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Successive phases of Holocene reef flat development: Evidence from the mid- to outer Great Barrier Reef

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ABSTRACT

A re-examination of 46 recently published U/Th reef flat ages from Heron and One Tree reefs in the southern Great Barrier Reef (GBR) identified several distinct Holocene reef growth phases with a clear 2.3-kyr hiatus in lateral reef accretion from 3.9 ka to 1.5 ka. An analysis of all available published radiocarbon reef flat ages (165) from 27 other mid-outer platform reefs revealed a similar hiatus between 3.6 ka and 1.6 ka for the northern, south-central and southern GBR. However, no hiatus in reef flat growth was observed in reefs from the central GBR with ages ranging from 7.6 ka to 0.9 ka. Increased upwelling, turbidity and cyclone activity in response to increased sea-surface temperature (SST's), precipitation and El-Nino Southern Oscillation variability have been ruled out as possible mechanisms of reef turn-off for the mid-outer platform reefs. Rather, a fall (~0.5 m) in relative sea level at 4–3.5 ka is the most likely explanation for why reefs in the northern and southern regions turned off during this time. Greater hydro-isostatic adjustment of the central GBR and long term subsidence of the Halifax-Basin may have provided greater vertical accommodation for the mid-outer reefs of the central GBR, thus allowing these reefs to continue to accrete vertically despite a fall in sea level ~ 4–3.5 ka. Further evidence for greater subsidence in this region includes the lack of senile reefs and dominance of incipient and juvenile reefs in the central GBR. This suggests that these reefs approached sea level considerably later than the northern and southern reefs, consistent with their deeper antecedent substrates. Thus, these results not only provide important information about possible reef flat demise in response to natural environmental factors, but also provide insights into regional subsidence that affected relative sea level along the east Australian margin during the Holocene.

1. Introduction

Over the last few decades, the global decline of modern reefs has been linked to environmental and climatic changes in response to anthropogenic activities (Hoegh-Guldberg, 1999; Bruno and Selig, 2007). However, recent geological and ecological research on fossil reefs in the Great Barrier Reef (GBR) (Smithers et al., 2006; Perry and Smithers, 2010, 2011; Leonard et al., 2015; Ryan et al., 2016a, 2016b) and wider Indo-Pacific (Rooney et al., 2004; Engels et al., 2004; Hamanaka et al., 2012; Toth et al., 2015) identified intervals of significant reef "turn-off" in response to natural environmental forces earlier in their development during the mid- to late Holocene. It is therefore important to understand the longer term histories of coral reefs as they not only provide important information about significant palaeoenvironmental change, but also provide greater insight into the persistence (or not) of reef growth through time. Such insights allow us to better recognise when changes in reef conditions are in response to natural or anthropogenic factors (Pandolfi and Kiessling, 2014).

Successive reef growth phases of "turn-on" and "turn-off" were identified from numerous in-shore fringing reefs of the GBR within the past 7-kyr (Smithers et al., 2006; Perry and Smithers, 2010, 2011; Leonard et al., 2015; Ryan et al., 2016a, 2016b). Specifically, hiatuses in reef growth from 4.6 to 2.8 ka and from 5.5 to 2.3 ka were identified from these reefs and are attributed to falling sea level and or re-suspension of terrigenous material (Perry and Smithers, 2011; Leonard et al., 2015). Alternatively, Ryan et al. (2016b) suggested that intense cyclone activity during the mid-to late Holocene was capable of stripping the reef flat of an inshore reef, causing an age gap in core rather than a demonstrable lateral reef growth hiatus. Similar hiatuses in Holocene reef growth were identified in Japan from about 5.9 to 5.8 ka, 4.4 to 4.0 ka and from 3.3 to 3.2 ka. They were attributed to oscillating sea level and relatively cold sea-surface temperatures associated with a weakened Kuroshio Current (Hamanaka et al., 2012). In Hawaii (Rooney et al., 2004; Engels et al., 2004) and Panama (Toth et al., 2012, 2015), cessation of reef accretion at 5 ka and 4 ka, respectively, was linked to increased variability in ENSO events and/or increased upwelling.

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Reef growth models based on >100 reef cores from the mid-outer platform reefs of the GBR (Hopley et al., 2007) established two main phases of Holocene reef growth; a rapid phase of vertical accretion as reefs were forced to catch-up/keep-up with post glacial sea-level rise, and a subsequent lateral accretion phase once sea level stabilised (Davies et al., 1985). Regional variations in the evolutionary states (juvenile, mature and senile) of these reefs were also established, with younger reef flat ages and lack of senile reefs identified from the central GBR, particularly on the outer shelf (Hopley and Harvey, 1981; Hopley, 1982). Variation in relative sea level in response to hydro-isostatic adjustment and longer term crustal movement of the still active Halifax basin was identified as a possible factor influencing the timing of when these reefs first approached sea level (Hopley and Harvey, 1981; Lambeck and Nakada, 1990; Kleypas and Hopley, 1992; Hopley et al., 2007). However, controversy remains over the specific timing and magnitude of the mid-Holocene highstand and subsequent smooth or oscillating post highstand fall on the northeast coast of Australia (Lewis et al., 2013, 2015; Leonard et al., 2015). While it is generally accepted that relative sea level reached a maximum of 1–1.5 m above present mean sea level (pmsl) by ~7 ka (Lewis et al., 2013), interpretations of relative sea-level fall after the mid-Holocene highstand have varied and include: 1) a smoothly falling sea level to present (Chappell, 1983); 2) a highstand that remained until ~2 ka (Sloss et al., 2007) or 1.2 ka (Lewis et al., 2015) and then abruptly fell to present levels; and 3) an oscillating sea level, with meter scale fluctuations (Baker and Haworth, 2000; Lewis et al., 2008; Leonard et al., 2015). As reef growth is highly sensitive to variations in sea level (Woodroffe and Webster, 2014), a fall or possible oscillation in sea level should be reflected in the growth response of mid-outer platform reefs across the GBR. However, whether hiatuses in reef flat growth exist regionally from the northern to the southern mid-outer platform reefs has yet to be systematically investigated, with only a single study from One Tree Reef in the southern GBR suggesting a hiatus in reef growth at ~2 ka (Harris et al., 2015). Moreover, most of the previous reef growth models for the mid-outer platform reefs were based on either one, or a few, isolated cores distributed over a range of reef zones commonly biased towards windward margins (Davies and Hopley, 1983). As recently demonstrated by Webb et al. (2016) and Dechnik et al. (2016), only closely spaced (< 50 m) core transects can capture the full response of platform reefs to the Holocene stillstand, including the timing of when these reefs first approached mean sea level and the direction and rate of subsequent reef flat progradation. However, whether this progradational growth was continuous throughout the mid- to late Holocene or was interrupted by hiatuses in reef growth has yet to be explored.

To address these problems we re-analyzed chronostratigraphic data based on 46 U/Th ages from 34 closely spaced short cores from two mid-outer platform reefs in the Southern GBR (Dechnik et al., 2016), in conjunction with all other available previously published reef core data ($n = 165$ radiocarbon ages) from 27 other mid-outer platform reefs in the GBR. Our specific objectives were to: 1) undertake a detailed chronological analysis of closely spaced shallow core transects across the reef flats at Heron and One Tree reefs to establish the timing of when these reefs first approached sea level; 2) compare these results to those from 27 other mid-outer shelf reefs to identify any regional patterns in reef flat growth and development through the Holocene; and 3) identify, date and constrain any hiatuses in reef growth using age data and if possible attribute these responses to known sea level, climatic or environmental changes.

2. Location and methods

2.1. Study sites

In order to compare regional patterns in reef flat development we collated 165 previously published radiocarbon ages from 27 mid-outer shelf reefs (Fig. 1 and Supplementary Table 1) in combination with 46 recently published (Dechnik et al., 2016) U/Th ages from drilled short cores at Heron and One Tree reefs (Fig. 1). Previously published microatoll dates from One Tree Reef (Harris et al., 2015) were also included in our analysis to provide a spatial and temporal comparison between different data sets (i.e., short cores vs microatolls).

2.2. Regional setting, climate and oceanography

Variations in physical characteristics with latitude allow the GBR to be divided into four distinct regions (Great Barrier Reef Marine Park and Unesco, 1981; Wolanski, 1994; Hopley et al., 2007). 1) The northern GBR extends from 11° to 16° S and is dominated by ribbon reefs, characterised by steep elongate algal encrusted windward rims with no distinct leeward margins. Water depths are typically <36 m with the mid- to outer shelf reefs located approximately 40 km offshore. 2) The central GBR (16° S to 20° S) is characterised by scattered platform reefs separated by distances as great as 5–10 km. Water depths range from 36 to 55 m with the majority of mid-outer shelf reefs located 50–100 km offshore. 3) The south-central GBR, including the Pompey Complex, (20° S to 21° S) occur where the shelf is widest, with most mid-outer shelf reefs located 100–180 km offshore. The reefs on the mid-shelf are typically platform reefs, whereas the outer shelf is characterised by large deltaic reefs. The highest tidal currents of the entire GBR are located in this region, exceeding 4 m s^{-1}, and water depths reach 80 m. 4). The southern GBR extends from 21° S to 24° S and includes the Swains Reefs and the Capricorn-Bunker groups of reefs. Water depths reach 140 m in the Swains complex and 40–70 m in the Capricorn-Bunker groups with most reefs located 70–250 km offshore. The Swains reefs typically consist of a series of tightly packed lagoonal platform reefs, whereas reefs of the Capricorn-Bunker groups are characterised by isolated platform reefs, several of which have well developed shingle cays (Hopley et al., 2007).

The GBR has a tropical climate influenced by an equatorial low pressure zone during the summer months and subtropical high pressure zone during the winter months (Wolanski, 1994). The southeasterly trade winds dominate most of the year, with north-westerlies occurring from January to March (Kench and Brander, 2006). Rainfall patterns vary regionally, the highest rainfall occurring in the central GBR between 16° S and 18° S with a mean annual rainfall of 2049 mm (Australian Bureau of Meteorology, 2013). Rainfall averages generally decrease to the south but there are pockets of higher rainfall, such as around the Mackay region (Australian Bureau of Meteorology, 2013). Tropical cyclones are common throughout the region, with an average 2.8 cyclones per year coming most frequently from the northern to south-central GBR (12–20° S), with the most intense (category 4 and 5) cyclones occurring in the central and south-central regions (19–22° S) (Puotinen et al., 1997). Monthly mean Sea Surface Temperatures (SST) range from a summer maximum of 29 °C north of 14° S, to <22 °C during winter in the south (24° S) (Lough, 2007). Tides are typically semi-diurnal, becoming more diurnal towards the north near Torres Strait. The tidal range is typically 2.5–3 m along most of the coast except the northern section of the Swains reefs, between 21 and 23° S, where the maximum tidal ranges increase to 6–9 m (Wolanski, 1994).

2.3. Short core collection and logging

A total of 34 short cores, approximately 1 m in length, were collected with a hand held petrol driven motor attached to a 5 cm diameter diamond core bit (Dechnik et al., 2016). Cores were logged based on a combination of sample material, petrographic thin sections and digital images. Lithologic characteristics, coral identification and the presence of coralline algae and associated biota were identified and logged, the details of which can be found in Dechnik et al. (2016).