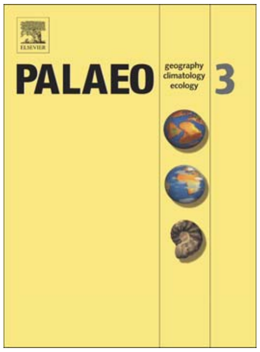

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Successive phases of Holocene reef flat development: Evidence from the mid- to outer Great Barrier Reef

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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, 2011, 2010, 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, 2011, 2010, 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.

Reef growth models based on more than 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-analysed 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).

>>Fig. 1<<

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 less than 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 36-55 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 2,049 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 less than 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 21-23° 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).

2.4 Core chronology and dating

Of the previously published dates, only ages within the top 3 m of cores were considered as this depth would have occurred when reefs were within the wave base depth range, representing the time at which reefs first approached modern sea level (Davies and Marshall, 1979, Davies and Hopley, 1983, Hopley et al., 2007). To provide a consistent comparison of reef flat surface elevation to sea level, core depths from all sites were re-plotted relative to Mean Sea Level (MSL). To the best of our knowledge we included only ages we consider to be in-situ based on available published literature (Supplemental Table 1). U-series dates from the shallowest 1.5 m of cores may be affected by a minor age anomaly (towards older), but age offsets most likely would have been less than 200 years (Webb et al., 2016).

All 46 coral dates from One Tree and Heron reefs, as well as details of the U/Th dating, were reported in Dechnik et al. (2016). Previously published radiocarbon ages were re-calibrated using calibration software (Calib7.0) (http://calib.qub.ac.uk/calib/; Accessed June 2014). Marine reservoir correction value ΔR 12 ± 5 was used in all calculations as this represents the best estimate of variance in marine reservoir effect for the mid-outer shelf reefs along the East Australian coast (Druffel and Griffin, 1999), at least for the last ~4.5 ka. However, for ages older than ~5.4 ka (49 ages in this study), there may be significantly larger *ΔR* (~410 yrs), potentially resulting in larger calibrated age errors (Hua et al., 2015).

3. Results

For the purposes of this study we define reef "turn-off" as the point where the reef flat, defined as including the reef crest, coralgal flat, rubble band and coral windrows, (Dechnik et al., 2016), ceases to accrete vertically and laterally, although significant amounts of coral and coralline algae may continue to grow on the outer reef slope and in deeper water in the back reef lagoon (Buddemeier and Hopley, 1988, Perry et al., 2011).

More than 80% of the recently dated in-situ reef flat corals at Heron and One Tree reefs approached MSL between 6.8 ± 0.02 ka and 3.9 ± 0.01 ka (Fig. 2) as the reefs exhibited catch-up behavior (Dechnik et al., 2015, Webb et al., 2016) corresponding to the approximate timing of the mid-Holocene warm interval (Gagan et al., 1998, Hopley, 1982). A 2.3-kyr hiatus followed, with no apparent significant reef flat growth occurring between 3.9-1.5 ka, indicating that the reefs "turned-off" during this interval (Fig. 2). Five recently published microatoll dates that range from 3.86 ± 0.18 ka to 2.23 ± 0.2 ka (Harris et al., 2015) were recovered from One Tree Reef at slightly higher elevations (~0.2 m) than the surrounding reef flat (Fig. 2). The upper growth limits of these microatolls are interpreted to represent palaeo-mean low water neap and their elevations to represent palaeo-mean low water spring. Hence, when combined with the short core reef flat data at One Tree Reef, no hiatus in reef flat growth is observed.

Fossil microatolls from the other mid-outer shelf reefs in the northern, south-central and southern GBR are yet to be discovered. Available reef flat core data (N = 79) across 27 reefs show a similar pattern to the Heron and One Tree reef core data, with a majority of reefs approaching MSL between 7.1 ± 0.2 ka and 3.6 ± 0.3 ka, with a distinct hiatus in reef growth between 3.6 ± 0.3 ka and 1.6 ka ± 0.2 (Fig. 3a). However, no such hiatus in reef growth is evident for reefs from the central GBR, with ages ranging continuously between 7.6 ± 0.3 ka and 0.9 ± 0.3 ka, suggesting uninterrupted growth through the Holocene. Furthermore, a clear pattern between age and distance from the coastline occurs across the mid- to outer shelf on the central GBR, with the oldest ages (~7.5-5 ka) clustering on the mid-shelf and the youngest ages (< 4 ka) clustering on the outer shelf within the bounds of the Halifax Basin (Fig. 4). It should also be noted that the previously established depths of the Pleistocene foundations (Hopley et al., 2007) for the fore-mentioned reefs of the outer central GBR are on average 5-10 m deeper than for reefs of the northern, south-central and southern GBR (Fig. 5).

>>Fig. 2<<

>>Fig. 3<<

>>Fig. 4<<

>>Fig. 5<<

4. Discussion:

4.1. Reef flats first approach mean sea level

With the exception of the microatoll data at One Tree Reef, the timing of reefs reaching mean sea level and accreting laterally (i.e., progradation) in the mid-outer platform reefs in the northern, south-central and southern GBR is broadly consistent at ~7.1-3.6 ka across the three regions (Fig. 3), confirming and better constraining the previously established reef growth models for mid-outer shelf reefs (Davies and Hopley, 1983, Hopley et al., 2007). Conditions from 8 ka to 6 ka were thought to be ideal for vertical reef accretion, as sea level was on average 5-15 m above the antecedent reef platforms, creating optimal accommodation for reef growth (Davies and Hopley, 1983, Hopley et al., 2007, Dechnik et al., 2015). Reduced mass accumulation rates of fine siliciclastic sediments in the northern (Dunbar and Dickens, 2003) and southern (Bostock et al., 2009, Dechnik et al., 2015) GBR during this interval also may have helped facilitate optimal conditions for reef flat accretion, with evidence of less intense rainfall regimes and decreased flushing of terrigenous sediment from approximately 8 ka to 5.5 ka (Hopley, 1984, Smithers et al., 2006, Perry and Smithers, 2011, Roche et al., 2014). This is consistent with marine palaeoclimate records from tropical Australasia, suggesting that increased monsoon conditions did not occur until after 4 ka, providing optimal conditions for reef "take-off" ~8-6 ka (Reeves et al., 2013). Specifically, in the Capricorn Bunker groups, reef growth initiated ~ 8 ka following an initial 0.7-2-kyr time lag between substrate flooding and first reef colonization, a result of previously documented reduction in fine siliciclastic sediments in the region (Dechnik et al., 2015). Lateral progradation followed (~6 ka to 3.6 ka) (Fig. 6A) in response to the stabilisation of relative sea level and reduced vertical accommodation (Davies and Hopley, 1983, Hopley et al., 2007). Progradation occurred as either seaward or lagoonward expansion of the reef flat, the direction of which was controlled by hydrodynamic exposure and/or sediment residence time (Dechnik et al., 2016).

>>Fig. 6<<

These results are broadly consistent with both wider Indo-Pacific (Cabioch et al., 1995, Camoin et al., 1997, Montaggioni, 2005) and Caribbean reefs (Neumann and Macintyre, 1985, Gischler and Hudson, 1998, Gischler and Hudson, 2004), showing both initial vertical accretion and then lateral progradation of the reef flat in response to sea-level stabilisation and reduced accommodation. Differences in the precise timing of when these reefs first approached sea level and the transition to progradational growth at these locations (ranging from 6 ka to 2 ka) are related, in part, to differences in the timing of relative sea-level changes that result from glacial isostatic adjustment or tectonic movement (Lambeck et al., 2010). This is best demonstrated in the Caribbean, where relative sea level has been continuously rising until the present (Toscano and Macintyre, 2003, Dullo, 2005). Consequently these reefs were only able to “catch-up” to sea level ~2 ka, resulting in a more recent transition to progradational growth as compared to many Indo-Pacific reefs (Montaggioni, 2005).

For inshore fringing reefs of the GBR, >90% of reef flat vertical and lateral accretion occurred prior to 5.5 ka (Smithers et al., 2006). However, the majority of inshore fringing reefs developed on much shallower initial substrates (5-10 m below MSL) compared to the mid-outer platform reefs (12-25 m below MSL) (Fig. 5). Hence, these inshore fringing reefs would have rapidly filled available vertical and lateral accommodation, outgrowing their foundation more rapidly than the mid-outer platform reefs. Only minor amounts of progradational growth were documented on these reefs from 5.5 to 4.8 ka. However, similar to the results of the mid-outer platform reefs in this study, active fringing reef flat progradation ceased or slowed considerably by ~4.6- 3 ka (Smithers et al., 2006, Leonard et al., 2015, Ryan et al., 2016a).

4.2. Hiatus in reef flat growth

Distinct periods of reef “turn-off” during the mid- to late Holocene have been identified in reefs from the inner GBR, Pacific Panama, Japan and Hawaii. Along the inner central GBR, Smithers et al. (2006) and Perry and Smithers (2010, 2011) found distinct hiatuses between 3.0 and 2.3 ka, 4.5 and 1.3 ka and 5.5 and 2.3 ka, respectively. A more recent study of fossil microatolls in the Keppel Islands identified a 2-kyr hiatus in reef flat growth between 4.6 and 2.8 ka, with a possible earlier fall in relative sea level at ~5.5-5.3 ka (Leonard et al., 2015) (Fig. 7). Cessation of reef growth in Hawaii and Panama occurred at approximately 5 ka and 4 ka, respectively (Grigg, 1998, Grossman and Fletcher, 2004, Engels et al., 2008, Toth et al., 2012), whereas in Japan, three distinct hiatuses were identified at approximately 5.9 to 5.8 ka, 4.4 to 4 ka and 3.3 to 3.2 ka (Hamanaka et al., 2012). Although the timing of these hiatuses differs, these authors suggested that the reefs turned off when sea level fell from its maximum during the mid-Holocene highstand and/or were impacted by changing sediment flux and increased ENSO variability, both of which are associated with subtle changes in sea level and SST over the last 7-kyr.

>>Fig. 7<<

Increased turbidity in the inner GBR was linked to increased terrigenous sediment accumulation and the seaward extent of the Terrigenous Sediment Wedge (TSW), a product of post-highstand shoreline progradation in response to falling sea level (Larcombe and Woolfe, 1999, Perry and Smithers, 2010). This significant volume of easily re-suspended sediment would have increased turbidity, creating inhospitable conditions for reef growth on the inner GBR (Smithers et al., 2006, Perry and Smithers, 2011). Furthermore, spectral luminescence ratios from inshore *Porites* microatolls on the central GBR suggest that these reefs experienced strong flood events and greater annual range of salinity at ~4.7 ka than at present (Roche et al., 2014). The difference was attributed to a more active Australian-Indonesian Summer Monsoon system, which may have further exacerbated conditions that limited significant reef growth on the inner GBR

(Griffiths et al., 2010, Roche et al., 2014). However, for the mid-outer shelf reefs in this study, the greater distance from terrigenous sources would greatly reduce their exposure to sediment flux and discharge (Orpin et al., 1999, Neil et al., 2002). Whilst evidence of siliciclastic sediment has been identified in cores along the outer northeast Australia margin (Dunbar et al., 2000, Dunbar and Dickens, 2003), peak siliciclastic discharge occurred between 11 ka and 7 ka, significantly earlier than the hiatus reported in this study.

In the northwest Pacific increased swell and hurricane events associated with increased ENSO variability were interpreted to be responsible for significantly reduced reef accretion around several Hawaiian Islands (E.g. Kaua'I, O'ahu and Moloka'i) ~5 ka (Rooney et al., 2004). Increased ENSO variability, coupled with seasonal upwelling in Pacific Panama, is thought to have caused a 2.5-kyr hiatus in reef growth in the tropical eastern Pacific beginning at 4 ka (Toth et al., 2012, 2015). Whilst increased ENSO variability (~4-5 ka) in the Indo-Pacific remains controversial (Clement et al., 2000, Corrège et al., 2000, Cobb et al., 2013, McGregor et al., 2013, McGregor and Gagan, 2004), warmer and wetter conditions during the mid-Holocene have been identified both from fossil corals in the GBR (Gagan et al., 1998, Gagan et al., 2004, Roche et al., 2014) and from terrestrial records from northeast Australia (Kershaw, 1976, Kershaw, 1983, Nott and Price, 1994, Shulmeister and Lees, 1995, Reeves et al., 2013). Wetter climatic conditions during the mid-Holocene would have resulted in stronger flood events and a greater annual range of salinities, particularly for the central GBR (Roche et al., 2014) located adjacent to the Burdekin River (the largest river in northeast Queensland). However, continuous reef growth in this region throughout the mid-Holocene suggests that these factors did not significantly affect reef growth on the mid-outer shelf. Additionally, storm deposits at Curacoa Island on the central GBR showed no increase in the frequency of cyclones over the past 5-kyr, suggesting that these warmer and wetter conditions were not accompanied by more frequent cyclones (Hayne and Chappell, 2001). However, a more recent investigation by Ryan el al. (2016b) at Middle Island on the inner central GBR, identified a distinct age hiatus from 6.4 to 1.6 ka during the mid-Holocene which they attributed to stripping of the reef flat by intense cyclone activity. They suggested that reef growth was continuous throughout this period but was continually removed by destructive cyclones. However, Nott and Hayne (2001) demonstrated that there has been no regional increase in cyclone frequency and intensity across the GBR over the last 5-kyr. Therefore, as no regional differences were observed between northern, central and southern reefs (Fig. 3), climatic variations and associated cyclone frequency and intensity during the mid-Holocene is not a plausible mechanism for the observed reef "turn-off" on the mid-outer shelf.

Intense seasonal upwelling was identified as a secondary contributor to reef turn-off on many eastern Pacific Panama reefs, resulting in increased turbidity and decreased oceanic pH (Toth et al., 2012, 2015). Increased upwelling of cool, nutrient-rich water via shelf break upwelling or tidal jetting in the northern and central regions of the GBR at ~11 ka has been considered responsible for supporting the construction of large *Halimeda* bioherms behind reef platforms on the mid-outer shelf (Searle and Flood, 1988, Wolanski et al., 1988, Hopley et al., 2007, McNeil et al., 2016). However, only small accumulations of *Halimeda* have been identified within the Holocene platform reefs themselves with no regional variations in *Halimeda* abundance in the northern, central or southern reefs (Davies and Hopley, 1983, Hopley et al., 2007). This suggests little or no enhanced upwelling has occurred in these regions over the last 8-kyr.

The three distinct reef hiatuses (5.9-5.8 ka, 4.4-4.0 ka and 3.3-3.2 ka) at Kodakara Island in Japan were attributed to both variations in sea level and millennial-scale climate instability (Hamanaka et al., 2012). Specifically, the first reef flat hiatus was attributed to cold events in the North Atlantic and low SSTs in the Western Tropical Pacific (Hamanaka et al., 2012), while the subsequent two hiatuses were associated with sea-level oscillations of < 2 m, over centennial time scales. Similarly, a fall or subtle oscillation in sea level from 4.8 to 4.6 ka was considered the most likely cause of reef-turn off on the inner GBR (Smithers et al., 2006, Perry and Smithers, 2011, Leonard et al., 2015) (Fig. 7). Smithers et al. (2006) suggested that a 0.1-0.15 m fall in sea level during this interval was adequate to turn off reef flat production on the inner shelf and restrict growth to reef edge environments (Smithers et al., 2006). However, a more recent investigation of microatoll data from an inner shelf fringing reef suggests a more complicated story with possible centennial scale sea-level oscillations (Leonard et al., 2015). Those authors suggested that relative sea level fell by at least 0.4 m from a +0.75 m highstand between 5.5 to 5.3 ka, which was maintained for ~ 200 yr before returning back to higher levels. A second fall in sea level (~0.5 m) at 4.6 ka was identified, followed by a 2-kyr hiatus in reef flat growth (Leonard et al., 2015). In a comprehensive re-analysis of all sea level proxies collected from the northeast Queensland region, Lewis et al. (2013) concluded that a ~0.5 m fall in sea level at ~4-3.5 ka reflected the most reliable data for a mid-Holocene sea level fall for the GBR region, with a further ~1 m fall at 1.2 ka (Lewis et al., 2015). Despite the ambiguity in our own data set (reef flat elevations represent the minimum height of relative mean sea level), cessation of reef growth between 3.6-1.7 ka is consistent with this fall in relative sea level (Fig. 3). However, the larger palaeo-depth errors associated with reef flat data may have masked an earlier sea-level fall at approximately 5.5-5.3 ka, which was suggested by inner shelf microatolls (Leonard et al., 2015).

Nevertheless, a fall in sea level and subsequent reef turn off at ~3.6 ka is not supported from microatoll data at One Tree Reef (Fig. 2). These microatoll dates suggest that that sea level remained at a +1-1.3 m highstand until approximately 2 ka and then abruptly fell, resulting in the turn-off of reef flat carbonate production and the consequent cessation of lagoonal filling (Harris et al., 2015). However, it remains unclear whether these microatolls located on the inner reef rim were ponded at higher elevation than the surrounding relative sea level, possibly masking an earlier fall in sea level at 4-3.5 ka. Thus, whilst the reef flat ages obtained from reef cores in both the northern and southern regions of the GBR show a distinct hiatus in reef flat growth correlating with an apparent 0.5 m regional fall in sea level (Fig. 3), additional microatoll data obtained from open reef flat habitats from these reefs are needed to confirm (or not) this hiatus in reef flat growth.

Data from the central GBR do not record a relative fall in sea level at ~3.9 ka (Fig. 3). Hopley and Harvey (1981) recovered a series of short cores representing the inner to outer reefs in the central GBR and noted a decline in reef flat elevation seawards, with progressively younger reef flat ages on the outer reef margin (Fig. 4). Similar patterns were observed in the south-central GBR where the inshore fringing reefs first approached MSL 2-3-kyr earlier than the mid-outer shelf reefs (Kleypas and Hopley, 1992). This pattern was interpreted as a result of continental shelf margin down-warping owing to glacio-hydro-isostatic adjustment and subsidence along tectonic lineaments and/or within the still active Halifax Basin (Hopley and Harvey, 1981, Hopley, 1982, Kleypas and Hopley, 1992). A subsiding outer shelf would allow continued vertical accretion on the mid-outer shelf (Hopley and Harvey, 1981) even through a minor regression or fluctuation in sea level at ~4-3.5 ka (Fig. 6B). Subsequent geophysical models of the northeast coast of Australia showed sea-level highstands varying from 0.5-2.4 m above present MSL ~6 ka, with the largest predicted highstands occurring on the coast adjacent to the central GBR (Nakada and Lambeck, 1989, Lambeck and Nakada, 1990). Those authors suggested that the greater width of the shelf on the central GBR in comparison to the northern and southern regions would allow greater water loading, producing a hinge response of continental shelf margin down-warping on the outer shelf and uplift along the coast. Using these predicted amplitudes of Holocene highstands, based on upper and lower mantle viscosities (1-2 X 10^{20} Pa s^{-1} and 10^{22} Pa s^{-1} respectively), Nakada and Lambeck (1989) suggested a maximum 6 m cross shelf tilting of the continental edge from the inner to outer shelf (145° to 150° E) along the central GBR (18°S). Specifically for the mid-outer platform reefs, this corresponds to approximately 2 m of shelf tilting over the last 8-kyr (Nakada and Lambeck, 1989).

Further evidence of hydro-isostatic adjustment and/or subsidence on the central mid-outer shelf comes from the notable absence of mature lagoonal and senile reefs from Cairns to south of Townsville (Hopley et al., 2007). This absence was first noted by Hopley and Harvey (1981), who suggested that the degree of development of reefs on the central GBR appeared more juvenile and less developed than for the northern and southern GBR. Lewis and Hutchinson (2001) mapped the distribution of reef maturity across the GBR using a GIS-based depth elevation model. Results showed planar reefs dominated only in the northern and southern GBR, north of 16°E and south of 20°E , respectively (Lewis and Hutchinson, 2001). These data suggest that reefs of the intervening latitudes reached sea level much later and had less time to develop from juvenile to senile growth phases, consistent with the models of reef maturity for the mid and outer platform reefs of the GBR (Hopley et al., 2007, Hopley, 1982). Long term subsidence of the central GBR is also reflected in the maximum depth to the Pleistocene of mid-outer platform reefs over the entire GBR region. Fig. 5 shows that the Holocene-Pleistocene unconformities of the outer central platform reefs are on average 5-10 m deeper than for the northern or southern platform reefs. This suggests that the outer central GBR has been subsiding at a greater rate than the northern and southern GBR, most likely in response to development of the still active Halifax basin (Hopley, 1982). The lack of a reef flat hiatus in the present data suggests that this increased subsidence was active through the Holocene.

4.3. Reef flat accretion since 1.5 ka

Reef flat growth on the inner GBR was suggested to have re-initiated at approximately 2 ka following a 3.2-kyr hiatus in reef growth (Perry and Smithers, 2011). Those authors suggested that new reefal habitat would have become available for colonisation following sea-level stabilisation and the consequent stalling of the terrigenous sediment wedge (Perry and Smithers, 2011, Smithers et al., 2006). Re-initiation of microatoll growth in the Keppel Islands also was identified at ~2.8-2.5 ka at slightly higher elevations (Leonard et al., 2015). Thus, it was postulated that a final rise in sea level occurred during this interval, before finally falling to present levels. However, this remains an issue of contention with multi-proxy data (e.g., microatolls, tubeworm-barnacles, reef flat cores) showing divergent sea-level trends within this region (Harris et al., 2015, Baker and Haworth, 2000, Perry and Smithers, 2011).

What caused the renewed phase of reef flat turn-on remains unclear for the mid outer platform reefs. Nevertheless in this study, a majority of the ages showing evidence for reef accretion after 1.6 ka are located at either Heron or One Tree reefs (Fig. 3). For Heron Reef these ages come from the most seaward core -from the edge of the reef slope, whereas at One Tree

Reef they are located on the lagoonal sloping windrows (Dechnik et al., 2016). Similarly the ages from the northern (Ribbon Reef 5) and south-central (Redbill and Gable reefs) cores are located close to the seaward or lagoonal margins (Supplemental Table 1), suggesting that this pattern is not likely biased by the greater number of ages obtained from Heron and One Tree reefs. This suggests that these reefs were able to accrete following the suggested fall in sea level ~4-3.5 ka as the framework growing communities were located on the outer-most reef margins, representing the top-most living reefs growing on the seaward reef slopes or lagoonal walls (Fig. 6). This is consistent with recent models of Holocene reef accretion in relation to stillstand sea-level history, which show the youngest reef flat ages consistently occurring on the outermost seaward or lagoonal margins (Dechnik et al., 2016). Furthermore, Harris et al. (2015) suggested that the termination of live microatoll growth at One Tree Reef ~2 ka was a result of a 1-1.3 m fall in sea level, resulting in an ecological phase shift from a live coral dominated reef flat to a less productive algal rubble dominated reef flat. Alternatively, ponding may have been breached at this time and the internal sea level dropped, changing the sediment dynamics and exposing the previously ponded microatolls. Nevertheless, despite the difference in the timing of the relative sea-level fall suggested by the different data sets, the microatoll and short core data suggest active reef flat progradation would have been restricted after ~2 ka, across the majority of the reef flat, with continuous progradation limited to outer reef margin environments. It is therefore unlikely that the mid-outer reef flats turned back on, as was suggested for the inner GBR fringing reefs, but rather continued to prograde laterally on the outer reef margins, following a regression in sea level.

5. Conclusions

Based on analysis of 46 shallow coral U/Th ages from Heron and One Tree reefs and 165 recalibrated previously published radiocarbon ages from 27 other mid-outer platform reefs, we draw the following conclusions about Holocene reef flat growth over the last 7-kyr; Heron and One Tree reefs first approached modern sea level and began prograding between 6.8 and 3.9 ka, when climatic conditions were optimal for reef accretion. This was followed by a distinct hiatus in reef growth between 3.9 ka and 1.5 ka. An analysis of all other available previously published radiocarbon ages from 27 mid-outer shelf reef flats revealed a similar hiatus between 3.5-1.6 ka for the northern, south-central and southern GBR. Reefs of the central GBR, on the other hand, do not show this apparent hiatus in reef flat growth. Microatolls that date to the time of the hiatus at One Tree Reef could reflect ponding at this time, but additional dates are required from microatalls on reefs across the different regions. A relative fall in sea level of ~0.5 m represents the most likely explanation for this reef flat turn-off in the northern and southern regions; supporting the hypothesis that sea level fell from its maximum highstand at approximately 4-3.5 ka. Increased turbidity and cyclone activity, in response to close proximity to terrestrial sources and increased SSTs, precipitation, upwelling and ENSO variability have been ruled out as mechanisms of reef turn off at this time.

The absence of hiatus in reef flat growth in reefs from the central GBR, with reef flat ages ranging continuously from 7.6-0.8 ka, may reflect greater subsidence of the mid-outer central GBR in response to hydro-isostatic adjustment and long term subsidence from the still active Halifax Basin, which provided adequate accommodation throughout the Holocene to maintain a healthy carbonate factory capable of progradation. This interpretation is supported by younger reef flat ages on the central outer shelf and lack of senile reefs between Cairns and Townsville. Whilst the cause of the renewed reef flat turn-on remains unclear, of the few ages that show evidence of recent reef flat accretion after 1.6 ka, all occur on the most seaward or lagoonward reef flat, representing progradational growth on the outermost reef margins, consistent with previously documented accretional growth directions for the mid-outer platform reefs.

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Figure 1: Locality map of the GBR on the North-East Queensland coast, showing the location of the Halifax Basin Boundary (red dotted line) and all 29 reefs studied in this paper from the; 1) Northern, 2) Central, 3) South-Central and 4) Southern GBR including Heron and One Tree reefs.

Figure 2: Age elevation plots of reef flat corals collected from 34 short cores at Heron and One Tree reefs (Dechnik et al., 2015) and micro-atoll data collected from One Tree Reef (Harris et al., 2015). Only the reef flat core data shows a distinct hiatus in reef growth (grey rectangle), from 3.9 ka to 1.5 ka. Error bars are smaller than reef core symbols. All ages are plotted relative to MSL. Dates not considered to be reliably in-situ (IS) are shown as crosses (NIS) or open squares (NEI)-see methods for details.

Figure 3: A) Age elevation plots of all previously published reef flat ages from the Northern, Central, South-Central and Southern GBR. Error bars may be smaller than symbols. All ages plotted relative to MSL. B) Relative sea-level curve from the North-East Queensland coast, composed of the most reliable sea-level indicators for the Queensland region (Lewis et al., 2012). C) ENSO events (Blue line) (McGregor and Gagan, 2004) and Sea-Surface temperature anomalies for the Tropical Western Pacific (red line) (Linsley et al., 2010) and the GBR (Green symbols) (Gagan et al., 2004, Roche et al., 2014) over the past 9 ka.

Figure 4: Oldest in-situ age for each of the mid-outer platform reef flats analyzed in this study in; A) Northern, B) Central, C) South-Central and D) Southern GBR. Note the younger reef flat ages on the outer shelf of the Central GBR (B) in relation to the boundary of the Halifax Basin (Hopley & Harvey, 1981).

Figure 5: Depth of Holocene/Pleistocene boundary based on all available published reef core data from the mid-outer platform reefs and inshore fringing reefs of the GBR, relative to distance from the East Australian Coast. Note that reef substrates are mostly deeper in central GBR reefs than in northern, southern or south-central GBR reefs.

Figure 6: A) Conceptual figure showing reef flat development in relation to relative sea-level changes throughout the Holocene in the Northern, South-Central and Southern GBR and B) outer Central GBR.

Figure 7: Summary of spatial and temporal patterns of reef flat growth on the inner and outer GBR based on reef flat core data and fossil micro-atolls. A) Location of each of the reefs studied (note each individual colored circle may represent more than one reef), with the colored circles corresponding to the studies listed in panel B. Periods of distinct reef flat growth are shown as blue and black stripped bars, whilst hiatus events are shown in orange (B).

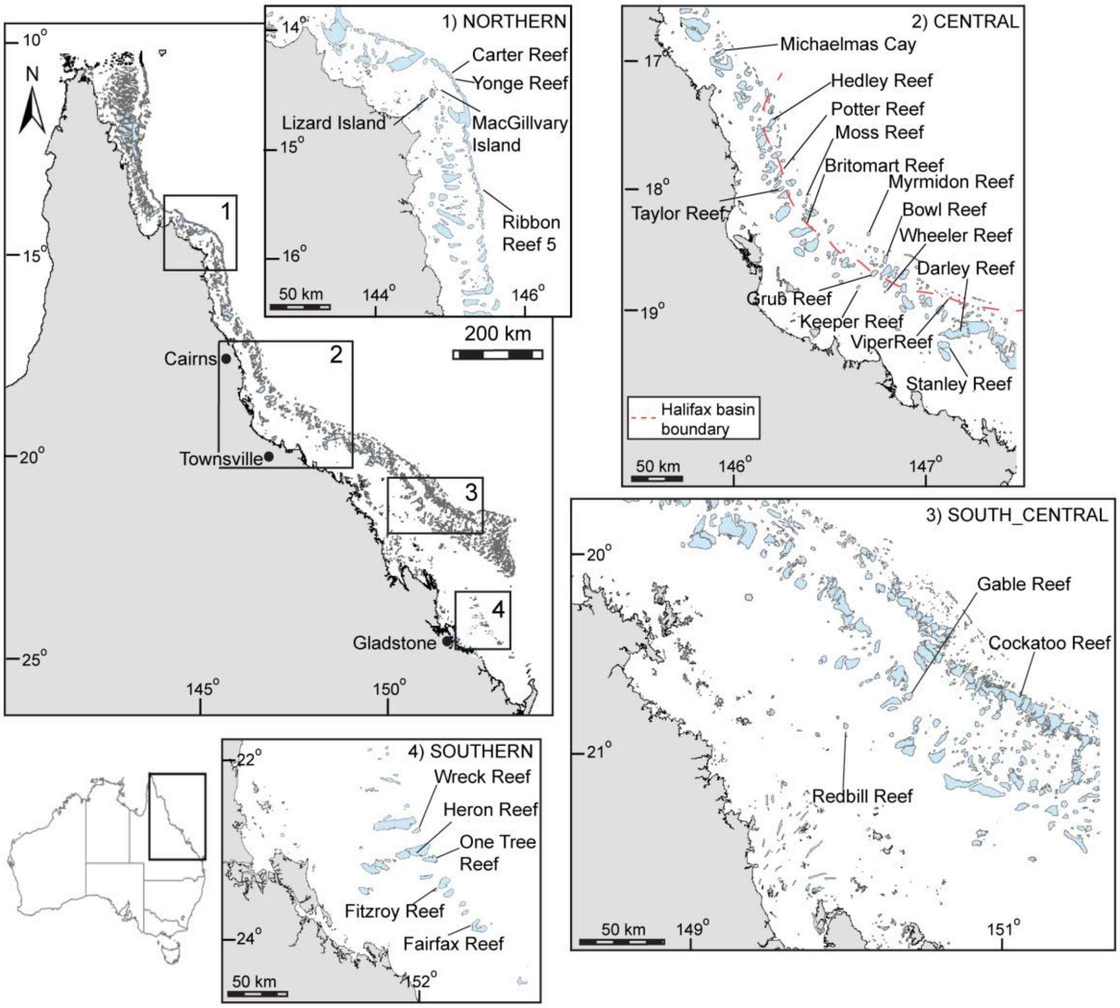

1) NORTHERN
Carter Reef
Yonge Reef
Lizard Island
MacGillvary Island
Ribbon Reef 5
14°
15°
16°
144°
146°
50 km
2) CENTRAL
Michaelmas Cay
Hedley Reef
Potter Reef
Moss Reef
Britomart Reef
Myrmidon Reef
Taylor Reef
Bowl Reef
Wheeler Reef
Darley Reef
Grub Reef
Keeper Reef
ViperReef
Stanley Reef
Halifax basin boundary
17°
18°
19°
146°
147°
50 km
N
10°
15°
20°
25°
145°
150°
1
2
3
4
Cairns
Townsville
Gladstone
200 km
3) SOUTH_CENTRAL
Gable Reef
Cockatoo Reef
Redbill Reef
20°
21°
149°
151°
50 km
4) SOUTHERN
Wreck Reef
Heron Reef
One Tree Reef
Fitzroy Reef
Fairfax Reef
22°
24°
152°
50 km

Figure 1

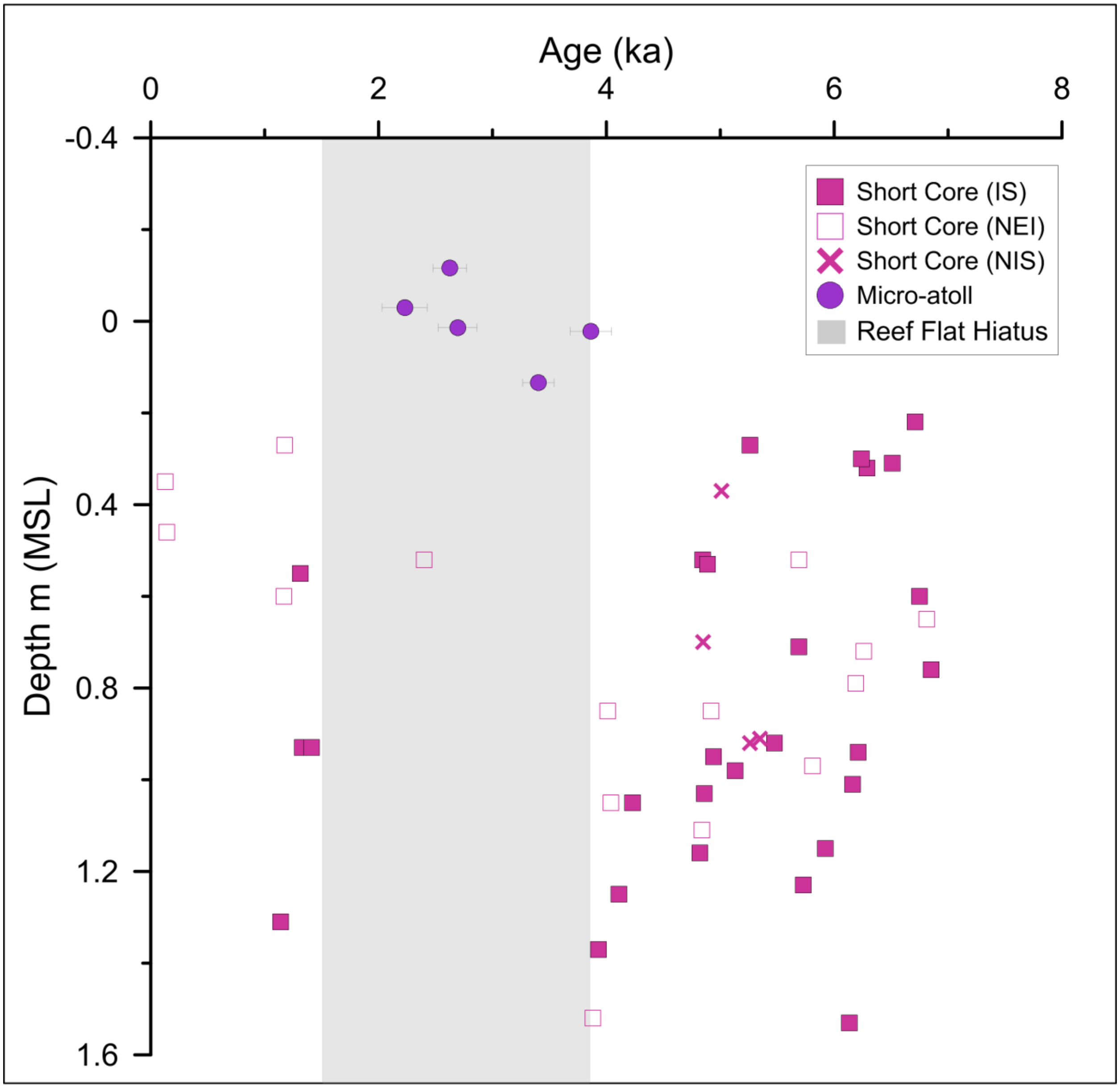

Age (ka)
0
2
4
6
8
-0.4
0
0.4
0.8
1.2
1.6
Depth m (MSL)
Short Core (IS)
Short Core (NEI)
Short Core (NIS)
Micro-atoll
Reef Flat Hiatus

Fig. 2

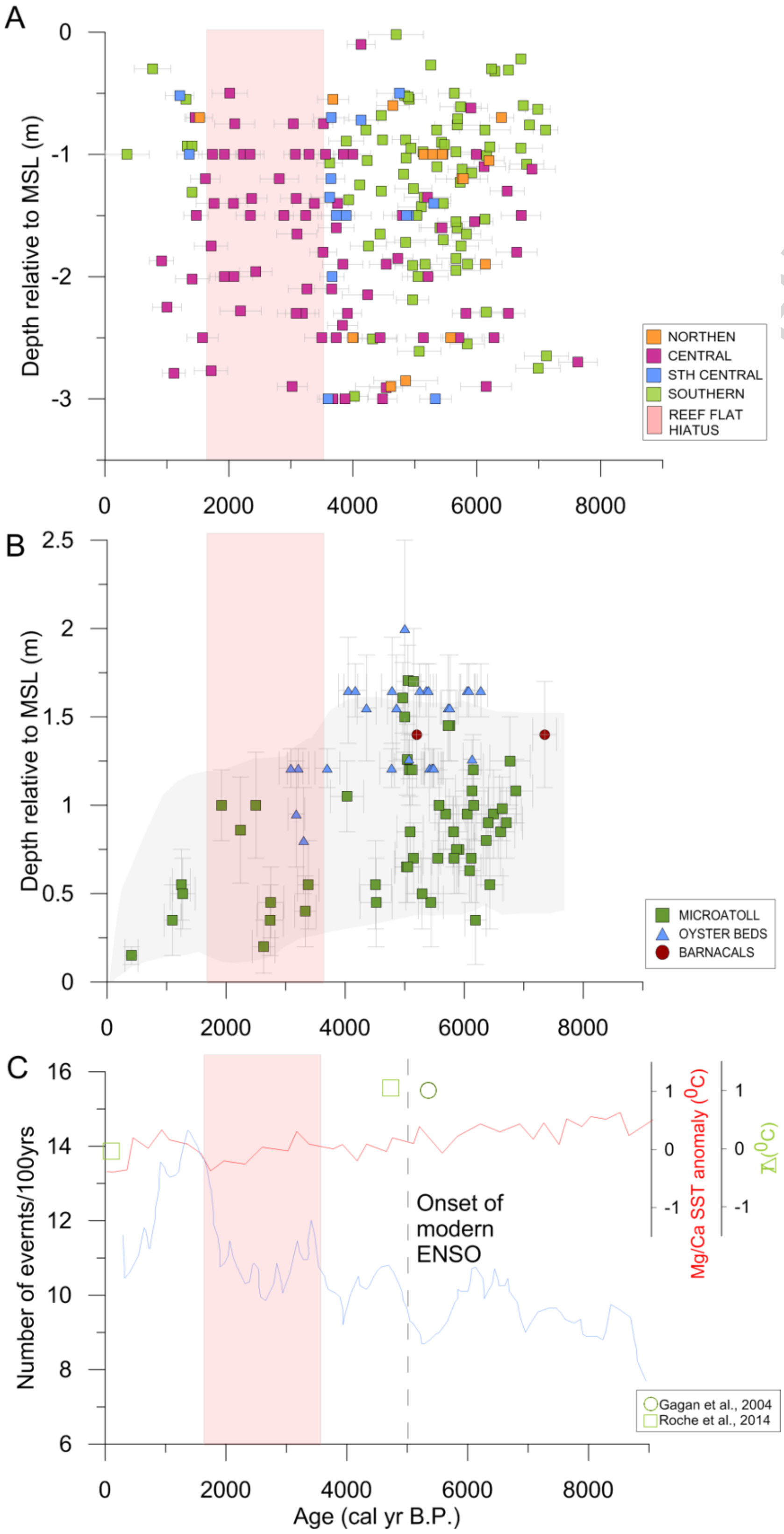

A
Depth relative to MSL (m)
0
-1
-2
-3
0
2000
4000
6000
8000
🟧 NORTHEN
🟪 CENTRAL
🟦 STH CENTRAL
🟩 SOUTHERN
🟥 REEF FLAT HIATUS
B
Depth relative to MSL (m)
2.5
2
1.5
1
0.5
0
0
2000
4000
6000
8000
■ MICROATOLL
▲ OYSTER BEDS
● BARNACALS
C
Number of everts/100yrs
16
14
12
10
8
6
0
2000
4000
6000
8000
Age (cal yr B.P.)
Onset of modern ENSO
1
0
-1
Mg/Ca SST anomaly (^{0}C)
1
0
-1
Δ(^{0}C)
○ Gagan et al., 2004
☐ Roche et al., 2014

Figure 3

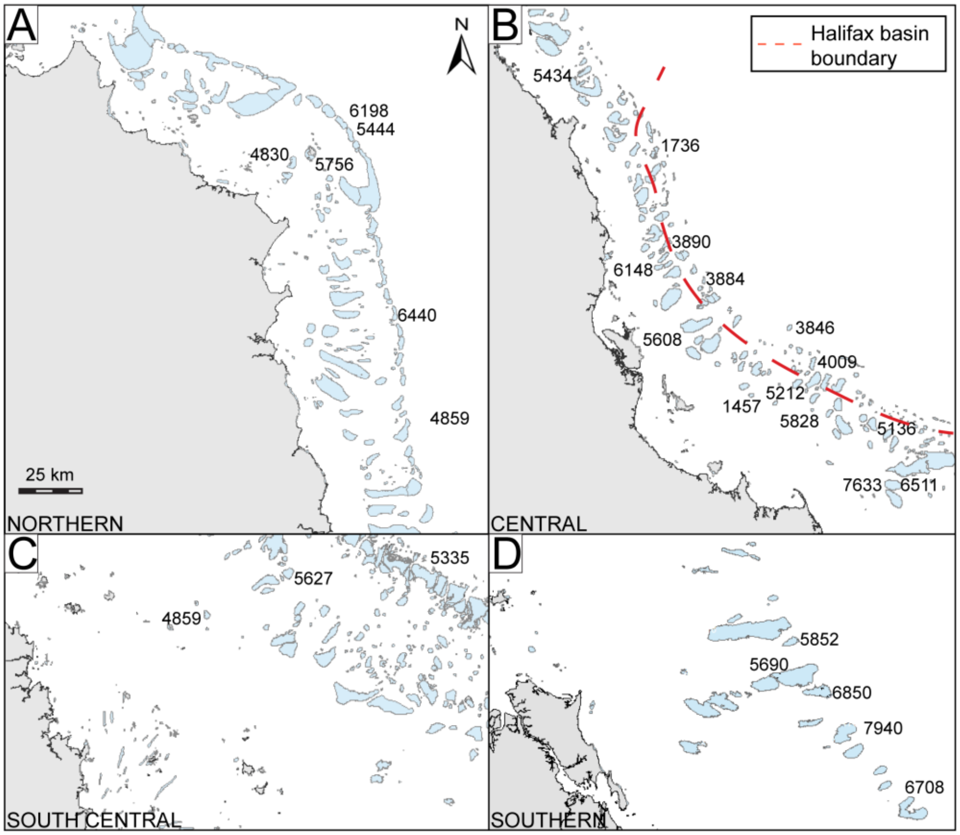
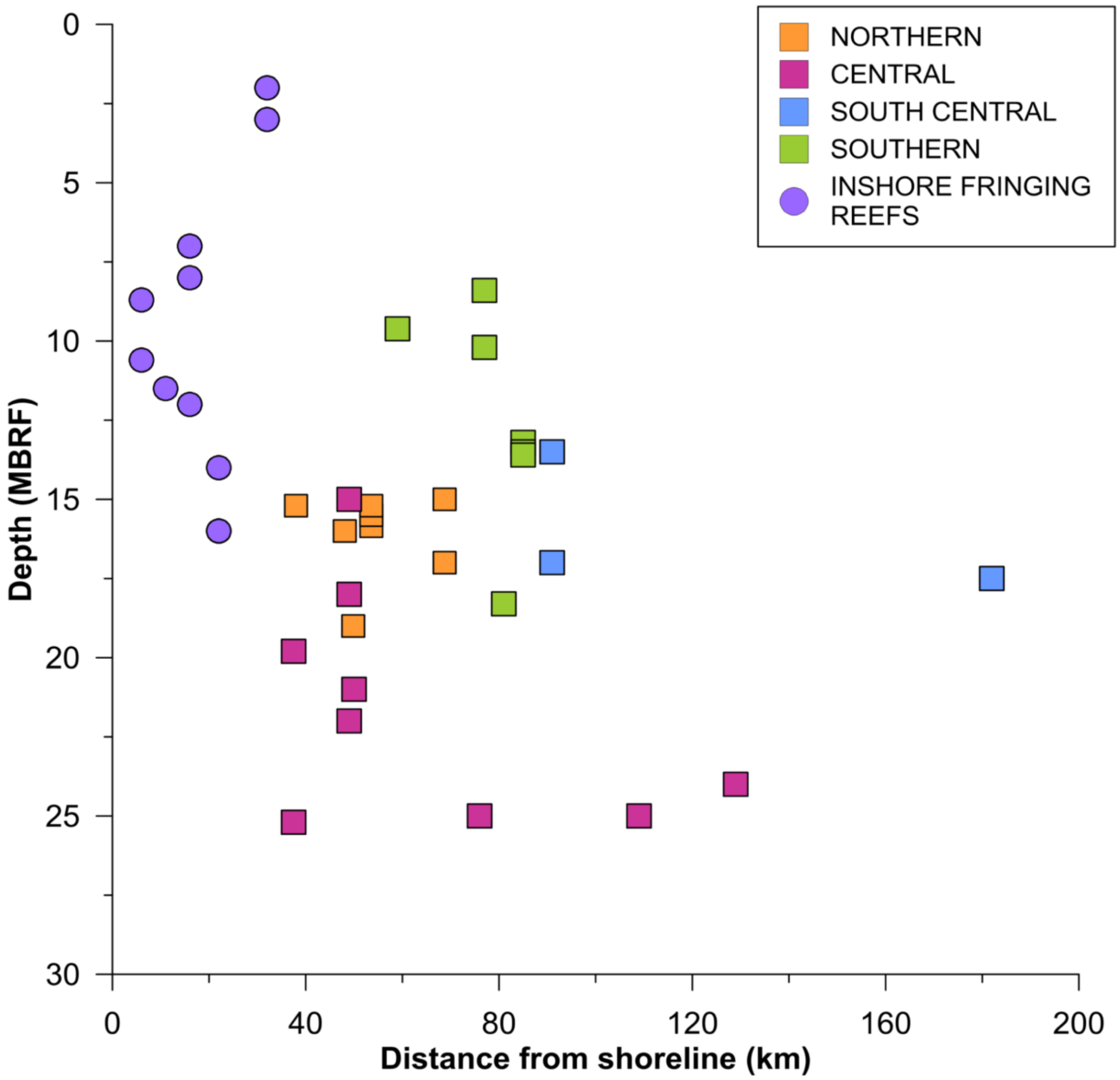
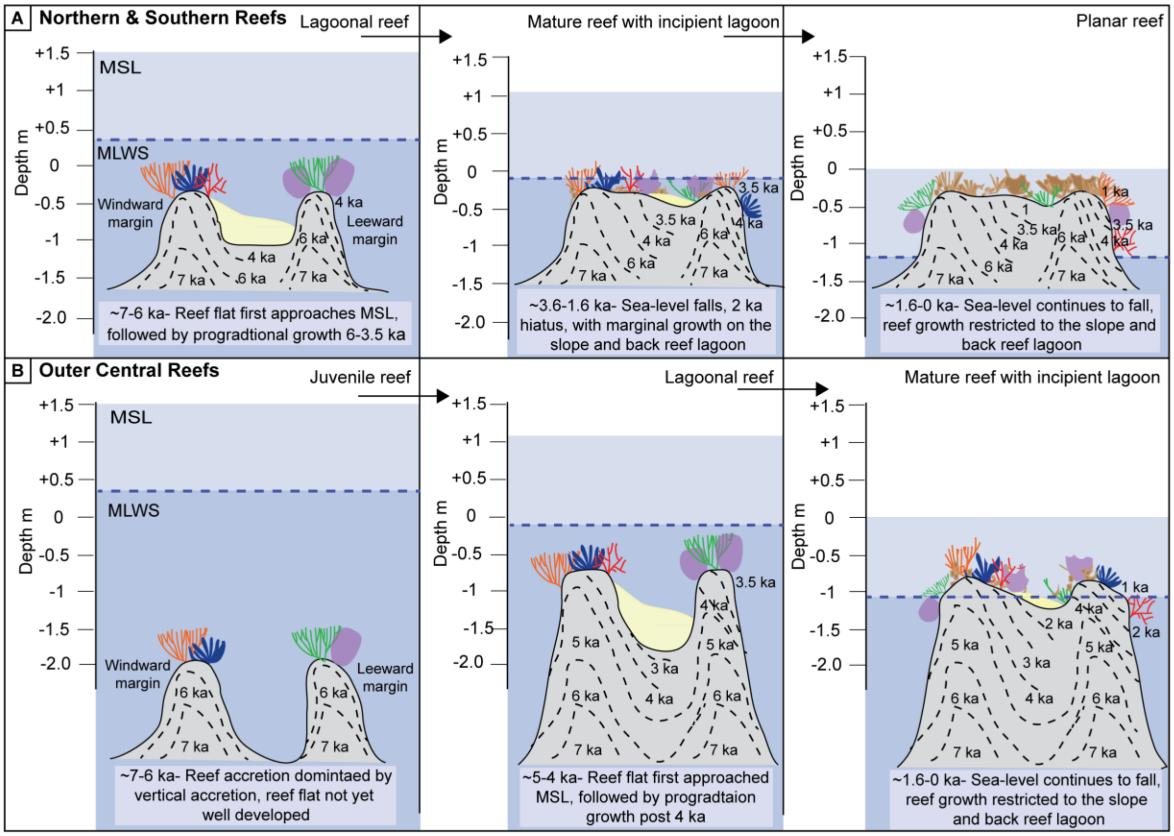

A
N
6198
5444
4830
5756
6440
4859
25 km
NORTHERN
B
Halifax basin boundary
5434
1736
3890
6148
3884
3846
5608
4009
1457
5212
5828
5136
7633
6511
CENTRAL
C
5335
5627
4859
SOUTH CENTRAL
D
5852
5690
6850
7940
6708
SOUTHERN

Figure 4



0
5
10
15
20
25
30
Depth (MBRF)
0
40
80
120
160
200
Distance from shoreline (km)
NORTHERN
CENTRAL
SOUTH CENTRAL
SOUTHERN
INSHORE FRINGING REEFS

Figure 5



~7-6 ka- Reef flat first approaches MSL, followed by progradtional growth 6-3.5 ka

~3.6-1.6 ka- Sea-level falls, 2 ka hiatus, with marginal growth on the slope and back reef lagoon

~1.6-0 ka- Sea-level continues to fall, reef growth restricted to the slope and back reef lagoon

~7-6 ka- Reef accretion domintaed by vertical accretion, reef flat not yet well developed

~5-4 ka- Reef flat first approached MSL, followed by progradtaion growth post 4 ka

~1.6-0 ka- Sea-level continues to fall, reef growth restricted to the slope and back reef lagoon

Figure 6

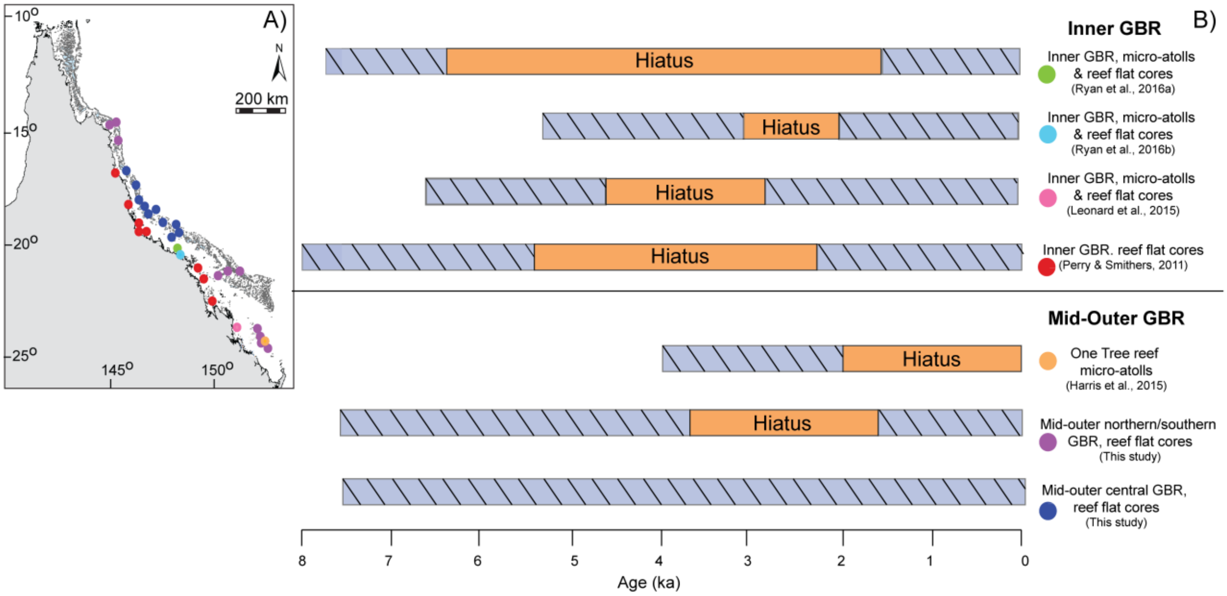

A)
10°
15°
20°
25°
145°
150°
N
200 km
B)
Inner GBR
Hiatus
Hiatus
Hiatus
Hiatus
Inner GBR, micro-atolls & reef flat cores (Ryan et al., 2016a)
Inner GBR, micro-atolls & reef flat cores (Ryan et al., 2016b)
Inner GBR, micro-atolls & reef flat cores (Leonard et al., 2015)
Inner GBR. reef flat cores (Perry & Smithers, 2011)
Mid-Outer GBR
Hiatus
Hiatus
One Tree reef micro-atolls (Harris et al., 2015)
Mid-outer northern/southern GBR, reef flat cores (This study)
Mid-outer central GBR, reef flat cores (This study)
8
7
6
5
4
3
2
1
0
Age (ka)

Figure 7

Highlights

- 2 ka hiatus in reef flat growth identified from the northern and southern GBR
- Hiatus supports a relative fall in sea-level regionally across the GBR 3.5-4 ka
- No hiatus across the central GBR as a result of local subsidence
- Turbidity, upwelling and cyclones ruled out as other possible mechanisms for reef-flat hiatus