Micropalaeontological evidence for Late Quaternary sea-level changes in Bonaparte Gulf, Australia

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ABSTRACT

The shallow seas surrounding Northern Australia, far away from former ice sheets and on a tectonically stable margin, is ideally suited for sea-level reconstructions as hydro-isostatic effects there are minimal. Detailed examination of ostracod and foraminifer remains, recovered from gravity core RS176/GC 5 from Bonaparte Gulf, and which is located at 118 m water depth, provides a detailed history of sea-level transgression coinciding with the end of Last Glacial Maximum [LGM]. For the period spanning ~30,000 to 20,100 cal years BP, the paucity of sediment may represent some erosion, but there is no sign of pedogenesis for that interval in the core. After 20,100 cal years BP, estuarine conditions prevailed at the site, followed by an obvious sea level rise at 19,400 years BP that is well constrained by 14C dates and high sedimentation. The evidence of a sea-level rise after 19,400 cal years BP of the order of 10 m is based on observations made on microfossil remains. Higher in the core, the presence of aragonitic pteropods is a clear indication of open marine conditions because they could not have been reworked, due to their fragility.

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1. Introduction

There is currently much debate on the timing and extent of the sea level drop that coincided with the Last Glacial Maximum [=LGM] (refer to papers presented in a single issue of *Quaternary Science Reviews* 21 (1–3), and the current volume herewith). One key issue has been to constrain the global ice volume in time and space and its effects on the global ocean. In particular, there has been also much debate on the termination of the LGM, on what caused it, as well as the rate of sea level rise immediately after the LGM.

A major difficulty in reconstructing past sea level from local geological observations of past sea level changes is that these cannot be directly applied to global sea-level reconstructions. Every sea-level reconstruction is relevant to its specific location as sea-level data relate to local phenomena and conditions such as geomorphological and geophysical settings. Isostatic effects are imprinted on all sea-level records, but the best possible sites are those where local effects are minimal, such as on tectonically stable margins where glacio-hydro-isostatic effects are minimal, and consequently will not strongly influence the global sea level signal.

The shallow seas around northwestern Australia are particularly well suited for the study of sea level changes as they are located far away from the former ice sheets of North America, northern Europe and Antarctica and they occur on a tectonically stable margin where glacio-hydro-isostatic effects are clearly minimal. Bonaparte Gulf which is situated on the northwestern shelf of Australia (Fig. 1), is particularly ideal as there is no major tectonic activity in this region. The Gulf has a wide continental shelf and subtle changes of sea level could be detected there. Any accurate dating of sea-level indicators will have to be done on material not affected by the carbon reservoir imprinted in the skeleton of marine organisms that live in the open ocean. Thus, by working with organisms that live in estuaries or lagoons, we can be assured that a minimal or no reservoir effect would interfere with the radiocarbon 'age' of organic remains of fossils used to date past sea-level conditions during which they grew. The reason being that it is unlikely that a 'reservoir effect' is going to affect the carbon uptake of calcareous organisms since the waters in which they live are mostly in equilibrium with the atmospheric carbon reservoir and not a marine one. The shallow water organisms are in no way in contact with deep [frequently old] marine waters that could have upwelled. This latter phenomenon does not occur along the northern shelf of Australia, especially since the shelf is so wide. Consequently, by studying *in situ* (non reworked) brackish organisms, we can obtain a fairly precise timing of events associated with a sea-level transgression or regression. The strategy used here is to identify a core site which remained marginal to the ocean at a specific period of the geological record [here chosen to be at the LGM] in order to specifically identify and date the timing of the lowest sea level and the sea level rise subsequent to the LGM.

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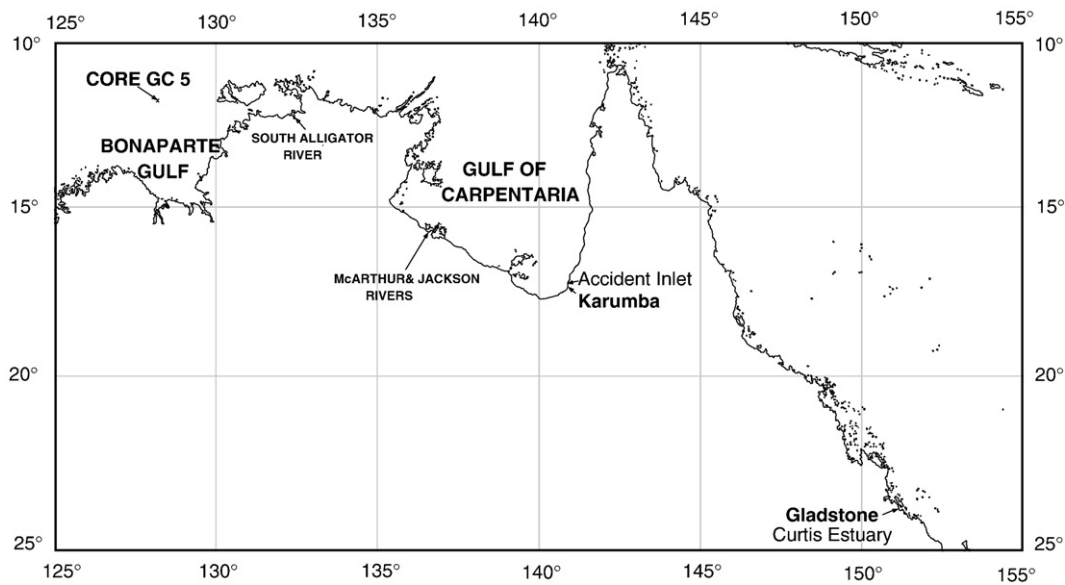 E-mail address: patrick.dedeckker@anu.edu.au (P. De Deckker).

Fig. 1. Map showing the location of the adjacent cores GC4 and GC5 in Bonaparte Gulf and all the other sites mentioned in the text.

Our work presented here aims at further detailing the sea-level history reconstructed by Yokoyama et al. (2000, 2001a,b) through additional analysis of microfossil remains for the same core RS176/GC5 studied by these authors. In addition, the chronology has been recalibrated using the CALIB 5.0.1 program (Stuiver et al., 2005). For calculating the ages for samples ANU8812 and 8820 [see Table 1], we used the formula given by Bard et al. (2004) since the ages are out of range for the INTCAL program. Bard et al.'s (2004) calibration curve is based on sediment core sampled from the Iberian Margin. The calendar ages were obtained from the GISP2 ice core. They look slightly different from original but overlap within analytical uncertainties.

The additional purpose of our work made on this core is to refute the objections made by Shennan and Milne (2003) on the previous findings made on this core, and to further substantiate the reply to those objections provided by Yokoyama et al. (2003) together with additional information on the glacio-isostatic sea-level equation determined by Lambeck et al. (2003). Those discussions highlighted the need for more documentation of the original findings made by Yokoyama et al. (2000, 2001a,b), and these are contained in the present paper. To this end, we carried out additional observations on the key gravity core RS176/GC 5 from Bonaparte Gulf, together with a reassessment of the micropalaeontological data, and by paying particular attention to the microfossil taphonomy.

Table 1
List of radiocarbon dates and relevant calibrated ages for various horizons from core RS176/GC 5 from Bonaparte Gulf

Depth in core (cm)	14C age	Error	Calendar age	Error	Lab number ANU-A	Dated material
42	11,410	180	12,970	130	6900	F
113	14,160	200	16,375	315	8813	B
227	16,240	240	19,070	200	6928	F
227	16,540	170	19,300	165	6807	B
229	16,690	190	19,400	180	7531	F,B
320	17,360	230	20,100	230	6930	F,B
340	18,040	150	20,700	235	9317	B
353	25,750	300	30,035	320	8812	B
453	32,630	480	37,020	470	8820	B

For procedures, refer to text. F=foraminifers, B=bivalve molluscs.

2. The use of microfossils for palaeoenvironmental reconstruction

Microfossils which have a mineralized skeleton can be used successfully to gather information on the environments in which they lived, as well as about post-mortem conditions [=thanatocoenosis]. In particular, the minute crustacean ostracods which possess calcitic, bivalved shells can be used to determine environmental conditions in which they grew, formed shells and later on became preserved. In the process of growing to adulthood, ostracods have to moult on average up to 9 times (Kesling, 1951). This implies that a single ostracod will have generated 18 valves of different sizes during its life and that will eventually be deposited on the sea floor before death occurs. Those valves will range in size from a few microns for the initial embryonic (nauplius) stage, and eventually reach up to 1 mm for some large adults (De Deckker, 2002).

Of importance to the palaeoecological reconstruction presented here is that microscopic remains of organisms, such as ostracods and foraminifers, will behave more or less in the same way as sediment particles on the floor of a waterbody. For example, a strong water current, as frequently found under shallow-water conditions, will cause some of the fragile valves of ostracods to break, to become abraded, or even be completely destroyed. On the other hand, very quiet conditions will favour the preservation of all the different sized valves generated by a single ostracod in the surrounding sediment. Thus, the absence of any current will prevent the 'sorting' of ostracod valves of specific sizes. The same cannot easily be applied to foraminifers, or even molluscs, such as gastropods and bivalves, as over the life of such organisms, additional chambers are added to an individual foraminifer, or additional layers are added to the mollusc. Consequently, examination of a sediment sample containing ostracods can fairly accurately reveal the nature of the environment in which the organisms lived and became preserved. Additional information on the different techniques using ostracods for reconstructing palaeoenvironments is available in De Deckker (1988, 2002) and in the volume edited by Holmes and Chivas (2002).

The recognition of various thanatocoenosis processes are the key to a good palaeoenvironmental reconstruction. In the case of Bonaparte Gulf sediments and microfossil remains, adequate palaeoecological interpretations are paramount for reconstructing the regressive and transgressive sea-level history of the region during the Late Quaternary. This is what we are aiming for with the study of core RS176/GC 5.

3. Fossil assemblages of use for the reconstruction of palaeoenvironments in Bonaparte Gulf

Yokoyama et al. (2000, 2001a) reconstructed the palaeoenvironmental history of Bonaparte Gulf based on the examination of numerous cores located at specific water depths in order to identify the sea-level regression and transgression associated with the LGM. Those studies relied principally on the examination of microfossils to determine four main bio-sedimentary facies that were also placed in a tight chronological control based on 39 AMS radiocarbon dates done on molluscan and microfossil remains. The four facies of Yokoyama et al. (2000, 2001a) were: *Open Marine, Shallow Marine, Marginal Marine* and *Brackish/estuarine*. These are repeated below:

(1) *Open marine* (oM): is identified by the presence of the extremely fragile shells of pelagic pteropods and specimens usually are well preserved. Planktic foraminifers are rare due to the shallow bathymetry of the Gulf. The extrapolated water depth has to be in the vicinity of 20 m or more.

(2) *Shallow marine* (sM): presence of numerous and usually well-preserved benthic foraminifera and marine ostracod taxa, which include *Aglaiella, Argilloecia, Callistocythere, Loxoconcha, Pterygocythereis* and *Uroleberis*. In addition, bairdiid ostracods are common. Terrigenous [=land-derived] components are rare; presence of bryozoan and echinoid spine remains and holothurian spicules; all these are indicative of normal sea-water salinity and water depths less than ~10 m. Pteropods are absent in these samples.

(3) *Marginal marine* (mM): low diversity of benthic marine ostracod commonly *Neocytheretta* ssp., *Xestoleberis*, and taxa accompanied by scaphopods, all of which show signs of abrasion; bivalve molluscs are abundant and often damaged; frequent occurrence of terrigenous material: these are indicative of water depths <5 m, within the tidal zone influence with salinities fluctuating from normal sea-water values.

(4) *Brackish* (Br): paucity of typically marine foraminifera and ostracod taxa; presence of *Ammonia beccarii* often in large numbers and usually in minute (dwarf) sizes as a result of environmental stress (e.g. high temperature, low salinities), *Leptocythere* sp., *Neocytheretta* spp., *Cyprideis australiensis*; common signs of "bleaching" of the calcareous shells by corrosive waters; terrigenous particles (mostly clays), organic (vegetal) fibres, and insect remains forming a substantial fraction of the sample. All these are indicative of salinities well below normal sea-water and strongly influenced by continental waters.

To accurately reconstruct a sea-level record based on information obtained from sediment cores, it is therefore critical that a sequence of palaeoenvironments be recognised. For example, in order to identify in the core any evidence for a sea levels change, a sequence of events must be recognised such that a sea level rise must be preceded by indicators of lower sea level in a logical manner without any evidence of a gap/hiatus in the stratigraphic record, otherwise information may be missing due to erosional processes. In practice, a horizon that implies estuarine or lacustrine conditions – to be interpreted as the lowest possible sea level at one site – must be intercalated between two horizons indicative of marginal marine conditions. If, on the other hand, sea level dropped below that site, erosion or non-aquatic conditions must be recognised in the core by the absence of remains of aquatic organisms, and by the presence of only terrigenous material in addition to pedogenic features, such as root casts, mottling features in the sediment and possibly calcareous nodules. The same environmental reconstructions (of sea-level transgression/regres-

sion) could be confirmed through the use of geochemical analyses of sediments and associated microfossils (see De Deckker 1988, 2002).

Of significance to the palaeoecological study undertaken here is Table 2 in the publication of Yassini et al. (1993) which lists a number of ostracods species from the Gulf of Carpentaria region, and in particular, which identifies several taxa found in Accident Inlet located in the southeastern corner of the Gulf near Karumba (see Fig. 1). A total of seven localities were sampled for ostracods by Yassini et al. (1993), which ranged from being at mid-tide and low-tide level, to 2 m below high tide level, 1 m below low tide level, to eventually some ~25 km inland just below low tide level. Those 7 localities provide a unique opportunity to interpret the fossil data from core GC 5 from Bonaparte Gulf as many of the same taxa are shared between those areas. Two other localities in the Gulf near Karumba were sampled at mid-tide level. Unfortunately, no salinities were recorded in Yassini et al.'s (1993) study. The ostracod taxa of palaeoecological significance here are discussed below:

Neocytheretta adunca was found at sites ranging from 1 m below low tide and 2 m below high tide level [note that the
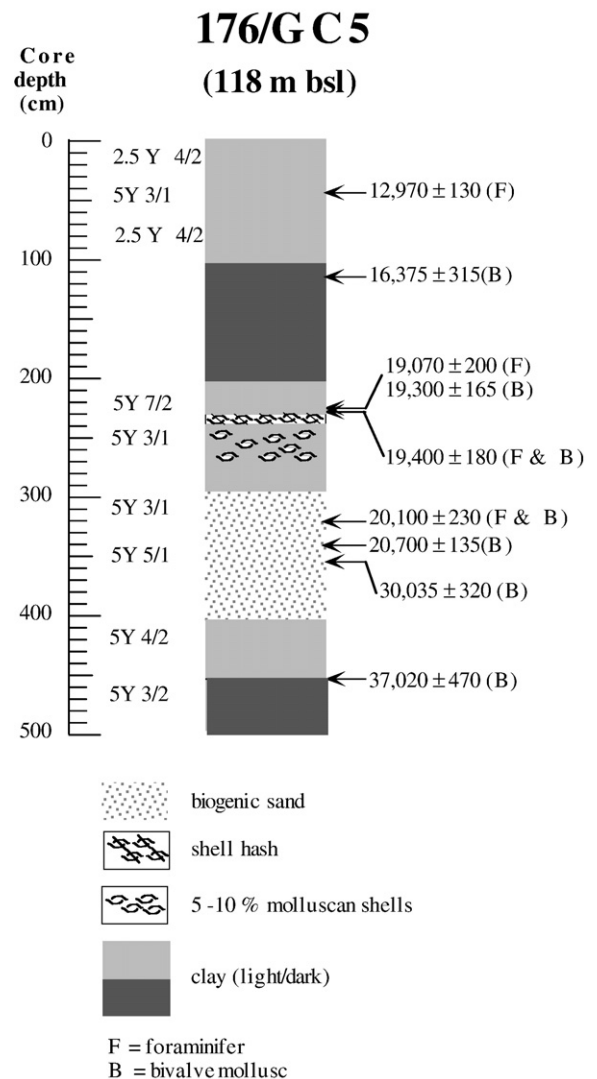

Fig. 2. Stratigraphic log of core Rig Seismic 176/ GC5 from Bonaparte Gulf listing also all the AMS radiocarbon dates done on biogenic remains and converted to calendar years.

GC5 118m

Facies		Ages (bold = dated)																																									

Top age labels (bold dated where indicated): **37,020±470**, **30,035±320**, **20,700±235**, 20,400, **20,100±230**, 20,025, 19,950, 19,875, 19,800, 19,724, 19,649, 19,574, 19,499, 19,461, 19,423, 19,415, **19,400±180**, **19,070±200**, 18,819, 18,567, 18,315, 18,063, 17,811, 17,559, 17,307, 17,055, 16,803, 16,551, **16,375±315**

Facies	Taxon	492	453	400	390	380	370	360	353	350	340	330	320	310	300	290	280	270	260	250	240	235	230	229	227	220	210	200	190	180	170	160	150	140	130	120	113	100	90	80	70	60	50	45
	Facies	oM	M	M	M	M	M	M	M	mM	mM	mM	mM	Estuarine / mM				Estuarine / brackish							mM	mM	M	M	M	M	M	M	M	M	M	M	M	M	oM	oM	oM	oM	oM
oM	Planktonic Forams	+																																				+	+					+
oM	Pteropods																																					+	+	+	+	+	+	+
M	Aligocythere																							+																				
M	Argilloecila						+						+													+			+		+		juv		+		+							
M	Paranesidea	+	+				+	+	+		+		broken															+																+
M	Calistocythere												+																									+		+		+		
M	Cytherella						+	+	+		+		+					+		+	+				+	+	+	+	+							+		+		+	+	+	+	+
M	Loxoconcha									+	+	+							+												+		+	+						+				
M	Macrocypris			+																								+												+				
M	Phlyctenophora																	+		+					+																			
M	Pterygocythereis	+	+				+																			+																		
M	Uroleberis	+																								+																+	+	+
M	Marine forams		+	+	+	+							+																											+	+	+	+	+
M	Bryozoan remains					+		+	+					rare		+	+											+				+		+						+	+		+	+
M	Echinoid spines					+		+	+	+	+	+				+	+					+		+		+		+	+	+	+	+		+	+				+	+				+
M	Holothurian spicules									+	+																							+										+
mM	Neocytheretta	+					+		+	+	+	+	+	+	+	++	+	+	+	carap	carap	+	+	+	+	++	+	+	LA	LA	+	LA	+	+		+	+							
mM	Neomonoceratina																				+																							
mM	Tanella													+	+	+	+	+	+	+	+	+				+	+	+	+	+	+		+	+	+	+								
mM	Xestobeberis						+	+		+		+									+							+																
mM	Scaphopods						+	+		+	+	+		+			+		+	+	+	++	+					+				+	+	++	+				+	+				
mM	Bivalve molluscs									+	+	+	++		+	++	+	+++	+++	+++	+++	+++	+++	+++	+	+		+	+			+	+++	++	+				+	+				
mM	Gastropods														+	+	+	+	+	+	+	+	+			+			+					+										
Br	Ammonia									+	+	+	few	few	+	+	few	++	+	+	++	+	+	+	++	++	+	+	+	+	+	+	++	++	+++		++	++	+	+	+	+	+	
Br	Elphidium										+	+	+	+	+									+	+	+	+	+	+	+	+													
Br	Leptocythere																								+	+	+	+																
	Fish fragments													+	+	+																												
	Quartz		++	++	++	++					++	+						+																										

Legend:
- oM: open marine
- M: marine
- mM: marginal marine
- Br: brackish

IN SITU TAXA: + few; ++ many; +++ abundant
RELICT TAXA: + few; ++ many; +++ abundant
carap = carapace; LA = life

Fig. 3. Diagram to show the distribution of the key taxa and other environmental parameters which have been used to reconstruct the sea-level history recorded in GC5. All ages presented here are in calib. years BP [see Table 1]. Only ages printed in bold relate to dates obtained from calcareous fossils for those specific levels; other ages were calculated using a constant sedimentation rate between the nearest two dated levels.

tidal range at Karumba is <1 m for neap tides and up to 4 m during spring tides (Munro *in* Yassini et al., 1993)]. Several specimens were found at various depths in the Gulf, but these could have been reworked. This is particularly obvious as, in Yassini et al.'s (1993) investigation, specimens of the non-marine *Cyprideis australiensis,* found at the ~25 km site inland, were also recorded in the Gulf at several stations at 42, 64 and 67 m water depths. Obviously these latter three occurrences are relict ones.

Two subspecies of *Tanella gracilis* were found in the Inlet at and 1 m below low tide level.

Phlychtenophora zealandica in very common in all the Accident Inlet stations, except the one below low tide level some ~25 km inland.

Neomonoceratina bataviana is found in all stations, except the one furthest inland.

The surprise absence of *Xestoleberis* species from Yassini et al. (1993)'s study cannot be explained, but unpublished observations by De Deckker in estuaries along the east coast of Australia has found extensive numbers of this smooth-shelled ostracod in among beds of the sea grass *Zostera*. It may be that Yassini et al. (1993) failed to sample such sites especially in Accident Inlet. Nevertheless, the unpublished study of Labutis (1977) of some 19 dredge samples from Curtis Estuary in Gladstone Harbour in Queensland (see Fig. 1) recognised numerous species of *Neocytheretta, Neomonoceratina, Tanella* and *Xestoleberis*, further confirming that they are marginal-marine ostracods. Hartmann (1978), who surveyed the coastline of Western Australia from Derby to Perth, recognised several species of *Xestoleberis* from hypersaline conditions (S=36.2) and remarked on the affinity of this genus with aquatic plants, but unfortunately he did not sample estuaries. Nevertheless, for the study here, we consider *Xestoleberis* to be indicative of marginal-marine conditions. Hartmann (1978) also noted that *Tanella gracilis* can live in hypersaline conditions (S=38.4, 42.2) as well as *Neomonoceratina koenigswaldi* (S=37.5, 38.4).

Of relevance to the study here are also the works of Wang (1992) and Wang and Chappell (2001) on the foraminiferal distributions in the South Alligator River near Darwin (see Fig. 1) which is characteristically macrotidal. There, the maximum tidal range is ~6 m and the tidal influence is felt up to 105 km inland due to the very

low gradient (<1 in 60,000) (Wang and Chappell, 2001). The South Alligator River also undergoes flooding by fresh water during the monsoonal wet season spanning December to April each year (Wang and Chappell, 2001). Those authors identified a number of foraminifers such as *A. beccarii* at the far inland sites, with up to 30% of the total foraminiferal population consisting of dead and living specimens of this taxon in salinities below 20 g l^{-1}. Wang (1992) further found *A. beccarii* in the channel of the McArthur and Jackson Rivers (see Fig. 1) where this taxon is represented by over 70% of the total fauna in salinities <10 g l^{-1}. Wang (1992) further noted that living and dead *Ammonia* specimens are equally represented in these diurnal rivers with a tidal range of 3 m. Of importance also, at those sites, was for Wang and Chappell (2001) to recognise the presence of small tests of other foraminifers which would have reached the inland sites by floating and transport by the tides. Wang and Chappell (2001) list *A. beccarii, Schackoinella globosa,* and *Reussella spinulosa* as taxa that can easily be transported; the first species is listed by these authors as being an estuarine organism, whereas they list the other two species as shallow marine. Wang and Chappell (2001) also noted the presence of typical open-marine taxa such as globigerinids at a site some 47 km upstream from the South Alligator River mouth. These globular planktonic foraminifers possess obvious sac-like chambers that would help in the floatation process if filled with an air bubble or gas resulting from decaying organic matter. Consequently, the presence of exotic, allochthonous planktonic foraminifers, when mixed with estuarine foraminifer and ostracod taxa, would indicate a mixed assemblage. It is only when planktonic foraminifers are found in association with the fragile, uncoiled conical shells of pelagic cavoliniid pteropods (which could not float due to their morphology and absence of chambers/partitions) that open-marine conditions can be considered. Coiled pteropods such as limacinids, on the other hand, could possibly float, but would easily be destroyed if under high energy environment due to their fragility.

4. The Bonaparte Gulf: core RS176/GC 5

Crucial to the understanding of the history of sea level changes in the Gulf is core GC5 obtained at the request of Y. Yokoyama during Rig Seismic cruise 176 conducted by the Australian Geological Survey Organisation [now called Geoscience Australia]. Critical information in this core are the sedimentary and micropalaeontological records it
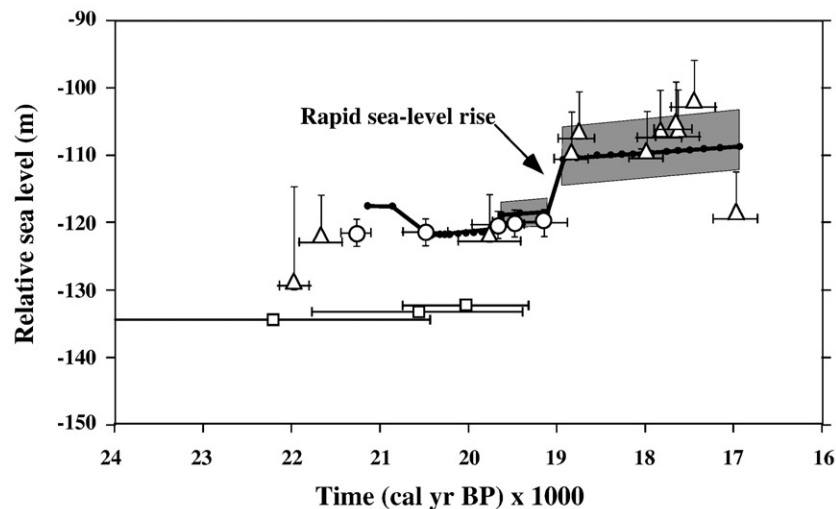

Fig. 4. Diagram to show the relative sea-level data obtained from Bonaparte Gulf for the Last Glacial Maximum and the beginning of the deglaciation. Open circles and triangles represent the data obtained by Yokoyama et al. (2000, 2001a) from Bonaparte Gulf using microfossil assemblages. Squares represent the data reported from the same region by van Andel et al. (1967) The black dots represent the new data presented in Fig. 3 and are linked together to show the change of sea level between 21,000 and 17,000 cal years BP. Note that the LGM ended at ~19,000 cal years ago as a result of a rapid melting of ice sheets, although there is also rise in sea level after ~19,700 cal years BP, but it is only after 19,000 cal years BP that a rise in sea-level reached a magnitude of 10–15 m. The estimated range of errors is indicated by the shaded areas along the curve.

yields, but its depth also enables us to identify definite sea-level fluctuations through time.

Core GC5 is located at a water depth of 118 m and is 495 cm long. Overall, the core consists of beige-grey to dark grey clay with evidence of calcareous biogenic remains in places (see Fig. 2). The interval between 453 and 303 cm appears more sandy, but this is due to the large amount of biogenic, calcareous remains. There is also a transition in the upper part of the core as evidenced by a paler colour above 65 cm. Below 403 cm, the sediment colour is grey, but becomes darker grey below 453 cm. The core also contains an obvious amalgamate of mostly bivalve molluscs [called "shell hash" here] for the interval 234–228 cm, and similar shells are prevalent for the 278–234 cm interval; it is estimated that shells account for ~10% of the sediment in this horizon. Many of the shells show partial sign of reworking and transport. For interval 203–103 cm, biogenic remains appear rare to the naked eye. The clay component of the core is considered to originate from rivers peripheral to Bonaparte Gulf, with much of it having been deposited in areas marginal to the sea [either estuary or even open marine]. For a complete list of biotic remains encountered in the core, refer to Fig. 3.

There is an apparent hiatus in this core between interval 353 and 340 cm as shown by the 2 radiocarbon dates which would otherwise imply a sedimentation rate of about 9000 years over 13 cm. Additional dates are required to pinpoint the exact location and extent of the hiatus.

We have examined additional samples from core GC5 in addition to those analysed by Yokoyama et al. (2000, 2001a), and believe we now have a more complete palaeoenvironmental reconstruction for this core site. Of importance is the interval consisting of a high concentration of molluscan remains between 278 and 234 cm which is considered to have been deposited under extremely shallow-water conditions. The presence of marginal marine-ostracod taxa (*Neocytheretta*, *Tanella*) in association with the brackish water ostracod *Leptocythere hartmanni* and the foraminifer *A. beccarii* throughout this horizon is indicative of an estuary with brackish-water conditions. Note that *L. hartmanni* is not found in other parts of the core. This interval also contains a number of reworked marine ostracod taxa. The presence of the shell hash above this horizon further confirms the shallowness of the site at that time. It is very likely that this thick layer was deposited under a very short period of time, compared to other intervals in the core. It is of no surprise therefore to identify at level 230 cm several specimens of *Neocytheretta* with complete carapaces (with the 2 valves still attached), further implying rapid sedimentation that would have prevented the valves from becoming separated as normally occurs under slow sedimentation (De Deckker (2002).

Above the sand interval rich in bivalve molluscs, conditions changed to estuarine after 20,700±235 cal. yr BP as more marine ostracods and abundant specimens of *Neocytheretta* and *Tanella* are found, plus a few *A. beccarii* and *Elphidum* specimens. After deposition of the shell layer, marginal marine to marine conditions appeared as shown by the presence of *Cytherella* together with *Neocytheretta* at 19,070±200 cal yr BP [the 2 dates for this horizon overlap within the range of errors – see Table 1 – but the date obtained from foraminifera is used here as being possibly more reliable considering that it would have been possible to eliminate reworked foraminifers, had there been any. The appearance of several marine taxa indicate that fully marine conditions appear by the time of the interpolated date of 18,800 cal yr BP. This would imply a substantial sea level rise, possibly of the order of ~10 m, in line with the arguments presented in Yokoyama et al. (2000, 2003). It is not possible to be more definite with our bathymetric interpolation as we believe that maintenance of shallower depth conditions during the deposition of this interval (227–120 cm) would have resulted in the reworking or damage of ostracods, which is not the case here. For example, we find in several horizons (170, 160, 140 cm) life assemblages of *Neomonoceratina* as well as well-preserved marine taxa. Any shallow environment would have reworked and sorted those

complete *Neomonoceratina* specimens. Consequently, these data best constrain a water depth determination of ~10 m, although the water depth could have even been greater.

We emphasize the euryhaline nature of the foraminifer *A. beccarii*, which is found in all the sampled intervals between 350 cm and 45 cm. This almost spherical foraminifer is made of a number of chambers which help strengthen the test of the organism, and an apparently poorly-perforated hyaline test that would prevent rapid destruction. In addition, this taxon tends to proliferate in vast number through a broad range of salinities (De Deckker and Geddes, 1980; Cann and De Deckker, 1981; De Deckker et al., 1988), to such an extent that the floor of saline lakes or estuaries may consist of a large amount of *A. beccarii* specimens, giving the appearance of the sediment to be a coarse sand. It is not surprising, therefore, that during a sea-level transgression, relict specimens of *A. beccarii* from pre-existing estuarine sediments would be redeposited in marine sediments. In addition, we need to refer to the *allochthonous* nature of *A. beccarii* specimens that could have been transported by tidal current activity as floats (Wang and Chappell, 2001). The same phenomenon would not occur during a sea-level regressive phase, like seen in the lower portion of core GC5 where, below 350 cm, no *A. beccarii* have been found.

5. Discussion

The AMS radiocarbon chronology used for the reconstruction of past sea-level fluctuations recognised in core GC 5 relies on a combination of analyses done on foraminifera and bivalve mollusc material. Although some of the bivalve material may have undergone some transportation/reworking, as recognised by the fact that many specimens are broken, the identical ages, within 1σ uncertainties, obtained for samples from 227 cm, just above the shell hash for foraminifers and bivalves separately, and for a combination of material from the shell hash at 229 cm (see dates in Fig. 2 and Table 1), further indicates that if reworking of material had occurred, it would only have been local.

The shell hash is considered to have been deposited under marginal marine conditions and, prior to that, all the indicators point to estuarine brackish conditions, as exemplified by the presence of *Leptocythere* ostracods and for some horizons by the presence of *A. beccarii* considered to be *in situ* for all the examined horizons. The occurrence of some marine components in the shell hash (see Fig. 3) is consistent with the nature of deposition for this horizon, but we note that marine indicators were absent lower down in the core for the brackish/estuarine water phase, apart from a few relict marine taxa. We also find that marine conditions were well established for level 210 cm (with an extrapolated age of ~19,000 cal yr BP) and, therefore, we interpret this environmental change to relate to a rapid increase of water depth (see Fig. 4). We also found in core GC4, taken adjacent to GC 5 at a water depth of 121 m (see location in Yokoyama et al., 2000, 2001a), a large concentration of bivalve molluscs for the interval 195–176 cm with an extrapolated age range of ~20,700 to 19,300 cal yr BP, which is interpreted as marginal marine conditions. We continue to maintain that the rapid sea level rise was of the order of about 10 m, although we acknowledge that a more precise measure cannot be determined, especially since the tidal range for that period may have changed through time as the topography and morphology of the entire area would have changed dramatically as a result of sea-level change in the Bonaparte Gulf region (see the shaded area in Fig. 4).

Obvious open-marine conditions became established by the time of deposition of sediments as evidenced with the presence of fragile pteropod shells in the core GC 5 at 80 cm and above, but additional AMS radiocarbon chronology will be required to date this event.

The original Barbados coral sea-level records younger than ca. 19,000 years ago were reconstructed using the depth of *Acropora*

palmata which is an excellent sea-level indicator since it lives in less than 5 m water depth in the present Caribbean Sea (Fairbanks, 1989). Recently, Peltier and Fairbanks (2006) published extended sea-level records into the Last Glacial Maximum using corals but most of the listed samples consisted of *Montastrea annularis*. This coral cannot derive accurate palaeo-sea level information because its living depth can range down to 30–40 m. Yet, these authors reconstructed a relative sea-level curve for this region. The curve was compared with the Bonaparte sea-level data and these authors (Peltier and Fairbanks, 2006) claimed that the northern Australian sea-level data are significantly lower than their reconstruction (see Fig. 6 in Peltier and Fairbanks, 2006). In our original publications, we observed relative local sea-level low stand at about −125+/−5 m in Bonaparte region and this was isostatically corrected to the LGM sea-level to about −135 m (Yokoyama et al., 2000, 2001a,b). Therefore, the figure in Peltier and Fairbanks (2006) proved misleading since it plotted the Barbados relative sea-level data with the isostatically-corrected Bonaparte sea-level data in the same figure! As we discussed previously, the importance of isostatic corrections when sea-level data need to be plotted in a same figure (e.g., Lambeck et al., 2002), otherwise the figure will be meaningless since the record contains two separate effects: ice volume changes and geographically not a uniform response of solid earth. In fact, both the Barbados and Bonaparte data are consistent if they are isostatically adjusted. It is important to note that Fig. 6 in Peltier and Fairbanks (2006) is a good example to exhibit this importance.

The sudden sea level rise registered in core GC5 is synchronous with 2 significant 'hikes' in the oxygen-isotope record obtained from planktonic foraminifera from 2 well-dated, high-resolution deep-sea cores in the Australasian region. Core SO136-GC11, located west of the South Island of New Zealand (43° 26.40′S, 167° 51.04′E, water depth 1556 m, see Barrows et al., 2007), shows a shift of 0.51‰ between 18,972 and 18,837 cal. y. BP, whereas for 900 years prior to the shift values had varied little, and the same applies for the 700 years following the shift. The other core MD032611, located further west, South of Australia near Kangaroo Island (36° 43.79′S, 136° 32.90′E, 2420 m water depth; see Gingele and De Deckker, 2005; Calvo et al., 2007, plus unpubl. AMS radiocarbon dates), also displays a shift in oxygen isotopes of 0.56 per mil over a 500 year period between 18,840 and 18,300 cal. y. BP, despite only a slight increase of sea-surface temperature (0.6 °C) recorded from alkenones (Calvo et al., 2007). Obviously, these records demonstrate a sudden and significant shift of the global sea level curve seen through the isotopic composition of sea water. These isotopic data, within the uncertainty of errors fit well with the rapid sea level rise recognised in the Bonaparte Gulf core GC5.

6. Conclusion

Through a combination of taphonomic observations and generic identifications, our micropalaeontological investigations support our earlier arguments that *relative* sea level at the LGM prior to ~19,000 cal years BP had dropped by ~120 m below today's level. In contrast with the Gulf of Carpentaria, which during the LGM was filled by an athalassic (*sensu* Bayly, 1967) lake – called Lake Carpentaria by Torgersen et al. (1988) [for recent findings refer to Reeves et al., 2007], the topography of the deeper basin occupied by Bonaparte Gulf was never entirely closed from the ocean as the deepest part of this Gulf remained estuarine or marginally marine. It is likely that the high tidal range, as seen today in the region, contributed during the estuarine phase at the LGM to the transport of several marine taxa into an estuarine environment. It is only at ~19,000 cal yr BP that a true marine transgression occurred after a rapid sea level rise, estimated here to be of the order of 10 m. Such a rise is also registered in the oxygen isotopic record of planktonic foraminifers from 2 deep sea cores in the vicinity of the Australian continent.

We believe that there is no hiatus in the core over the interval covering the low sea level and subsequent rise as ages are well constrained and sedimentation rate was high.

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