formation of a huge saltwater lake, Lake Carpentaria, during the sea-level low-stand at the Last Glacial Maximum. The timing of marine inundation across the sills is recorded in the sedimentary facies, ostracod assemblage and its shell chemistry

Table 1
Sea level around Australia in the Late Glacial time[a]

Region	Reference	Reported relative sea level (m)	Age (^{14}C yr BP)	^{14}C dated material or method[b]
Gulf of St. Vincent	Cann et al. (1993)	−27 to −30 m	32,000–40,000	RAD
Off shore of Sydney	Ferland et al. (1995)	shallow than −130 m	17,320	AMS and RAD
Gulf of Carpentaria	McCulloch et al. (1989)	> −53 m	~35,000	RAD
	Torgersen et al. (1988)	−53 m	12,000	RAD
Central GBR	Carter and Johnson (1986)	−114 to −133 m	18,000	No dated samples
	Veeh and Veevers (1970)	−150 to −175 m	13,600 and 13,8600	Coral, Beach rock RAD
	Yokoyama et al. (2000b)	−150 to −175 m	14,390	AMS[c]
Timor Sea	van Andel and Veevers (1967)	−130 to −135 m	17,400–19,100	Total carbon RAD
	Yokoyama et al. (2000a, 2001a)	ca. −120 m	18,000–16,000	AMS[c]
		−110 to −100 m	15,880–14,000	AMS[c]
Arafura Sea	Jongsma (1970)	−130 to −175 m	18,700	Beach rock RAD

[a] MIS = marine oxygen isotope stage.
[b] Using conventional radiometric method (RAD) and accelerator mass spectrometry (AMS).
[c] AMS with severe etching. All samples underwent etching equivalent to approximately 30–50% of weight loss to discard any possible younger carbon contamination in outer shell.

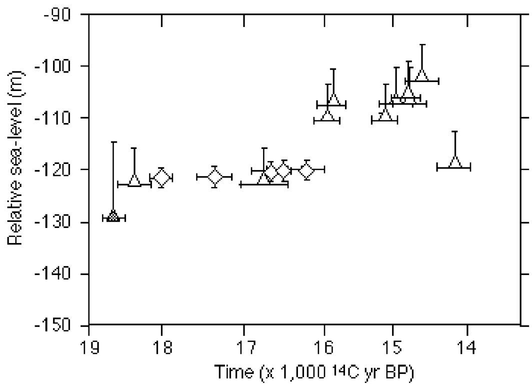

Fig. 2. Relative sea-level observations obtained from Joseph Bonaparte Gulf of northwestern Australia (Yokoyama et al., 2000a). Sedimentological and micropalaeontological studies together with AMS radiocarbon dating on shallow marine, marginal marine and brackish fossil shells provided well constrained sea-level markings for the period during the LGM and the early stage of the Late Glacial period.

(Torgersen et al., 1988; Chivas et al., 1986; De Deckker et al., 1988) and strontium isotopic signals in the shells clearly mark the transition between brackish-lacustrine and marine regimes (McCulloch et al., 1989). A flooding event due to sea-level rise since the LGM was marked at about 12,000 ^{14}C yr BP indicates that sea level during this epoch was as approximately 53 m lower than that at present.

Off-shore Queensland is characterized by well-developed coral reefs and this area has been extensively studied for evidence of Holocene sea-level change. Examination of sedimentary facies led to the conclusion that LGM sea level was lowered locally by 114–133 m (Carter and Johnson, 1986). Corals from fore-reef slopes have been sampled by submersible and dated using both conventional radiocarbon dating and uranium series dating (Veeh and Veevers, 1970). The *Galaxia* corals, which grow in the depth range 0–75 m, were recovered at a depth of 175 m. These corals have again been radiocarbon dated using step-wise leaching preparation with Accelerator Mass Spectrometry (AMS) and uranium-series dated using Thermal Ionisation Mass Spectrometry (TIMS) (Yokoyama et al., 2000b). The results obtained using the new mass spectrometric methods for both radiocarbon and uranium-series (14.390 ± 0.150 and 16.980 ± 0.110 ka, respectively) were in good agreement with the originally reported values (13.600 ± 0.220 and 17.000 ± 1.000 ka) of Veeh and Veevers (1970).

Samples from the outer continental shelf, offshore of Sydney, have been dated both by radiocarbon methods (AMS and conventional) and amino acid racemization analysis (AAR) (Ferland et al., 1995). They established the lower limit of maximum sea level fall as less than 130 m at the LGM but a more precise constraint could not be established.

The shallow gradient that dominates bathymetry in the Bass Strait increases the likelihood of past sea levels being preserved and Blom (1988) reported preliminary data obtained from sedimentological features. However, high-energy oceanological conditions tend to perturb in-situ sea-level indicators, making it difficult to accurately reconstruct the evolution of paleo-sea-levels in this region.

3. Sea-level prediction around the Australian continent

Sea-level change on a viscoelastic earth can be separated into isostatic and equivalent sea-level contributions as in Eq. (1) (following Farell and Clark, 1976; Nakada and Lambeck, 1987)

$$\Delta\zeta_{rsl} = \Delta\zeta_e + \Delta\zeta_i \qquad (1)$$

where $\Delta\zeta_{rsl}$ is the change in relative sea level, $\Delta\zeta_e$ the ice-equivalent sea level term and $\Delta\zeta_i$ the glacio-hydro-isostatic term. Detailed description of the formulation is given by Nakada and Lambeck (1987) and Johnston (1993, 1995). These models have previously been applied to the Australian region by Nakada and Lambeck (1989) and Lambeck and Nakada (1990).

The ice models used in this study are based on detailed reconstructions from the available geomorphological evidence. For the Northern Hemisphere, the major ice sheets are located in Fennoscandia and the Barents-Kara sea (Lambeck et al., 1998), and North America and Greenland (a derivative of the ICE 1 model of Peltier and Andrews, 1976). The Antarctic ice model used here is a version of the maximum reconstruction of Denton and Hughes (1981) scaled to give a total equivalent ice volume of 25 m of sea level at the LGM sea level. Detailed descriptions of these ice models can be found in Fleming et al. (1998) and Lambeck et al. (2000). The equivalent sea-level curve for the LGM to the Late Glacial Stage for the ice sheets used in the present study is shown in Fig. 3.

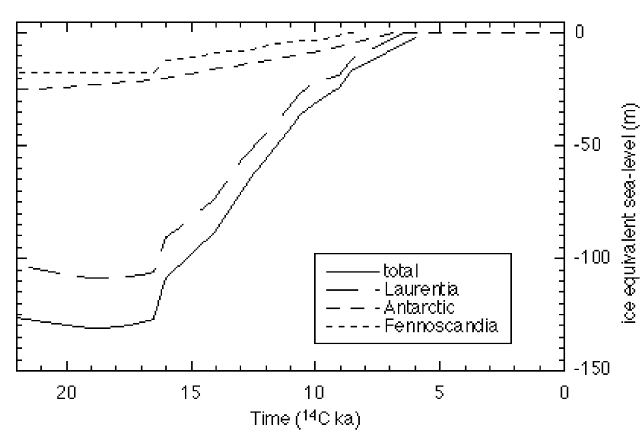

Fig. 3. Ice-equivalent sea-level curve since LGM to the present in radiocarbon time scale.

The glacio-hydro-isostatic calculations were performed using a radially symmetric Maxwell viscoelastic formulation so that the earth's physical properties were taken to be a function of depth. The model consists of four layers, an elastic lithosphere, upper and lower mantle, and a liquid core. For the range of earth models considered in this study, the lithospheric thickness was allowed to take values between 50 and 100 km, the upper mantle is defined to be that portion of the mantle lying between the base of lithosphere and a depth of 670 km, and the lower mantle to be the remaining portion of the mantle lying between a depth of 670 km and the core-mantle boundary (taken in these models to lie at a depth of 2891 km). The base earth model has a lithospheric thickness of 65 km, an upper mantle viscosity of 4×10^{20} Pa s, and a lower mantle viscosity of 10^{22} Pa s. Previous studies have demonstrated that this model is the most consistent with the observational evidence available for the Australian continent and elsewhere (Nakada and Lambeck, 1989; Lambeck et al., 1998).

The changing shape of the coastlines during glacial melting affects the sea level predicted at the coastline through the isostatic term as well as the ice-equivalent sea-level contribution term. The geometry of the ocean surface is time-dependent and the sea surface area expands as ice sheets melt such that the ice grounding line defines the ocean basin margin (Lambeck and Nakada, 1990; Johnston, 1993). The effect of time-dependent coastline geometry, on sea-level change at broad continental shelves, such as northwestern Australia, is particularly large and cannot be neglected. In the numerical model employed for this study, an iterative procedure is used to allow for time-dependent variations in coastline geo-metry. Convergence to cm precision is achieved after three iterations.

4. Results and discussion

4.1. Comparison of LGM sea level observations from Bonaparte Gulf and other regions around the Australian continental shelf

Reliable sea-level observations from the LGM may be used to calculate a 'standard' equivalent sea-level curve after removing glacio-hydro-isostatic effects. Such an analysis has already been performed by Yokoyama et al. (2000a,2001a) for observations from the Bonaparte Gulf as well as for observations from Barbados (Fairbanks, 1989; Bard et al., 1990). The reliability of sea level observations is dependent on the nature of the sample, its environment of deposition, and the methodology of the dating procedure. We now consider these factors for a number of sites around the Australian continental shelf (Table 1) and examine the extent to which these results are consistent with those obtained previously and numerical calculations.

At a point just beyond the outer edge of the Bonaparte Gulf, beach rock samples were recovered from depths ranging from 130 to 175 m and dated using conventional radiocarbon techniques (Jongsma, 1970). The resulting sea-level observations are as much as 10–55 m deeper than those obtained from samples of the same age taken within the Bonaparte Gulf. This discrepancy could be the result of a number of contributary factors. Beach rock is normally found in the intertidal zone where it is produced as a result of chemical weathering processes. The beach rock samples in this study were collected from the ocean floor by dredging from a sampling point located at the edge of the continental shelf. The influence of ocean wave action in such a location is likely to be large, so that the possibility of secondary storm deposition should be carefully considered when interpreting these results. Reliability of the radiocarbon date of the beach rock should also be closely examined. Submerged calcareous samples are often found to be contaminated by surface accretion of younger material (see Carter and Johnson, 1986). The beach rock samples from the Jongsma (1970) study did not receive pre-treatment to eliminate surface contamination, raising the possibility that the obtained radiocarbon dates are not an accurate indicator of the time of deposition. According to the marine oxygen isotope signal (Shackleton and Opdyke, 1973) more water was stored as ice during earlier glacial stages than was stored in the ice sheets of the LGM (Stage 2). The location of the beach rock samples investigated in the Jongsma (1970) study might therefore reflect shoreline positions of previous glacial stages, the age of which has been substantially underestimated due to inadequate sample preparation. This observation can, however, be used to establish a minimal depth and age.

A wood sample obtained from the base of the gravity core at a depth of 99 m water yielded a radiocarbon date of $14{,}500 \pm 700$ yr BP. The difficulties of interpretation raised for the beach rock samples of Jongsma (1970) also apply here, though the age–depth relationship for this data point is in good accord with the 'standard' equivalent sea-level curve (Fleming et al., 1998; Yokoyama et al., 2000a; Fig. 2). We may, therefore, tentatively conclude that this sample was deposited close to sea level at approximately 14.5 ^{14}C ka, though further investigation on this particular sediment core to confirm this conclusion is desirable.

Extensive sedimentological investigation has been conducted at the continental shelf off-shore of Sydney (Ferland et al., 1995). As opposed to the Bonaparte Gulf, the narrow continental shelf in this region produces a high wave energy environment. Secondary deposition due to reworking by wave action is thus significantly more likely for samples from this area

(Murray-Wallace et al., 1996). Sub-littoral dwelling bivalves are, however, generally well preserved and dating results obtained using both conventional liquid scintillation counting (LSC) and AMS show that sea level during the LGM was lower than present values by less than 130 m in this region (Ferland et al., 1995). This is consistent with the Bonaparte results, and is a useful constraint for determining the lower limit of sea level during the LGM.

A similar conclusion can be drawn from observations from the GBR. Many submerged shoreline features have been reported for the GBR (e.g. Maxwell, 1973; Marshall, 1977; Scoffin and Tudhope, 1985). Carter and Johnson (1986) detected submarine shoreline features using continuous seismic profiles. Their investigations produced direct geomorphological evidence of palaeo-shorelines at several points. Although they did not directly date these features, the LGM shoreline at about 18,000 ^{14}C yr BP was deduced to lie between 114 and 133 m below the present. This former figure is slightly shallower than the Bonaparte Gulf observations, though it is in good agreement with the predicted relative sea-level curve for this region (Fig. 4).

Corals taken from depths between 150 and 175 m off the GBR by submersible have been reported by Veeh and Veevers (1970). Given that the LGM low-stand will lie approximately 125 m below present sea level, this coral will never have been aerially exposed during the Late Glacial. Pristine aragonite structures were detected by inspection with a petrographic microscope and further investigation using XRD indicated that no calcite was present, confirming the quality of the sample. The agreement between the originally reported ages and those obtained after severe etching of the samples give us reasonable confidence in the validity of the ^{14}C dates obtained. From the depth of recovery and the approximate value of the LGM low-stand, we infer that the *Galaxea clavus* samples obtained in the study of Veeh and Veevers (1970) were not living at sea level but are more likely to have grown at a depth of approximately 50 m at 14 ^{14}C ka BP. This coral is also found at Bikini and Jamaica where it grows at depths as great as 75 m (Veeh and Veevers, 1970).

The Gulf of Carpentaria consists of a broad basin surrounded by shallow sills that resulted in the formation of a large brackish lake during the Late Glacial (e.g. Torgersen et al., 1985). Sea-level information in this case is most readily available for epochs in which sea level rose above or fell below the height of the lake sill producing a rapid transition to or from marine

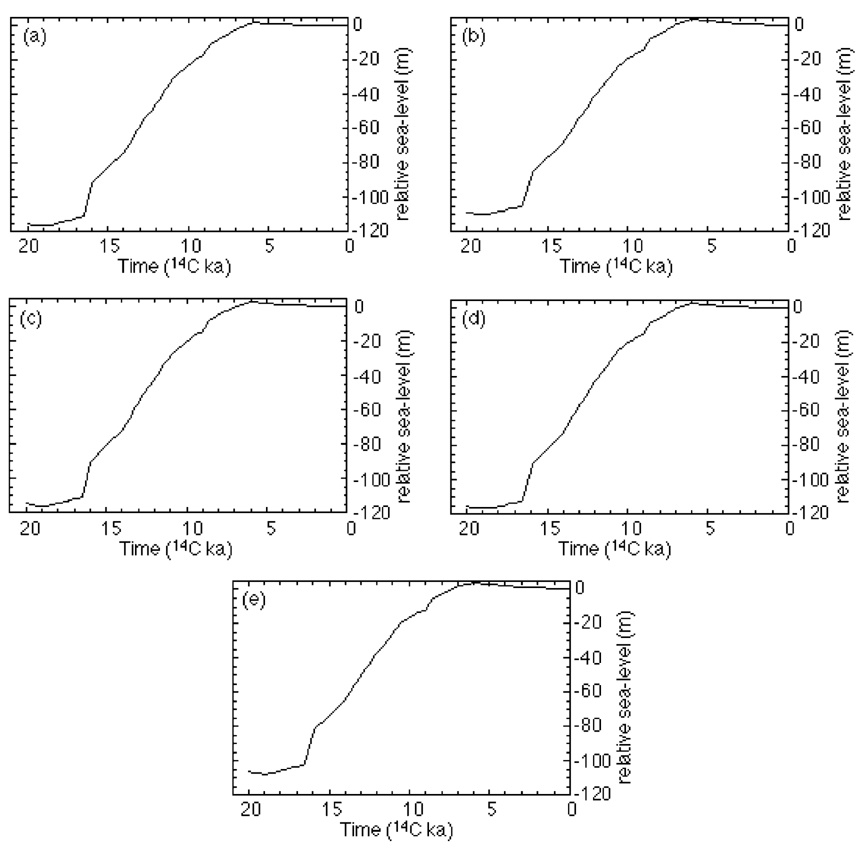

Fig. 4. Predicted relative sea-level curves for: (a) Joseph Bonaparte Gulf (11°44′S 127°57′E), (b) Gulf of Carpentaria (12°30′S 140°20′E), (c) off the Great Barrier Reef (23°30′S 152°15′E), and (d) off the Sydney coast (33°24′S 151°58′E) using rigorous glacio-hydro-isostatic modeling. The rheological parameters used for these calculations are: lithospheric thickness of 65 km, an upper mantle viscosity of 4×10^{20} Pa s, and a lower mantle viscosity of 10^{22} Pa s.

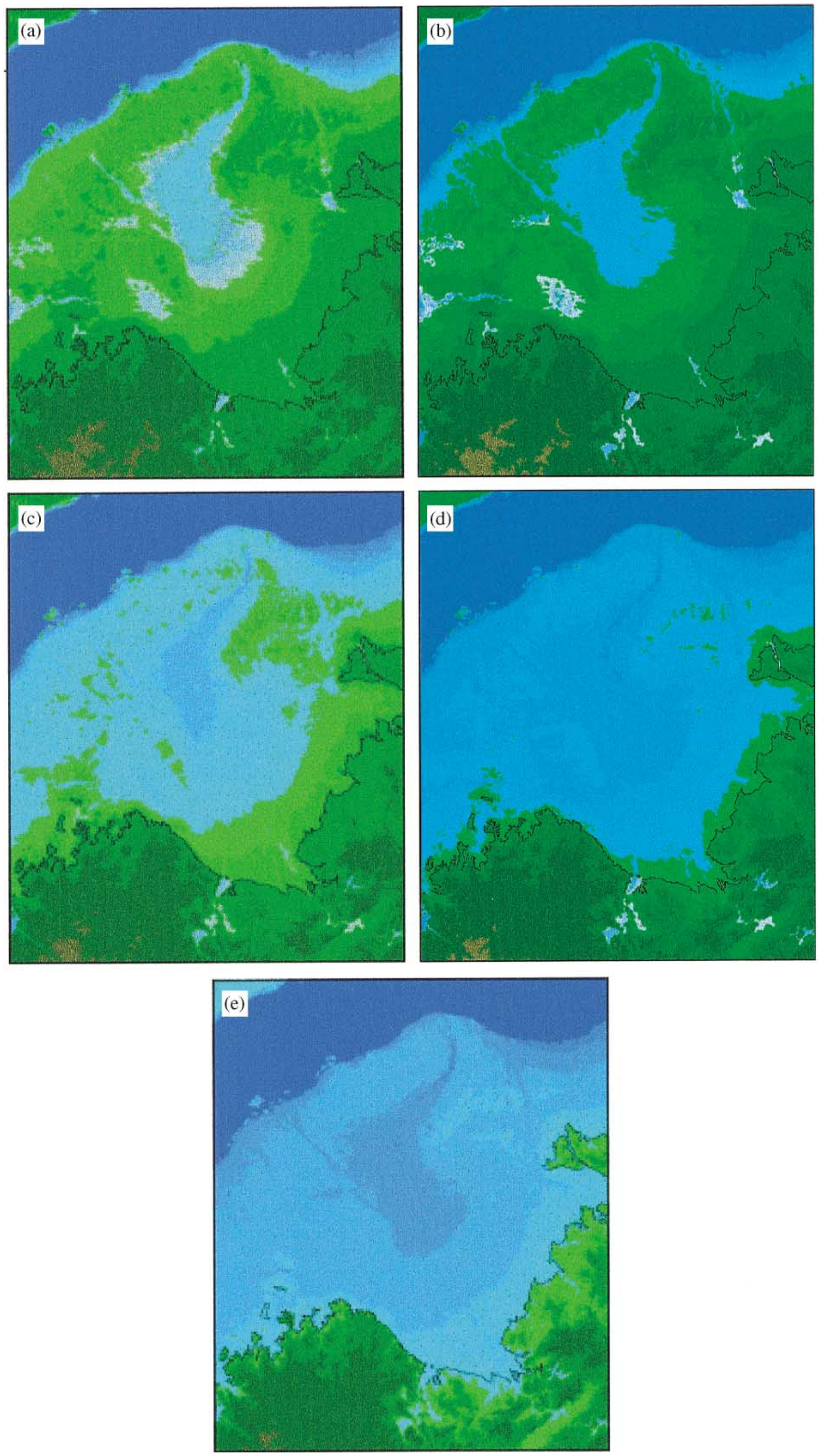

Fig. 5. Palaeo-shoreline maps for the Joseph Bonaparte Gulf; (a) LGM (~18,000 ^{14}C yr BP), (b) 16,000 ^{14}C yr BP, (c) 12,000 ^{14}C yr BP, (d) 9000 ^{14}C yr BP and (e) 6000 ^{14}C yr BP. Bathymetric contours are indicated by changes in colour scheme at depths 0, 25, 50, 100, 150, and 200 m. Topographic contours are indicated by changes in colour scheme at heights 0, 25, 50, 75, 100, 200, 500 and 1000 m. Catchment basins above sea level are indicated by a separate color scheme, catchment depths with respect to the lip of the basin sill are contoured at 0, 5, 10, 25, 50, and 100 m. The location of the current coastline is indicated in black. These catchment areas mark locations of potential lake formation.

conditions. The timing of the last inundation of the sill has been determined from analysis of sediment cores which yield ^{14}C dates of approximately 12 ka BP. The timing of this inundation is in good accord with the results of numerical modeling for this region (Fig. 4).

4.2. Palaeoshorelines around Australian continent

Palaeogeographic maps are drawn using high resolution topography data bases in conjunction with the results of the glacio-hydro-isostatic modeling discussed in Section 3. The data sets are combined by processing through various general purpose software packages and displayed using purpose-built code (see Acknowledgements).

Numerical modeling of sea-level rise in northwestern Australia indicates that large areas of the continental shelf were exposed above sea level during the LGM (Fig. 5). The Sahul rise is located at the edge of the continental shelf and acted to protect the inner shelf from the action of the open ocean. The Bonaparte Depression represents a substantial catchment area and would have contained a large body of water which was connected to the open ocean through the Malita shelf

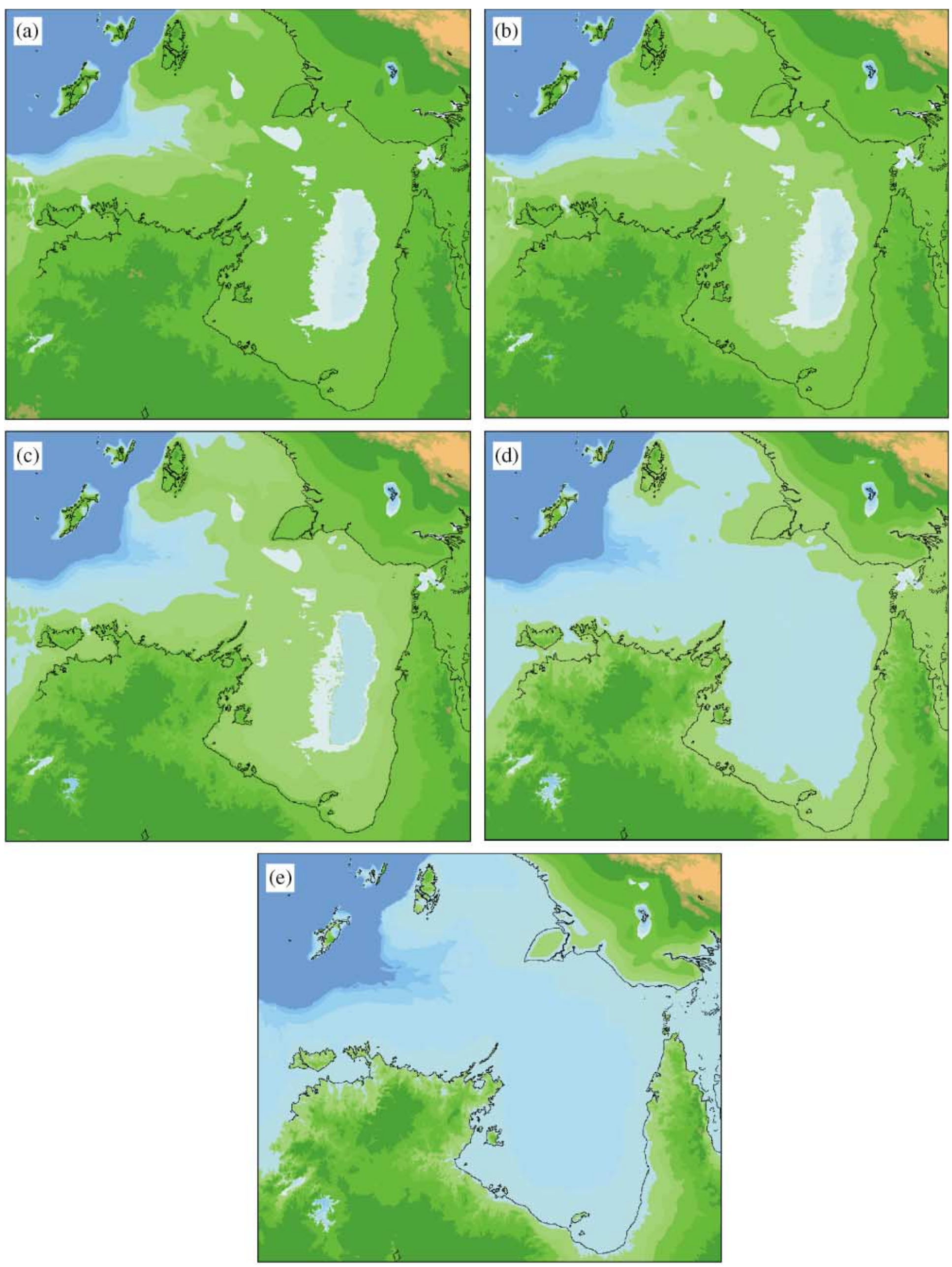

Fig. 6. Same as Fig. 5 but for the Gulf of Carpentaria. The time steps and color schemes are the same as those used in Fig. 5.

valley. This reconstruction is consistent with the sedimentological information from cores recovered from the Bonaparte Depression indicating a brackish rather than fresh water environment during the LGM (Yokoyama et al., 2000a, 2001a). The first sea-level rise after the LGM occurs at about 16,000 ^{14}C yr BP and can be determined from transitions found in the sediment cores. This timing accords well with the results from Fig. 5 where the process of inundation of the Bonaparte Depression can be observed to begin. By 12,000 ^{14}C yr BP, the majority of the shelf had been submerged.

In contrast, Lake Carpentaria persisted as an isolated lacustrine environment from the LGM to 12,000 ^{14}C yr BP (Fig. 6). This is preserved in facies boundaries in the sediment cores obtained from the Gulf of Carpentaria (Chivas et al., 1986; McCulloch et al., 1989).

5. Conclusions

Tectonically stable shorelines around the continental margin of Australia represent a variety of diverse paleomarine environments that are well-suited for studies of post-glacial sea-level change. Studies in areas where the continental shelf is both wide and shallow in tropical Australia provide particularly useful data for constraining sea-level evolution during the LGM and Late Glacial stages (Yokoyama et al., 2000a). Incorporating these results with those of similar studies of other far-field sites, Fleming et al. (1998) has permitted the construction and refinement of an equivalent sea-level curve representing the integrated history of ice-sheet melting since the LGM. The ice models used to obtain the numerical results for this study all had melting histories in accord with the equivalent sea-level curve thus obtained. Further refinement of this curve relies on identification and investigation of regions likely to preserve datable indicators of Late Glacial marine transitions.

Palaeobathymetric maps were produced for several key areas around the Australian continent in this study. From the results of our numerical modeling, we see that Lake Carpentaria was isolated from the open ocean by elevated sills and that it persisted as a brackish lacustrine environment until the inundation of the gulf at 12,000 ^{14}C yr BP. Similar models for the Great Barrier Reef, the Bonaparte Gulf, and off-shore Sydney were compared with reported observational data. The close agreement between the results of numerical modeling and the observed sea-level data for the regions considered indicates that the numerical procedures discussed here, may allow a detailed a priori determination of possible sites for future investigation in addition to qualitative insights into the large-scale nature of the marine transitions preserved in the observational record.

Higher spatial and temporal resolution in the observational data during the LGM and the early stage of the Late Glacial phase for the eastern and southeastern Australian margins may be more reliably located using the results of these numerical procedures. Such data would in turn allow refinement of the equivalent sea-level curve and the melting history of the ice sheets during the Late Glacial. Detailed observations from these regions could also be used to resolve the magnitude and timing of rapid sea-level rises reported from other far-field sites (e.g., Fairbanks, 1989; Bard et al., 1990, 1996; Chappell and Polach, 1991; Hunebuth et al., 2001). Such data will provide important constraints for future glaciological or palaeoclimatological studies.

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