The sedimentary record of Quaternary glacial to interglacial sea-level change on a subtropical carbonate ramp: Southwest Shelf of Australia

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ABSTRACT

In the last decades, the understanding of temperate carbonate systems has improved considerably, but their development over glacial–interglacial time-scales is still understudied in comparison to their tropical counterparts. A key question is how do temperate carbonate platforms respond to high-amplitude, glacial–interglacial sea-level changes? Integrated Ocean Drilling Program Site U1460 was drilled at the uppermost slope of the Southwest Shelf of Australia at the transition between the subtropical Carnarvon Ramp and the warm–temperate Rottnest Shelf. The origin and composition of the sediments in the upper 25 m below seafloor at Site U1460 were investigated using X-ray diffraction, scanning electron, and light microscopy. The Middle Pleistocene to Holocene sequence at Integrated Ocean Drilling Program Site U1460 contains a record of sea-level controlled sedimentary cycles. Carbonate sediments deposited during interglacial sea-level highstands (Marine Isotope Stages 1, 5, most of 7, 9 and 11) are mainly fine-grained (<63 µm) and dominated by low-Mg calcite from pelagic bioclasts such as planktic foraminifera. The glacial lowstand intervals (Marine Isotope Stages 2 to 4, 6, 8, 7d, 10 and 12), instead are coarser-grained and relatively rich in aragonite and high-Mg calcite from neritic bioclasts, such as bryozoans. These changes in texture, mineralogy and composition are best explained by the deposition of neritic bioclasts closer to the shelf edge during glacial sea-level lowstands. During early transgression, reworking of bioclast-rich coastal dune deposits likely leads to transport and redeposition of neritic clasts on the upper slope. In contrast, dominantly pelagic sediments characterize deposition at the platform edge during interglacial highstands. These results highlight regional differences in the response of temperate carbonate systems to sea-level change: A previously published model developed for early Pleistocene temperate carbonates from the Great Australian Bight indicates that shelfal material was exported to the upper slope during sea-level highstands. It is argued that this difference is related to the change in duration and amplitude of glacial–interglacial sea-level cycles before and after the Mid-Pleistocene transition.

Keywords Aragonite, International Ocean Discovery Program, IODP Expedition 356, Pleistocene, sedimentary cycles, temperate carbonates.
INTRODUCTION

Up to one third of all carbonate produced on continental shelves today comes from subtropical (James et al., 1999) and temperate environments (James, 1997). Such deposits provide important modern analogues for many geologically ancient carbonate deposits (Nelson, 1988; James, 1997; Pedley & Carannante, 2006; Ryan et al., 2008). Much of what is known about these carbonate systems has been learned from the study of modern seafloor sediments, with the southern and western Australian Shelves serving as key locations for warm–temperate carbonate settings (Collins et al., 1993; James et al., 1999; James & Bone, 2011). However, the accumulation rate on the southern Australian Shelf is low since most of the sediments are transported offshore by vigorous swells and storms (James et al., 1994). Over much of the inner shelf this results in patchy sediment cover of palimpsest carbonates of Late Pleistocene to Holocene age (James et al., 1994; Ryan et al., 2008). On the outer shelf and slope sediment accumulation has been nearly continuous during the Quaternary (Feary et al., 2000; Hine et al., 2004; Deik et al., 2019). These deposits provide an important archive for the response of the carbonate system to the high amplitude, glacial to interglacial, sea-level fluctuations of the Middle Pleistocene to Holocene age (Andres & McKenzie, 2002; Hine et al., 2002; Saxena & Betzler, 2003; Betzler et al., 2005; Deik et al., 2019).

Despite the progress in understanding of subtropical and temperate carbonate systems, they remain considerably less well studied compared to their tropical counterparts. For example, the widely used ‘highstand shedding’ concept predicts that carbonate production on flat-topped, tropical platforms and distally steepened ramps peaks during interglacial sea-level highstand when the inner platform is flooded (Schlager et al., 1994). Because accommodation space is limited in the inner platform, the produced aragonite mud is transported into deeper water where it mixes with calcite from pelagic sources. This concept is underpinned by data from several tropical carbonate platforms showing higher aragonite and high-Mg calcite (HMC) content in slope sediments during interglacial times (Paul et al., 2012; Eberli, 2013). The response of subtropical and temperate continental shelf systems to glacial–interglacial sea-level change is much less well understood. Two different models have been developed based on evidence from the Great Australian Bight (GAB). One model proposes that the wide warm–temperate carbonate platform of the GAB responds to sea-level change in a similar manner to tropical systems. In this model, the amount of material exported from the shallow shelf to the slope increases with the shelf area flooded during sea-level rise and highstand (Betzler et al., 2005). The alternative model emphasizes increased export of shallow shelf sediments to the slope during sea-level lowstands, when the shelves are narrower and the high-energy zones closer to the shelf edge (James et al., 1997; James & Bone, 2011). It is essential to study other temperate carbonate platforms outside the GAB, to test which of the two models can be applied more widely.

To investigate sedimentary processes in subtropical to temperate sediments deposited during high-amplitude, glacial–interglacial sea-level fluctuations, data from the western Australian Shelf is presented. The upper 25 m below seafloor (CSF-A) of core at Integrated Ocean Drilling Program (IODP) Site U1460, drilled on the upper slope during IODP Expedition 356 (Gallagher et al., 2017), contains a nearly complete record of carbonate sedimentation from the Middle Pleistocene to the Holocene. The mineralogy, texture and composition of the sediment was analysed using X-ray diffraction, a scanning electron microscope equipped with an energy-dispersive X-ray spectrometer, light microscopy (Olympus BH-2; Olympus Corporation, Tokyo, Japan) and grain-size analysis. The results were compared with existing age models to characterize sea-level highstand and lowstand deposits and develop a conceptual model for their formation.

GEOLOGICAL SETTING

The environment of the western continental margin of Australia in the eastern Indian Ocean is transitional between warm–temperate and tropical carbonate settings. It comprises the warm–temperate Rottnest Shelf in the south (south of 28°S) and the subtropical Carnarvon Ramp in the north (22 to 28°S). Reef growth at this relatively high latitude is facilitated by the Leeuwin Current flowing southward along the west coast of Australia; it is a current of low salinity, warm surface water, sourced from the Indonesian Throughflow (ITF) (Cresswell et al., 1989). During glacia...
believed to be considerably weakened (Spooner et al., 2011; Petrick et al., 2019). The Houtman Abrolhos Reef complex, which contains the southernmost major tropical reef in the Indian Ocean (28 to 29.5°S), straddles the boundary between the Carnarvon Ramp and the Rottnest Shelf (Fig. 1). For both areas James et al. (1999) described the shelf morphology and facies distribution on the modern seafloor. The modern shelf sediments are characterized by a distinct cool-water composition (Nelson, 1988), but with subtropical attributes (James et al., 1997). The skeletal assemblage is dominated by coralline algae, bryozoans, molluscs (scaphopods, bivalves and gastropods) and foraminifera (James et al., 1999). The main difference from typical cool-water deposits is the presence of scattered zooxanthellate corals and large, symbiont-bearing foraminifera (James et al., 1999; Collins et al., 2014). Skeletons of serpulid worms, echinoids, azooxanthellate corals and sponge spicules are of local importance. The calcareous green algae Halimeda grows locally on the shelf and ramp but is poorly calcified and therefore generally does not contribute to the sediment outside Shark Bay. The seafloor above ca 50 to 60 m is subject to constant reworking and abrasion by waves, while the swell wave base is close to 100 m, leading to a lack of mud deposition above this depth (James et al., 1999).

The Carnarvon Ramp comprises the Ningaloo Reef and hypersaline Shark Bay on the inner ramp (Fig. 1A and B). The mid-ramp is euphotic, with relatively little calcareous benthos and low numbers of bryozoans, coralline algae and larger foraminifera, but is dominated by relict or stranded foraminiferal-dominated sand. The outer ramp is pelagic in character, covered by planktic foraminiferal sand or spiculitic mud. The outflow of highly saline waters from Shark Bay leads to periodic downwelling of relatively warm and saline waters across the ramp (James et al., 1999; Collins et al., 2014). Between 27°N and 28°N the Carnarvon Ramp transitions into the Rottnest Shelf (Fig. 1A and B). The Rottnest Shelf is flat-topped, with a wave-swept, 30 to 70 m deep inner-shelf plain characterized by rhodolith pavements, bryozoans, sponges and abraded sediments (Fig. 1C). An incipient rim formed by a linear ridge system covered by rhodolite gravel separates the inner shelf from the subphotic outer shelf that is dominated by bryozoans, benthic foraminifera and molluscs (Fig. 1). This ridge system likely represents a stranded coastal dune system that formed when sea-level was considerably lower than today during Marine Isotope Stages (MIS) 3/4 (Brooke et al., 2010, 2014). The upper slope contains fine sand and silt of bryozoan fragments, sponge spicules and planktic foraminifera (James et al., 1999). Essentially, this facies extends south to ca 34°S on the shelf offshore Cape Leeuwin (Collins, 1988). The eastward decreasing influence of the Leeuwin Current is reflected in the impoverished fauna of warm-water, benthic foraminifera east of Cape Leeuwin. However, the benthic foraminifera Amphisoris (Marginopora) occur commonly together with non-calcified green algae and scattered zooxanthellate corals along the inner Albany Shelf (Li et al., 1999). Subtropical faunal elements are missing further to the east in the Great Australian Bight but were present, for example, during the early Pleistocene (Gelasian) and interglacial MIS 5e (James & Bone, 2007, 2011).

The IODP Site U1460 was drilled during IODP Expedition 356 on the Southwest Shelf of Australia (27°22.4867’S and 112°55.4265’E; Fig. 1). The site is situated on the uppermost slope in a water depth of ca 214 m (Fig. 1C). It is situated north of the Houtman Abrolhos reef complex, at the transition between the Carnarvon Ramp in the north and the Rottnest Shelf towards the south (Fig. 1A and B). This transition zone shows a mixture of morphological and facies characteristics of both regions. Cores were recovered from two boreholes (A and B) at IODP Site U1460 (Fig. 2) and drilled with the long hydraulic piston core (HLAPC) system. The sediment recovery in both holes was generally excellent (97 to 98%), with minor gaps between cores resulting from the HLAPC system (Fig. 2). The shipboard correlation between holes is based on gamma-ray data. The correlation was not detailed enough to produce a continuous composite depth scale, but generally cores in both holes are at similar depth (Fig. 2; Gallagher et al., 2017). Coring of gravel-rich grainstone to floatstone layers produced minor gaps and intervals with reduced core integrity leading to reduced confidence in the correlations between holes (Fig. 2; Gallagher et al., 2017).

The sediments recovered at IODP Site U1460 consists of two lithostratigraphic units (I and II), with Unit I subdivided into three subunits (Ia, Ib and Ic) (Gallagher et al., 2017). The studied interval (0 to 25 m CSF-A) is entirely from subunit Ia (Fig. 2A to I; 0 to 44.94 m CSF-A).

Subunit Ia is characterized by beige to greenish-grey skeletal packstones (Gallagher et al.,...
Based on visual estimates, the skeletal assemblage is dominated by planktic foraminifera, fragments of bivalves and gastropods (including pteropods), bryozoans, echinoids, and some azooxanthellate corals, intraclasts and peloids (Fig. 3A to I; Deik et al., 2019). The packstones are interbedded with skeletal wackestones, mudstones and macrofossil-rich grainstones to floatstones (Fig. 2). The silt to sand size fraction in the grainstones to floatstones consists predominantly of bryozoan fragments, the rest is comprised of variable proportions of foraminifera, molluscs, serpulids, echinoids, and minor amounts of azooxanthellate corals, ascidians spicules and scaphopods. The gravel fraction has a similar composition but also contains many skeletal intraclasts. Faecal pellets (Fig. 3) and quartz grains are generally absent in all of these coarse-grained intercalations (Deik et al., 2019).

According to the interpretation of Deik et al. (2019) the composition of mud to packstones in Subunit Ia (Fig. 2) is very similar to the planktic sand and silt facies (P2; James et al., 1999) on
the present seafloor (Fig. 1). In contrast, the coarser-grained intercalations of grainstones to floatstones (Fig. 2) are similar in composition to the bryozoan skeletal sand facies (Hole B; James et al., 1999) on the modern-day seafloor (Fig. 1).

**AGE MODEL**

Based on the shipboard biostratigraphy (Gallagher et al., 2017) the cores U1460B-1F to 7F (0 to 25 m CSF-A) represent the last ca 450 kyr (Fig. 2). The inner shelf in the study area is up to 70 m deep (Fig. 1). For the studied time interval, global sea-level fell below this level during MIS stages 2 to 4, 6, 8, 10 and 12 and substage MIS 7d. These stages will be referred to as times of glacial sea-level lowstand in this study. During MIS 1, 5, 9, 11 and most of MIS 7 the shelf plain was most likely partially to completely flooded. Those MIS will be referred to as times of interglacial sea-level highstands. Further offshore western Australia, the aforementioned glacial stages were characterized by a weakening of the Leeuwin Current and several degrees colder seafloor temperatures compared to times of interglacial sea-level highstands (Spooner et al., 2011).

Two previously published age models are available for IODP Site U1460, which are based on temperature-dependent proxy records (Figs 2 and 3). Petrick et al. (2019) used the biomarker TEX$_{86}$ record tuned to the benthic isotope stack LR04 (Lisiecki & Raymo, 2005) to construct an
The absolute temperatures of this reconstruction have a two-sigma standard deviation of $\pm 5$ to $6^\circ$C, but relative changes in temperature are well constrained and reflect Leeuwin current dynamics (Petrick et al., 2019). Alternatively, Courtillat (2019) used a $\delta^{18}$O record of the planktic foraminifer Globigerinoides ruber in combination with $^{14}$C ages and G. menardii complex abundance data to construct an age model mainly based on samples from Hole A (Fig. 2). Generally, both age models show a good match over the studied interval (Fig. 2). A discrepancy between the age models exists for the time interval MIS 6 to 7, although the shape of the two temperature records is actually quite similar in this depth interval (Fig. 2). The generally warm MIS 7 contains the substage 7d (Fig. 2) that experienced very cold temperatures at a global scale that are unusual within an interglacial (Pahnke et al., 2003). This substage also stands out in climate proxy records from western Australia as a cold and arid time interval (Spooner et al., 2011; Stuut et al., 2014). The presence of this cold substage likely explains the difficulty in assigning an absolute age to this interval. However, the aim of the study presented here was to discriminate times of sea-level lowstands from highstands in the core, rather than to assign absolute ages. With few exceptions, glacial (interglacial) conditions are therefore interpreted for the intervals that were unanimously identified as cold (warm) intervals in both age models (Fig. 2). The MIS 1/2 boundary is defined following Courtillat (2019), who

Fig. 3. Lithostratigraphic summary for Integrated Ocean Drilling Program (IODP) Hole U1460A (A) and IODP Hole U1460B (B) (Gallagher et al., 2017). (C) Grain-size fraction $>63 \mu$m of sediments from holes A and B (Courtillat, 2019). (D) Siliciclastic (black) versus carbonate (grey) content. (E) Carbonate mineralogy (aragonite, red; high-Mg calcite, yellow; dolomite, blue; low-Mg calcite, green). (F) Integrated stratigraphy based on a comparison between the two alternative age models shown in Fig. 2. (G) Abundance of bryozoans in one gram of sediment. (H) Abundance of planktic foraminifera in one gram of sediment. (I) Relative abundance of faecal pellets in the fine to medium sand-sized (125 to 500 $\mu$m) sediment fraction (Deik et al., 2019).
constrained its position using 14C ages. The MIS 10/11 boundary is placed at the base of a grainstone/floatstone layer in both age models. The small depth offset of these two coarse-grained layers between holes likely results from small core gaps in Hole U1460B. The present study places the boundary of MIS 11/12 at 23.17 m CSF-A according to the age model of Courtillat (2019), since a core gap in Hole B prevented sampling of this interval for biomarker analysis (Petrick et al., 2019). Overall, the combination of the two proxy records enables attribution of most intervals to glacial or interglacial conditions with high confidence. The linear sedimentation rate for the entire interval is 5.8 cm kyr⁻¹.

**METHODS**

X-ray diffraction (XRD) analysis of 56 bulk samples from IODP Hole U1460B was used to quantify mineralogy. Six of these analyses were reported in Deik et al. (2019). In addition to the bulk samples, the mineralogy of the <34 µm and 34 to 63 µm fraction of those six samples was analysed. All XRD samples were oven-dried, ground and mounted on sample holders. The measurements were conducted using a Siemens D5000 X-ray diffractometer over an angle field of 4° to 64° with a step size of 0.02° per second [Bruker (Siemens), Billerica, MA, USA]. Identification and quantification of different mineral phases was achieved with the software DIFFRAC EVA (ver. 8.0) by Bruker. The relative abundance of mineral phases was determined using the I/I corundum values from the International Centre for Diffraction Data database. If quartz was present, it was used as an internal standard, and the measured quartz major peak d-spacing was adjusted to align with the known quartz major peak d-spacing. All other mineral phases were adjusted accordingly. Where dolomite or high-Mg calcite (HMC, >4 mol% MgCO₃) was present in a sample, their MgCO₃ content was calculated based on the d-value of the [104] peak (Lumsdzen, 1979).

A total of 84 samples from IODP Holes U1460A and U1460B were wet sieved through a 63 µm sieve, and the retained sand fraction (>63 µm) for each sample was weighed and reported as % sand fraction (Fig. 2). The >63 µm fraction was dry sieved through a 150 µm mesh. The abundance of planktic foraminifera and bryozoans was counted in the >150 µm fraction under a binocular microscope to quantify the contribution from pelagic versus neritic sources. Scanning electron microscopy (SEM; Zeiss Supra 55; Carl Zeiss AG, Oberkochen, Germany) was used to further analyse the bulk sediment. The mineralogy of grains was confirmed by elemental analysis (Sr, S, Fe and Mg) with an energy-dispersive X-ray spectrometer (EDX Xmax 150; Oxford Instruments, Abingdon, UK). All samples were carbon coated prior to analysis. Six thin sections were prepared for petrographic analysis (Olympus BH-2) of the bulk sediment.

**RESULTS**

**Mineralogy and grain size**

The upper 25 m CSF-A at the IODP Site U1460 is generally dominated by sand-sized grains. Gravel is concentrated in certain grain to floatstone intervals, for example, around 17 m CSF-A (Fig. 2). The coarse size fraction (>63 µm) on average contributes about two-thirds to the sediment, while less than 5% of all samples are dominated by the fine fraction (Fig. 2).

The abundance of planktic foraminifera shows high amplitude fluctuations, with the highest values in intervals that are dominated by low-Mg calcite (LMC) and smaller grain sizes (Figs 3A to I and 4A to F). The highest peaks in bryozoan abundance occur in coarser-grained, aragonite-rich and high-Mg calcite-rich intervals (Fig. 3) with lower planktic foraminiferal concentrations. Intervals that are rich in bryozoans are also characterized by other neritic skeletal components such as bivalves, gastropods, worm tubes (Fig. 4A and B) and echinoderms. Benthic foraminifera (Fig. 4D) and azooxanthellate corals indiscriminately occur in intervals with high and low LMC contents. Peloids typically occur in LMC-rich, fine-grained intervals (Figs 3 and 4C). Ascidian spicules (Fig. 4E), sponge spicules and coccolith plates are important components in the fine fraction (<63 µm).

The carbonate content in the selected interval varies between 57% and 100%. The average carbonate content of the sediment is ca 91%, with 43% low-Mg calcite, 23% aragonite, 21% high-Mg calcite (HMC) and 4% dolomite (Fig. 2). The siliciclastic minerals plagioclase feldspar and quartz in total contribute ca 9% to the sediment (Fig. 2). Quartz is present in almost all samples and its content varies between 0% and 11%, with an average of 4%. Based on six analysed
samples, quartz content is higher in the 34 to 63 μm compared to the bulk and the <34 μm size fraction, with an average of about 9%, 5% and 3%, respectively (Table 1). Feldspar abundance shows an average value of 5% but exhibits a maximum of about 34% concentrated at a depth of around 19 m CSF-A (Fig. 2). Feldspar grain size typically ranges from silt to fine sand. Celestite (SrSO₄) was detected in only four samples and its content ranges between 3% and 11%.

The average aragonite content of the carbonate fraction is 25% but decreases from 37% at the top to 17% at the base of the analysed section (to ca 25 m CSF-A; Fig. 2). In the six analysed samples, aragonite content is higher in the 34 to 63 μm compared to the bulk and the fraction <34 μm fraction, with an average of about 34%, 25% and 23%, respectively (Table 1). However, one of the highest aragonite peaks occurs in the gravel-rich floatstone layer at around 17 m (Figs 2 and 4B), where the silt fraction is a very...
Aragonite therefore seems to be concentrated on one hand in the coarse silt and on the other hand in the coarse sand to gravel fraction. The main aragonite producers in the sand fraction (>63 µm) are gastropods, bivalves, cheilostome bryozoans and some azooxanthellate corals (Fig. 4). Ascidian spicules contribute aragonite to the 34 to 63 µm fraction (Fig. 4E).

The HMC content in the carbonate fraction varies between 0% and 44%, with a mean of 23%. The HMC content shows stronger fluctuations compared to aragonite and a general decrease with depth. HMC is 17% slightly less abundant in the finest grain size fraction (<34 µm) compared to the 34 to 63 µm (21%) and bulk (19%) fraction (Table 1). The MgCO₃ in HMC varies between 8% and 16 mol%, with a mean of 12%. Most of the HMC is in a range that is sometimes referred to as intermediate-Mg calcite (IMC; 4 to 12 mol%; O’Connell & James, 2015). Less than one-third of all HMC samples actually have Mg values higher than 12%, and half of those occur in a depth shallower than ca 5 m CSF-A. HMC is mainly produced by echinoderms, benthic foraminifera such as miliolids and some serpulid worms (Fig. 4). Additionally, HMC occurs occasionally as cement.

Dolomite occurs below a depth of about 5 m CSF-A and its abundance is negatively correlated with aragonite content and HMC (Figs 2 and 3). The highest dolomite concentration is observed in the very fine fraction (<34 µm), with a mean of 5% compared to a mean of 4% and 3% in the 34 to 63 µm and bulk fraction, respectively (Table 1). The concentration of dolomite in the finest fraction is consistent with SEM observations; the euhedral rhombic dolomite crystals range in size from 5 to 20 µm (Fig. 4F), and occur in inter-particle and intra-particle pores similar to those described by Rivers et al. (2012). Unambiguous replacement of other carbonate phases by dolomite has not been observed, although sporadically dolomite crystals seem to engulf calcite grains (Fig. 4F). Therefore, they are interpreted to have formed as a cement phase. Detrital dolomites, characterized by signs of abrasion or weathering (Bone et al., 1992; James et al., 1994; Radwan et al., 2018) are absent.

The dolomite is Ca-rich with calculated MgCO₃ contents ranging between 41 to 46 mol% (mean of 43 mol%) based on XRD, but no clear

| Depth CSF-A (m) | 356-U1460B | Grain size | Aragonite (%) | LMC (%) | HMC (%) | Dolomite (%) | Quartz (%) |
|----------------|-------------|------------|---------------|--------|---------|--------------|-----------|
| 1.15           | 1F-1W-115/119 | <34 µm     | 30            | 37     | 33      | 0            | 5         |
| 1F-1W-115/119  | 34–63 µm     | 35          | 26            | 39     | 0       | 6            |           |
| 1F-1W-115/119  | Bulk         | 31          | 29            | 40     | 0       | 3            |           |
| 4.77           | 2F-2W-67/71  | <34 µm     | 26            | 46     | 28      | 0            | 3         |
| 2F-2W-67/71    | 34–36 µm     | 41          | 28            | 30     | 0       | 12           |           |
| 2F-2W-67/71    | Bulk         | 30          | 43            | 27     | 0       | 7            |           |
| 9.80           | 3F-2W-100/104 | <34 µm     | 20            | 66     | 11      | 3            | 5         |
| 3F-2W-100/104  | 34–63 µm     | 31          | 51            | 15     | 3       | 8            |           |
| 3F-2W-100/104  | Bulk         | 22          | 64            | 10     | 4       | 8            |           |
| 13.18          | 4F-2W-62/66  | <34 µm     | 22            | 56     | 14      | 8            | 2         |
| 4F-2W-62/66    | 34–63 µm     | 38          | 35            | 22     | 5       | 9            |           |
| 4F-2W-62/66    | Bulk         | 28          | 44            | 23     | 4       | 4            |           |
| 18.99          | 5F-2W-79/83  | <34 µm     | 19            | 65     | 7       | 8            | 2         |
| 5F-2W-79/83    | 34–63 µm     | 39          | 54            | 11     | 5       | 8            |           |
| 5F-2W-79/83    | Bulk         | 18          | 73            | 0      | 9       | 5            |           |
| 21.24          | 6F-2W-54/58  | <34 µm     | 21            | 64     | 5       | 11           | 2         |
| 6F-2W-54/58    | 34–63 µm     | 31          | 54            | 9      | 7       | 9            |           |
| 6F-2W-54/58    | Bulk         | 18          | 63            | 11     | 8       | 3            |           |
| Mean           | <34 µm       | 23          | 56            | 17     | 5       | 3            |           |
|                | 34–63 µm     | 34          | 41            | 21     | 3       | 9            |           |
|                | Bulk         | 25          | 53            | 19     | 4       | 5            |           |
DISCUSSION

Glacial–interglacial cycles

There is a strong control of glacial to interglacial sea-level on the sediment record (Figs 2, 3 and 5). During glacial sea-level lowstands (including MIS 2 to 4, 6, 8, 10, 12 and possibly 7d) the sediment is characterized by relatively high HMC and aragonite contents (Fig. 2). The sediment is coarser-grained and neritic components such as bryozoan fragments are more abundant (Figs 3 and 4). The intervals are poor in siliciclastics with quartz as the only significant non-carbonate phase. In contrast, intervals deposited during interglacial sea-level highstands (MIS 1, 5, most of 7, 9 and 11) contain more LMC, are finer-grained and show higher concentrations of pelagic material, such as planktic foraminifera (Figs 3 and 4). Dolomite is also enriched in interglacial highstand deposits. Detrital dolomite crystals showing variable degrees of rounding are a minor but recurring component on parts of the Eucla and Lacepede shelves (Bone et al., 1992; James et al., 1994). They are mainly derived from the erosion of Cenozoic sediments (James & Bone, 2011). These detrital dolomites are often overgrown by a late dolomite cement that formed directly beneath the modern seafloor (Bone et al., 1992). Dolomite crystals at IODP Site U1460 are always euhedral (Fig. 4F) and show no signs of abrasion. They probably formed preferentially in highstand sediments during early burial, likely favoured by the oxidation of organic matter as described by Swart & Melim (2000).

The siliciclastic content in interglacial intervals is higher and plagioclase feldspar is more abundant than quartz (Figs 2 and 3). Siliciclastic detrital grains on the modern-day Carnarvon Ramp are deposited in the coastal zone close to, for example, the Murchison River mouth, where locally, they can contribute up to 40% of the sediment (James et al., 1999). At IODP Site U1460, glacial intervals contain only quartz, while interglacial intervals have a higher siliciclastic content consisting of silt to fine sand sized quartz and feldspar. Glacial to interglacial climate variability is shown by surface water temperature changes with an amplitude of 3 to 5°C (Fig. 2; Petrick et al., 2019). It is also well-known that glacial intervals in western Australia were more arid (Rivers et al., 2009) and windy compared to the interglacials (Stuut et al., 2014; Hallenberger et al., 2019; Petrick et al., 2019). Wind-transported quartz was deposited offshore during the arid glacial (Stuut et al., 2014), while other siliciclastic phases including feldspar indicate a more fluvial origin during more humid interglacials (Groeneveld et al., 2017; Hallenberger et al., 2019; Petrick et al., 2019). The siliciclastic fraction at IODP Site U1460 therefore reflects the climatic variability of the late Middle Pleistocene to Holocene in Western Australia.

Could the increased wind strength also have contributed to the transport of relict carbonate grains to the shelf edge and slope during glacial sea-level lowstands? Detailed investigations by Nichol & Brooke (2011) and Brooke et al. (2014) have shown that relict skeletal grains were reworked into dunes on the exposed western Australian shelf during glacial sea-level lowstands. The ridge in the current study area that parallels the shelf break in a water depth of ca 60 m (Fig. 1) likely formed as such a coastal dune system during MIS 3/4 (Brooke et al., 2014). However, dune morphology and orientation of large-scale dune foresets further south on the Rottnest Shelf indicate that the dominant wind transport was directed onshore. It therefore seems likely that the aeolian transport of relict grains from the exposed shelf to the shelf edge during glacial sea-level lowstands was possible but likely limited due to the prevailing onshore winds.

The carbonate sediment on the modern, open to incipiently rimmed shelf is relatively coarse-grained bioclastic sand and gravel (Fig. 1; James et al., 1999). The mud fraction is constantly winnowed by high-energy wave and swell abrasion from the shelf and deposited onto the outer ramp and slope (Fig. 5; James et al., 1999), a mechanism very similar to the ‘shaved shelf’ proposed for the Great Australian Bight (GAB;
James et al., 1994). The skeletal assemblage on the shelf is dominated by coralline algae, bryozoans, molluscs (scaphopods, bivalves and gastropods) and foraminifera including large, symbiont-bearing foraminifera (Figs 1 and 5A to C; James et al., 1999). The upper slope contains fine sand and silt consisting of sponge spicules and mainly calcitic bryozoan fragments, planktic foraminifera and nannofossils (James et al., 1999; Collins et al., 2014). Aragonitic components, such as pteropods and ascidian spicules never contribute more than 10% to the modern seafloor sediments at the outer ramp and slope (Fig. 5; James et al., 1999). This difference in the depositional regime and skeletal assemblage between the shelf and slope results in coarser-grained, relative HMC-rich and aragonite-rich shelf sediments grading into fine-grained, more LMC-rich sediments on the slope (Fig. 5).

In the upper 25 m CSF-A at IODP Site U1460, relative HMC-rich and aragonite-rich, coarser-grained, neritic skeletal grain dominated glacial intervals alternate with finer-grained, LMC-rich, pelagic dominated, interglacial intervals (Figs 2 to 5). This pattern is interpreted as reflecting a higher proportion of shelf-derived components in glacial deposits, whereas interglacial deposits are dominated by LMC-rich pelagic sediments. This pattern is ubiquitous throughout the studied interval (Fig. 5A and B), highlighted by variations of abundance of analysed components such as bryozoans and planktic foraminifera (Fig. 3).

Similar patterns have been recognized in the GAB (Saxena & Betzler, 2003; Betzler et al., 2005): however the interpreted relationship to sea-level is reversed. Saxena & Betzler (2003) and Betzler et al. (2005) analysed mainly early Pleistocene (Calabrian) intervals of several ODP sites on the on the upper slope of the Eucla Shelf. One of the sites (1129) is located closest to the shelf edge in a water depth of ca 200 m, nearly identical to IODP Site U1460. Those authors postulated that interglacial sea-level highstand deposits on the slope are dominated by relatively coarse-grained, aragonite-rich and HMC-rich bioclasts including bryozoan debris. In contrast, lowstand deposits were micritic, low-Mg calcite-rich sediments. Saxena & Betzler (2003) and Betzler et al. (2005) concluded that HMC and aragonite-rich bioclasts were formed on the shallow, flooded shelf and exported to the slope during transgression and sea-level highstands. According to this model, the amount of material exported from the shelf to the slope increases with the shelf area flooded during sea-level rise and highstand, similar to the ‘highstand shedding’ concept developed for tropical platforms.

In contrast, other authors have emphasized the importance of redeposition events during glacial sea-level lowstand and early transgression, transporting coarser sediments from the relatively deep carbonate factory on the shelf to the slope, whereas highstands would be dominated by finer-grained, pelagic LMC sediments (Nelson et al., 1982; Boreen & James, 1993; James, 1997; Passlow, 1997; James & Bone, 2011). Similarly, Puga-Bernabéu & Betzler (2008) relate HMC-bioclast-rich intervals at the upper slope of the Pleistocene carbonate ramp of the GAB to the late sea-level fall and/or glacial sea-level lowstands. This increase in ramp sediment supply to the slope is interpreted to be a response to reworking by bottom currents. More pelagic LMC-rich intervals in contrast are related to interglacial sea-level highstands (Puga-Bernabéu & Betzler, 2008).

Results from the upper slope IODP Site U1460 from the Carnarvon Ramp (IODP Site U1460) indicate deposition of shelf derived, coarser-grained, HMC-rich and aragonite-rich bioclasts on the present-day upper slope during glacial sea-level lowstands (Figs 2 and 3). During sea-level lowstands, the zone of shelfal sediment production shifted towards the platform edge and therefore also closer to IODP Site U1460 (Fig. 5C). During sea-level minima, such as during MIS 2, the site would likely have been situated above the swell wave base, leading to winnowing of the finer fraction (Deik et al., 2019; Fig. 5C).

It is possible that initial flooding of the shelf during the post-glacial early sea-level rise led to a pulse of shelfal sediment production and export to the slope such as observed for the GAB (James & Bone, 2011). The flooding and partial erosion of bioclast-rich coastal dune systems during early sea-level rise likely led to enhanced export of carbonate grains from the shelf to the upper slope. Such now submerged dune systems likely form the ridge that parallels the shelf edge in the current study area (Brooke et al., 2014). However, production on the shelf and export to the slope seem to have diminished during interglacial sea-level highstands, leading to more pelagic sedimentation during the interglacials (Fig. 5A and B).

**Comparison to the Great Australian Bight**

The Eucla Shelf in the central GAB is a warm–temperate carbonate system (James & Bone,
Fig. 5. Conceptual model for the sedimentation during a single sea-level cycle. (A) Interglacial sea-level highstand. Facies zones at the slope to outer ramp/shelf and mud content after James et al. (1999). Faunal elements are from James et al. (1999) and core analysis from the present study. Mineralogy is derived from the dominant grain types. Skeletal sands are deposited exclusively in the shallowest part of the outer ramp above the storm wave base (James et al., 1999). Most of the slope and outer shelf is dominated by pelagic sedimentation. Sea surface temperatures (SST) are seasonal means from the World Ocean Atlas (Boyer et al., 2013). (B) Glacial sea-level minima, such as during Marine Isotope Stage (MIS) 2. Facies zones are shifted in depth with a sea-level fall of ca 120 m. Faunal elements and mineralogy are from the present study’s core analysis. Skeletal sands are deposited closer to the position of U1460 resulting in coarser sediments. Pelagic sedimentation is restricted to the slope. Sea surface temperatures (SST) are modern values minus the temperature change reconstructed by Petrick et al. (2019). Carbonate grains are produced but not deposited above base of wave abrasion, leading to redeposition to the platform edge and upper slope. (C) At Site U1460 a complete sea-level cycle leads to an alternation between LMC-rich pelagic dominated wackestones and HMC and aragonite-rich, packstones with abundance neritic detritus such as bryozoans and molluscs. HSD, highstand deposits; LSD, lowstand deposits; TSD, transgression deposits.

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CONCLUSIONS

The Middle Pleistocene to Holocene sequence (last ca 430 kyr) at Integrated Ocean Drilling Program (IODP) Site U1460, located at the platform edge to upper slope of the Carnarvon Ramp, contains a record of sea-level controlled sedimentary cycles. Siliciclastic phases are more abundant in the humid interglacials compared to the more arid glacials. Mineralogical differences are also apparent. Feldspar and quartz were deposited during the humid phases, while glacial intervals contain only quartz.

Carbonate sediments deposited during sea-level highstands are fine-grained and dominated by grains from a pelagic source with low-Mg calcite (LMC) mineralogy. The lowstand intervals, instead are coarser-grained, and dominated by grains from benthic organisms with aragonite and high-Mg calcite (HMC) as important mineral phases. During sea-level lowstands and early transgression, the high-energy zone was closer to the shelf during interglacial highstands, a situation similar to the initial flooding during the late glacial MIS 2. However, the off-shelf export before the MPT likely persisted during interglacials since the shelf was never as deeply submerged as during the peak flooding of the Middle and Late Pleistocene.

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Supporting Information

Additional information may be found in the online version of this article:

Table S1. Mineralogy of sediments at the IODP Site U1460.

Table S2. The MgCO_3 content in HMC and dolomite (mole%) for the studied interval at the IODP Site U1460.

Table S3. Grain size fraction >63 μm for the studied interval at the IODP Site U1460.

Table S4. Bryozoan count data for the studied interval at the IODP Site U1460.

Table S5. Planktic foraminiferal count at the IODP Site U1460.

Table S6. Faecal pellet count at the IODP Site U1460 (Deik et al., 2019).