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Research paper

Seismic and stratigraphic evidence for reef expansion and onset of aridity on the Northwest Shelf of Australia during the Pleistocene

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ABSTRACT

Modern reef (the Great Barrier Reef and Ryukyu Reef) distribution in the Indo-Pacific region is strongly controlled by warm currents (East Australian and Kuroshio Currents) that radiate from the Indo-Pacific Warm Pool. The modern distribution of reefs (south of 15°S) on the Western Australian shelf is related to the presence of the warm Leeuwin Current. However, the age of the reefs south of 15°S, and hence their temporal relationship to the Leeuwin Current, has been largely unknown. Seismic and subsurface stratigraphic data show that reef growth and expansion on the Northwest Shelf of Australia began in the Middle Pleistocene (~0.5 Ma). The oldest ooids in the region are approximately synchronous with reef growth. We suggest a two stage process for the spread of reefs to higher latitudes on the Western Australian coast; first an increase in Leeuwin Current activity at approximately 1 Ma brought warm waters and a tropical biota to the region; and second, increased aridity after ~0.6 Ma led to a decline in clastic input and increased alkalinity, triggering ooid formation and reef expansion to higher latitudes associated with the switch to higher amplitude glacio-eustatic cycles at the end of the Middle Pleistocene Transition. The timing and mechanisms for reef expansion south along the Western Australian coast has implications for the origin of the Eastern Australian Middle Pleistocene Great Barrier Reef, the New Caledonia Barrier Reef and Japanese Ryukyu Reef systems.

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1. Introduction

Knowledge of the timing and circumstances that triggered tropical reef development in the Indo-Pacific in the past is critical if we are to understand the resilience of modern reefs with future climate change (Frieler et al., 2012). The Great Barrier Reef and Ryukyu Reefs (Japan) initiated in the Middle Pleistocene (0.4–1 Ma) due increased global sea level amplitude and variability (Alexander et al., 2001; Braithwaite et al., 2004; Yamamoto et al., 2006; Sakai and Jige, 2006; Montaggioni et al., 2011) possibly associated with Indo-Pacific Warm Pool expansion (Sakai, 2003). Modern reefs are common in the Indian Ocean off the West coast of Australia (south of 15°S) where the warm Leeuwin Current (Fig. 1) extends their modern distribution to 29°S (Collins, 2002; Kendrick et al., 1991). The pre-200,000 history of these reefs is unknown (Collins, 2002). Here we use seismic and stratigraphic data to show that reef expansion on the Northwest Shelf of Australia began in the Middle Pleistocene (~0.5 Ma). The oldest ooids in the region are approximately synchronous with reef growth. We suggest a two stage process for the spread of reefs to higher latitudes in the region: (1) increased Leeuwin Current activity at approximately 1 Ma brought warm waters and a tropical biota to the area; followed by (2) increased aridity after ~0.6 Ma leading to a decline in clastic input and increased alkalinity, triggering ooid formation and reef expansion to higher latitudes coinciding with the onset of high amplitude Pleistocene glacio-eustatic cycles. The timing and mechanisms for reef growth off the Western Australian coast has implications for the origin of the Eastern Australian Middle Pleistocene Great Barrier, New Caledonia Barrier Reef and Ryukyu Reef systems.

2. Methods

We have identified a series of previously unidentified fossil reefs within the carbonate dominated Neogene Delambre Formation (Wallace et al., 2003) in seismic data from the Northwest Shelf of Australia (19°S to 21°S, Figs 2 to 4). Reefs in the Delambre Formation can be identified by the presence of: bathymetric highs and irregularities on the sea floor; lenticular masses containing no reflectors; and strong velocity 'pull-up' structures beneath lenticular masses (cf. Ryan et al., 2009; Rosleff-Soerensen et al., 2012). To constrain the age and environmental setting of these

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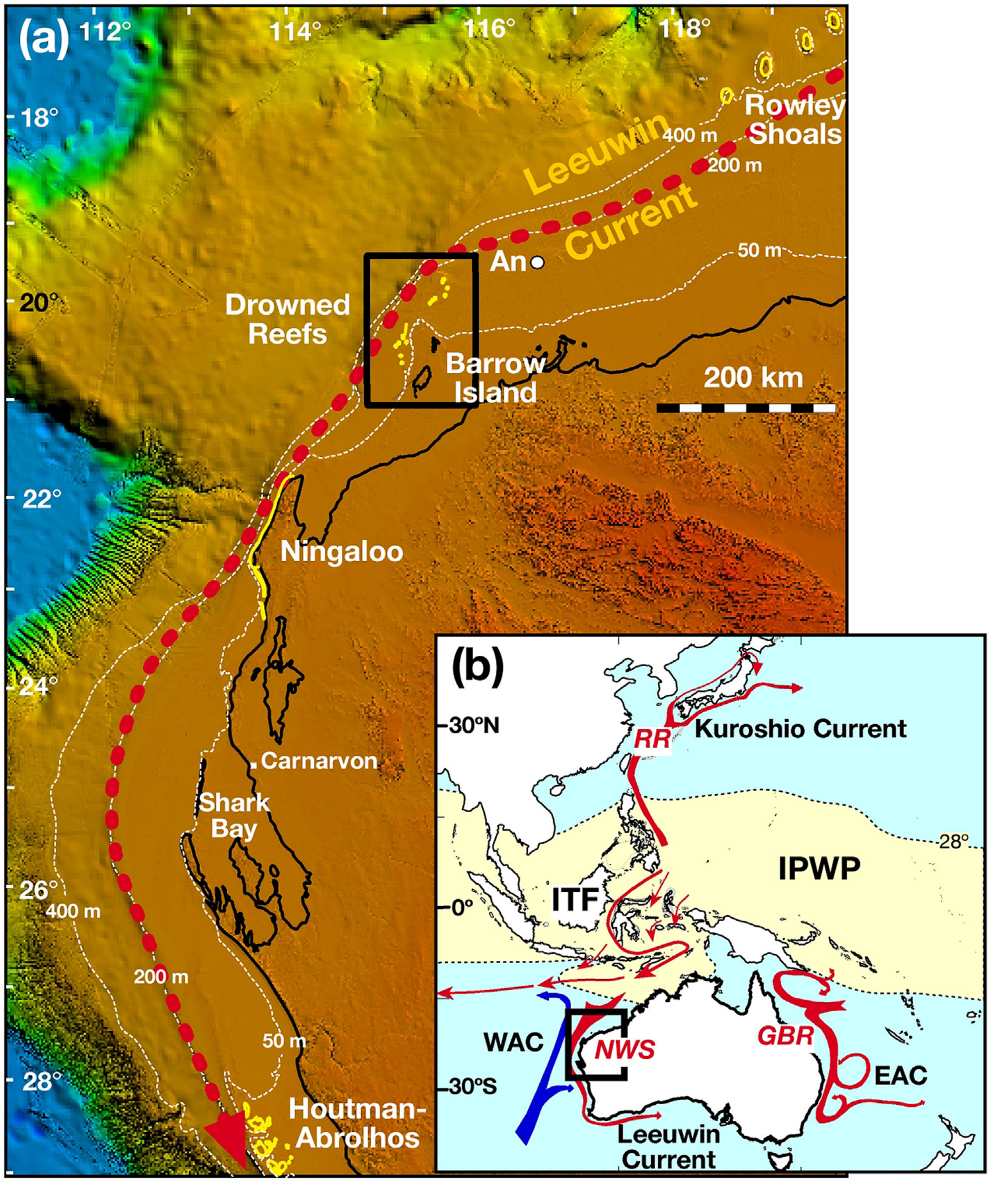

Figure 1. The location of the Northwest Shelf of Australia and it relationship to Indo-Pacific palaeoceanography (a) The bathymetry of the Northwest Shelf (NWS) from the Geoscience Australia: *Australian bathymetry and topography grid, June 2009* (http://www.ga.gov.au/meta/ANZCW0703013116.html#citeinfo). The path of the Leeuwin Current is shown along with the position of the nearest Recent reefs (the Houtman-Abrolhos, Ningaloo Reefs and Rowley Shoals) and the Drowned Reefs described in this paper (Box = Fig. 2). The position of the Angel field (An) is indicated. (b) Inset map of the oceanography of the Indo-Pacific Warm Pool (IPWP). WAC = West Australian Current, ITF = Indonesian Throughflow, RR = Ryukyu Reefs and GBR = Great Barrier Reef. The 28 °C isotherm is shown, the red currents are warm and the blue cold (Gallagher et al., 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reefs in the Delambre Formation we have used a combination of: biostratigraphic data from cuttings and sidewall cores (Gallagher et al., 2009), seismic stratigraphic, core and wireline log data. We analysed two continuously cored engineering bores (BHC4 and BHC1) near the Angel Field (Fig. 1) in water depths of around 80 m (Fig. 5). Facies, %$CaCO_3$ and wireline gamma log data are comparable to the LR2004 oxygen isotope record (Lisiecki and Raymo, 2005). For example the lower carbonate marly facies (with relatively high gamma response) were deposited during interglacial highstands and the high carbonate grainstone (with ooids, Fig. 6) were deposited as sea level fell to glacial conditions. Furthermore, the wireline log data for Maitland North-1 and Austin-1 (Figs. 5 and 7) also show a similar variability. Given this correlation, we have calibrated the wireline log data for Maitland North-1 and Austin-1 using biostratigraphic data (Gallagher et al., 2009) to constrain the age and climate context of the Pleistocene strata of the Delambre Formation (Figs. 5 and 7). Additional wireline log data and biostratigraphic data (Table 1) from other wells (Fig. 8) in the region are used to extend this record to the base of the Pliocene.

3. Results

A series of drowned reefs (occurring at water depths of *ca.* 60 m) are present near Barrow Island and extend *ca.* 100 km to the northeast of the island (Figs. 1 and 2). There are no modern reefs near Barrow Island, the nearest being the Ningaloo Reef (23°S, 200 km to the southwest, Fig. 1) and Rowley Shoals (17°S, 300 km to the Northeast, Fig. 1). Reefs are present in the upper 100 m below sea bed (<0.16 ms) in seismic sections and lie at or above the

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