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Invited research article

The evolution of the Great Barrier Reef during the Last Interglacial Period

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ABSTRACT

Reef response to Last Interglacial (LIG) sea level and palaeoenvironmental change has been well documented at a limited number of far-field sites remote from former ice sheets. However, the age and development of LIG reefs in the Great Barrier Reef (GBR) remain poorly understood due to their location beneath modern living reefs. Here we report thirty-nine new mass spectrometry U-Th ages from seven LIG platform reefs across the northern, central and southern GBR. Two distinct geochemical populations of corals were observed, displaying activity ratios consistent with either closed or open system evolution. Our closed-system ages (~129–126 ka) provide the first reliable LIG ages for the entire GBR. Combined with our open-system model ages, we are able to constrain the interval of significant LIG reef growth in the southern GBR to between ~129–121 ka. Using age-elevation data in conjunction with newly defined coralgal assemblages and sedimentary facies analysis we have defined three distinct phases of LIG reef development in response to major sea level and oceanographic changes. These phases include: Phase 1 (>129 ka), a shallow-water coralgal colonisation phase following initial flooding of the older, likely Marine Isotope Stage 7 (MIS7) antecedent platform; Phase 2 (~129 ka), a near drowning event in response to rapid sea level rise and greater nutrient-rich upwelling and; Phase 3 (~128–121 ka), establishment of significant reef framework through catch-up reef growth, initially characterised by deeper, more turbid coralgal assemblages (Phase 3a) that transition to shallow-water assemblages following sea level stabilisation (Phase 3b). Coralgal assemblage analysis indicates that the palaeoenvironments during initial reef growth phases (1 and 2) of the LIG were significantly different than the initial reef growth phases in the Holocene. However, the similar composition of ultimate shallow-water coralgal assemblages and slow reef accretion rates following stabilisation of sea level (phase 3b) suggest that reefs of both ages developed in a similar way during the main phase of relatively stable sea level.

1. Introduction

Numerous investigations on growth and development of fossil reefs have helped constrain sea level and palaeoclimate conditions during the peak Last Interglacial (LIG) highstand (~130–116 thousand years ago (ka)) (e.g. Crame, 1981; Pandolfi, 1996; Stirling et al., 1998; Lambeck and Chappell, 2001; Multer et al., 2002; Masson-Delmotte et al., 2013; Dutton et al., 2015b). Such studies are important as the LIG represents a future warm climate analogue, where sea level were thought to be 6–9 m above Present Mean Sea Level (PMSL) (Dutton et al., 2015a) and global mean temperatures were up to 1 °C warmer than present (Otto-Bliesner et al., 2013). Many studied LIG reefs occur as tectonically uplifted reef terraces or outcrops, several meters above PMSL, enabling easy access. In contrast, the origin and history of LIG reefs in the Great Barrier Reef (GBR) remain poorly understood, as the majority of these deposits occur as much as 40 m below the modern living reef surface. Rare exceptions include a few fringing reef outcrops located farther south of the GBR (Pickett et al., 1989; Kleypas, 1996) with poorly constrained open-system ages (119 to 155 ka). Additionally, few high quality cores of pre-Holocene substrate have been recovered in the GBR (Richards and Hill, 1942; Davies and Hopley, 1983; Marshall and Davies, 1984; Davies, 1974). Of those cores, few observations of specific coralgal assemblages and facies composition were made (Marshall and Davies, 1984; Webster and Davies, 2003; Braga and Aguirre, 2004; Braithwaite et al., 2004), resulting in limited interpretations of past sea level and palaeoclimate. Poor age control resulting from sparse open-system ages obtained using alpha-counting techniques produced ages ranging from 107 to 172 ka (Marshall and Davies, 1984; Pickett

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et al., 1989). Hence, whilst these studies broadly support LIG ages for these reefs, the precise timing and dynamics of reef growth have yet to be confirmed.

In the GBR, the most comprehensive coralgal assemblage information for the purported LIG reefs comes from the Ribbon Reef 5 core, in the northern GBR (Webster and Davies, 2003; Braga and Aguirre, 2004). There, coralline algae and sedimentary facies record a deepening upwards sequence with a transition from a shallow assemblage to a deep assemblages at ~21 m below PMSL, (Webster and Davies, 2003; Braga and Aguirre, 2004; Braithwaite et al., 2004). However, due to a lack of comparable detailed coralgal assemblage and facies composition data in other cores across the GBR (Marshall and Davies, 1984), a regional pattern was not able to be evaluated. A single U-series date form this core is consistent with an LIG age (125.7 ± 0.6 ka), but elevated initial $^{234}U/^{238}U$ ratios indicate that the sample was significantly diagenetically altered (Braithwaite et al., 2004). Regardless, abundant *Halimeda*-rich, non-framework facies were identified in Pleistocene cores by these and other studies from the GBR (Hopley, 1982; Hopley et al., 2007). Tidal jetting (Wolanski et al., 1988) and shelf margin upwelling (Searle and Flood, 1988) were identified as possible nutrient sources for *Halimeda* on the continental shelf during the Holocene, supporting *Halimeda* bioherms behind many of the reef platforms. However, a plausible upwelling mechanism producing *Halimeda*-rich deposits on the elevated reef-bearing platforms themselves has yet to be suggested (Hopley et al., 2007).

A recent study documented a pulse of siliciclastic sediment to the upper slopes, adjacent to the northern and central GBR during the penultimate deglaciation (TII) (Harper et al., 2015), similar to one during the last termination (TI) (Dunbar and Dickens, 2003a, 2003b). Maximum neritic aragonite export (i.e., reef sediments) of between 20 and 80 g/cm^{-2} ky to the upper slope occurred not during the peak LIG highstand (MIS 5e), as might be expected, but rather during MIS-5d to 5a (Harper et al., 2015). Those authors attributed the decline in neritic carbonate shedding during MIS-5e (i.e. from ~20 g/cm^{-2} ky to 0 g/cm^{-2} ky) to drowning on the GBR platform during the LIG highstand. This controversial hypothesis directly contradicts available age and facies information from the LIG platform reefs of the GBR, which suggests — albeit based on poor age control — significant reef growth during the LIG highstand (Marshall and Davies, 1984; Webster and Davies, 2003; Braithwaite and Montaggioni, 2009).

Far-field sites indicate that the timing and duration of LIG sea level highstand was ~129–116 ka (Masson-Delmotte et al., 2013), with global mean temperatures as much as 1 °C warmer than present (Otto-Bliesner et al., 2013). Debate continues over whether SSTs were also significantly warmer during the LIG highstand (Lawrence and Herbert, 2005; Turney and Jones, 2010; McKay et al., 2011), but latitudinal range extensions of reefs from equatorial regions towards the poles support warmer SST's during at least part of this interval (Kiessling et al., 2012; Pandolfi and Kiessling, 2014). Fringing reef outcrops, thought to be LIG in age occur in eastern Australia occur as far south as Newcastle (32°55′42 S) and Grahamstown (32°46′27 S) in New South Wales (Pickett, 1981; Pickett et al., 1989). Those authors postulated that the East Australian Current (EAC) extended much farther south during this period. This interpretation is consistent with a more recent study by Cortese et al. (2013) who suggested that a stronger and more intense EAC, from ~132 to 120 ka resulted in SST's as much as 2 °C warmer along the east coast of Australia. Hence, the implications of reef drowning and potentially increased SST for LIG reefs have direct bearing on forecasting reef behavior over the next centuries, as current climate is projected to warm to a level associated with palaeoclimate conditions in the peak LIG (Dutton et al., 2015a).

Detailed information about long-term abundance and diversity of reef-builder species is also important, as changes in reef composition could represent a distinct change in palaeoenvironmental conditions (Woodroffe and Webster, 2014). Specifically, studies from Pleistocene reefs in Kenya (Crame, 1981), Belize (Gischler, 2007), Barbados (Mesolella, 1967; Mesolella et al., 1970) and New Guinea (Pandolfi, 1996) revealed striking similarities between Holocene and Pleistocene reef faunas. However, other studies (Greenstein et al., 1998) show distinct dissimilarities in specific coralgal assemblages, implying significant differences between Holocene and Pleistocene environmental conditions. Such studies highlight the need to better characterise pre-Holocene coralgal reef assemblages in the GBR, as they not only provide important information about past reef response to palaeoenvironmental change, but also provide a base line for identifying levels of natural or anthropogenically induced disturbance. With the exception of the Ribbon Reef 5 core, no other studies in the GBR have investigated specific coralgal reef genera over longer geological timescales, i.e. >10 ka.

To address these problems directly, we first investigated the depth distribution of modern reef biota at a representative site in southern GBR. We then used these data to calibrate our reconstructions of palaeoenvironment (e.g. palaeowater depth, energy) using fossil assemblages from cores in the GBR. We then investigated spatial and temporal variations in LIG reef growth across seven reefs, representing the northern, central and southern GBR. Our specific objectives were to: 1) test the hypothesis that LIG-age reefs directly underlie the Holocene reef deposits, and determine the timing and duration of significant reef growth during that interval, 2) define new fossil coralgal assemblages based on comparisons with modern reef biota surveyed for this study and in the wider Indo-Pacific, and discuss the implications of these assemblages for constraining ambient palaeoenvironmental conditions, 3) use the chronologic and stratigraphic data to develop a new conceptual model, constraining the developmental history of the GBR during the LIG, and 4) identify any coralgal community change between Holocene and LIG reefs, to determine to what extent reef communities were able to re-establish themselves over glacial-interglacial periods (i.e., ~100 ka).

2. Location and methods

2.1. Study sites, climate and oceanography

Ten previously collected cores across seven reefs were chosen for analysis, including Ribbon Reef 5 (RBR_5) from the northern GBR; Myrmidon (MYR_3) and Stanley (STN_1) reefs from the central GBR; and One Tree (OTI_1, OTI_5, OTI_6), Fitzroy (FIT_2, FIT_3), Fairfax (FFX_3) and Heron (HRN) reefs from the southern GBR (Fig. 1). These cores were chosen as they represent the best preserved Pleistocene reef sections available (Hopley et al., 2007).

Ribbon Reef 5 is located on the shelf edge adjacent to the Queensland trough in the northern GBR, 49 km east of Cooktown, forming part of the outer barrier reef. The width of the continental shelf is narrowest in this northern region of the GBR, measuring just 50 km across (Hopley, 1977). Stanley Reef is located on the mid-shelf of the central GBR, whilst Myrmidon is located on the central outer shelf, within the bounds of the Halifax Basin, approximately 123 km east of Townsville, near the Townsville trough (Feary et al., 1991). The shelf dramatically widens in this region to 90–125 km. The highest rainfall and number of cyclones (Puotinen et al., 1997) occur in the central GBR between 16°S and 22°S. One Tree, Fitzroy, Fairfax and Heron reefs make up four of the 22 reefs of the Capricorn-Bunker groups in the southern GBR, located 70 km east of Gladstone (Feary et al., 1991). These reefs occur on the mid- to outer shelf and are structurally delineated along the Bunker high, on a narrow shelf margin approximately 55 km across (Davies and Hopley, 1983). The EAC diverges from the South Equatorial Current (SEC) at approximately 15°S (northern GBR), but maximum velocity is not reached until 30°S, close to the Capricorn-Bunker groups, where it then detaches from the coast at approximately 31° to 32°S (Cortese et al., 2013). A distinct cold core eddy (the Capricorn eddy) occurs north of this latitude, adjacent to the Capricorn Channel (Weeks et al., 2010).