Geomorphology and late Holocene accretion history of Adele Reef: a northwest Australian mid-shelf platform reef

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Abstract

The mid-shelf reefs of the Kimberley Bioregion are one of Australia's more remote tropical reef provinces and such have received little attention from reef researchers. This study describes the geomorphology and late Holocene accretion history of Adele Reef, a mid-shelf platform reef, through remote sensing of contemporary reef habitats, shallow seismic profiling, shallow percussion coring and radiocarbon dating. Seismic profiling indicates that the Holocene reef sequence is

25 to 35 m thick and overlies at least three earlier stages of reef build-up, interpreted as deposited during marine isotope stages 5, 7 and 9 respectively. The cored shallow subsurface facies of Adele Reef are predominantly detrital, comprising small coral colonies and fragments in a sandy matrix. Reef cores indicate a *'catch-up'* growth pattern, with the reef flat being approximately 5–10 m deep when sea level stabilised at its present elevation 6,500 years BP. The reef flat is rimmed by a broad low-relief reef crest only 10–20 cm high, characterised by anastomosing ridges of rhodoliths and coralliths. The depth of the Holocene/last interglacial contact (25–30 m) suggests a subsidence rate of 0.2 mm/year for Adele Reef since the last interglacial. This value, incorporated with subsidence rates from Cockatoo Island (inshore) and Scott Reefs (offshore), provides the first quantitative estimate of hinge subsidence for the Kimberley coast and adjacent shelf, with progressively greater subsidence across the shelf.

Introduction

Adele Reef is a large (200 km^2) platform reef located 15.5°S, 123.5°E on Australia's northwest shelf, approximately 80 km from the mainland Kimberley coast and 200 km from the shelf edge (Figure 1). Adele Reef is approximately 22 km long and 9 km wide, and is topped by a 4 km^2 vegetated sand cay. Four smaller submerged reefs, Churchill, Albert, Mavis and Beagle reefs, lie to the east. The surrounding shelf is 70-80 m deep and is incised by channels to approximately 90-100 m depth (Figure 1).

The regional climate is semi-arid and monsoonal, with two seasons: a 'wet' season from November to April and 'dry' season from May to October. Monsoon storms in the wet season bring intense rainfall, averaging 800-1,500 mm. The dry season is characterised by warm to hot temperatures and low humidity (DEWHA, 2008). Sea surface temperatures around Adele range from 22 to 28 °C (Pearce and Griffiths, 1991). The predominant swell is from the southwest and the predominant winds are westerly to south-westerly. The region is cyclone-influenced (average three per year. Lough, 1998) and has semidiurnal tides with a maximum range of 7 m.

Previous research on Adele Reef has described its surface geomorphology (Teichert and Fairbridge, 1948; Brooke, 1997), petroleum potential (Ingram, 1982; Marshall, 1995) and reef flat habitats (Richards et al., 2013). The stratigraphic sequence beneath the northern tip of Adele Island was investigated in a petroleum exploration well drilled in 1982 ('Adele Island 1'. Ingram, 1982; Marshall, 1995). The first 156 m of the borehole intersected multiple stacked sedimentary units consisting of Holocene and Pleistocene limestone, with abundant shell fragments and coral remains in the upper 30 m (Ingram, 1982). Palaeogene sandstone was found below 160 m, overlying a Cretaceous and Upper Jurassic sand/silt sequence; Proterozoic basement was intersected at 798 m (Ingram, 1982).

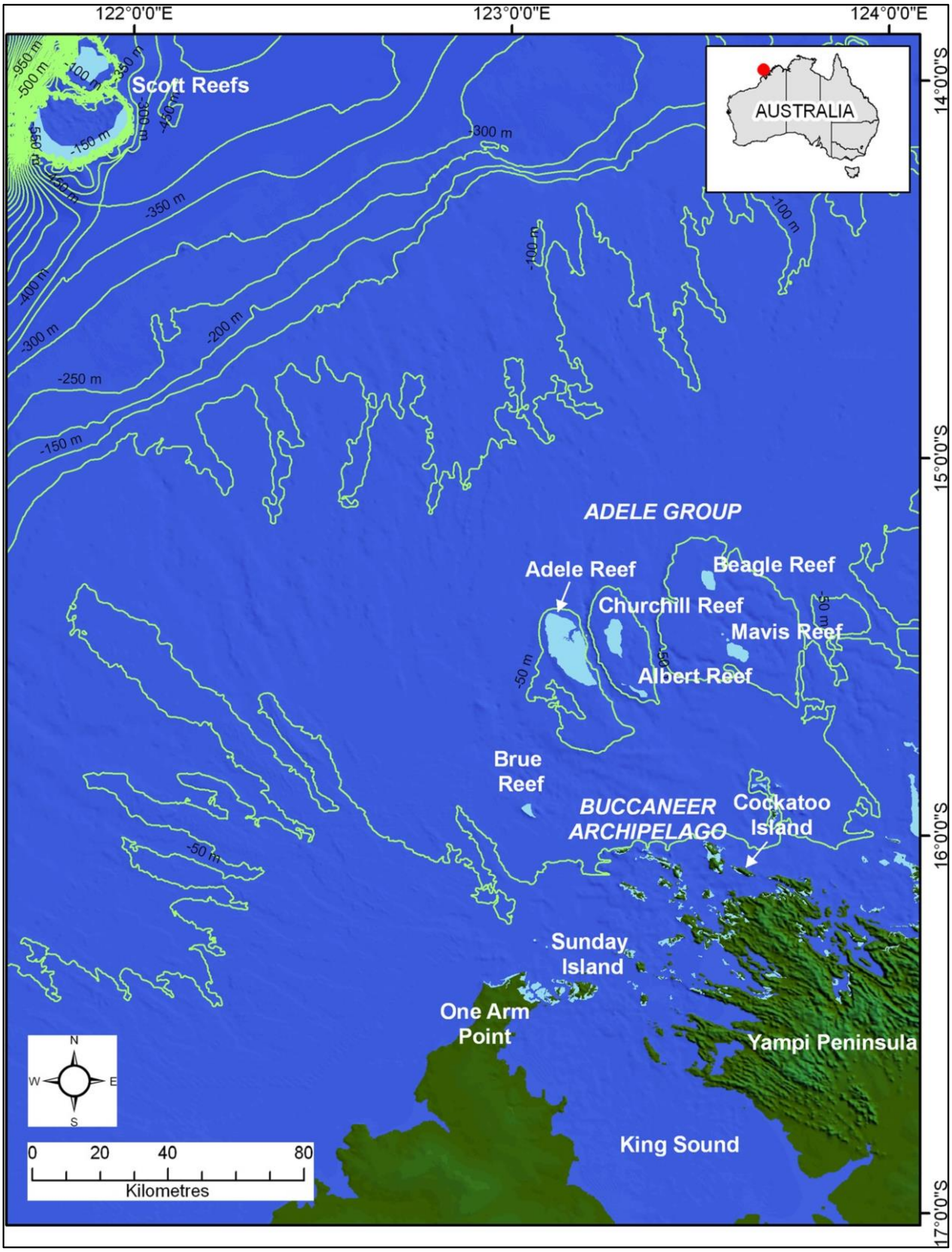


Figure 1. Map of the study area in the Kimberley Bioregion showing the bathymetry contour derived from 250 m resolution digital elevation model (DEM) sourced from Geoscience Australia (note: there is some uncertainty in the depths due to the coarse nature of the bathymetric grid). Light blue Reef habitat.

In a recent survey by the Western Australian Museum, Richards et al. (2013) reported the discovery of a unique *rollolith* habitat along the south-western margin of Adele Reef. This includes mobile corals (coralliths) and red crustose coralline algae (rhodoliths) that have coalesced to form low- relief banks on the outer reef flats. This atypical habitat likely formed in response to a combination of wave action and strong surface currents driven by the 7 m macrotidal range (Richards et al., 2013).

Compared to the relatively well-studied oceanic reefs such as Scott Reefs and the Rowley Shoals (Collins, 2011), and the inshore reefs of the Buccaneer Archipelago (Collins et al., 2015; Solihuddin et al., 2015, 2016; Bufarale et al., 2016), the Holocene development of the mid-shelf platform reefs of Australia's northwest shelf remains unknown. The present study attempts to address the information gap by investigating modern habitats, geomorphology and the late Holocene accretion history of Adele Reef through remote sensing, shallow sub-bottom pro- filing, reef core stratigraphy and radiocarbon dating.

Materials and methods

Landsat 8 imagery

Contemporary reef communities and associated habitats were mapped using a Landsat 8 multispectral satellite image taken on the 23rd May 2015 (path 110, row 071). This image was corrected geometrically to the WGS 84 reference datum. A digital unsupervised classification from Erdas' ER Mapper utility was used to define reef habitat zones based on a grouping of the reflectance spectra of Landsat 8 bands 2 (0.45-0.52 μm, blue), 3 (0.52-0.60 μm, green) and 4 (0.63-0.68 μm, red). Ground-truth observations of reef habitats from the current study and from the Woodside Collection Project (Kimberley) 2008-2011 (http://www.museum.wa.gov. au/Kimberley/marine-life-kimberley-region; accessed November 2015) were assigned to the corresponding Landsat 30x30 m pixels. All pixels with similar spectral characteristics were then automatically assigned to that ground-truthed habitat.

Seismic survey

A high-resolution shallow seismic survey of the reef subsurface was undertaken using a boomer/sub-bottom profiler sys- tem (AA201 Applied Acoustic Engineering Limited, Great Yarmouth, UK). A differential global positioning system (DGPS, Fugro Seastar 8200XP/HP) provided accurate positioning (decimetric differential accuracy, typically ±20 cm). Sub-bottom profiling data were digitally acquired, recorded, post-processed and analysed using SonarWiz 5 (Chesapeake Technology Inc., Mountain View, CA). Interpretation of the seismic reflectors depicted in the profiles was performed using a combination of inshore reef seismic data from Bufarale et al. (2016) and petroleum well-log data from Adele Island 1 (Ingram, 1982; Marshall, 1995). Geoscience Australia's 250 m bathymetry dataset was analysed using ESRI's Arc Hydro Tools Terrain Pre-processing toolset to map the position and bathymetry of shelf palaeochannels.

Reef coring, logging and sampling

Eight percussion cores were collected from Adele Reef. Coring sites were selected to ground-truth the seismic interpretations and to ensure a spatially representative record of reef accretion. A manual slide hammer or a hydraulic post driver was used to drive lengths of a 6 m long, 80 mm diameter aluminium pipe with near-100% core recovery. Compaction was measured onsite and corrected by linear stretching of the core logs. Logs were plotted to local mean sea level (MSL), which is 3.9 m above the lowest astronomical tide (LAT) and referred to metre below sea level (mbsl) in this article. Core locations were recorded by handheld GPS with an accuracy of ±5 m.

Core logging and sampling documented sediment characteristics including (1) the ratio of reef framework to matrix (after Embry and Klovan, 1971), (2) visual assessment of sediment textural characteristics using the Udden-Wentworth nomenclature (Wentworth, 1922) and (3) generic coral identification (after Veron, 2000). Reef framework analysis and facies descriptions followed the terminology proposed by Montaggioni (2005), which highlights the growth forms of the dominant reef builders and environmental indicators. Between 300-500 g samples of matrix sediment were collected for carbonate content analysis using the carbonate bombe technique (weight% loss after treatment with 50% HCL) following guidelines from Müller and Gastner (1971). A pipe dredge was used to collect subtidal sediment samples and these were analysed using the same methods as applied to the core samples.

Radiocarbon dating

Three to five coral specimens from the top, middle and base of each core were selected, based on size and preservation, for accelerator mass spectrometry (AMS) radiocarbon dating in order to establish a geochronological record of late Holocene reef accretion. Individual coral specimens were ultrasonically cleaned and cut into pieces with minimum weight of 50 mg. All samples were dated at Beta Analytic Inc. USA and recalibrated using the CALIB Version 7.0.4 and the Marine13 calibration curve (http://calib.qub.ac.uk/marine; accessed January 2016). A weighted mean Delta-R (ΔR) value of 58±21 (average calculation from three nearest points: Cape Leveque NE side, King Sound, Port George) was used as the best current estimate of variance in the local open water marine reservoir effect for Adele Reef and adjacent areas (Reimer et al., 2013). Ages discussed in the text are in calibrated years before present (cal years BP) with the 68.2% (2σ) probability range for all dated samples.

Results

Contemporary reef biogeomorphic zones

The Landsat-derived reef geomorphology and associated habitat map (Figure 2), supported by ground-truth observations, allowed delineation of six distinct biogeomorphic zones: (1) sand cay, (2) coral rubble and carbonate sand, (3) coralgal pavement, (4) crustose coralline algae, (5) mixed assemblage of coralliths and rhodoliths and (6) soft and hard corals. Each of these habitats is described in detail below.

Sand cay. The sand cay forms a NW-SE elongated, 12x3 km unvegetated island consisting of poorly sorted coarse carbonate sand with approximately 30% coral, 30% mixed shell fragments and foraminifera tests, and 40% unidentified sand to silt grain-size fractions. Comparing the Landsat image with aerial photographs of Teichert and Fairbridge (1948) indicates that the intertidal sand is relatively stable in the south where it encircles Adele Island (the vegetated sand cay), but forms mobile sand waves in the north (Figure 2).

Coral rubble and carbonate sand. Coral rubble and coarse carbonate sand is the dominant reef flat sediment facies. This habitat is distributed around the sand cay and on the outer reef flat especially along the north side of the reef platform. The sediments around the sand cay are exposed at every low tide whereas those on the outer reef flat and especially on the NE side are exposed only below mean low water spring (MLWS).

Coralgal pavement. An extensive coralgal pavement is distributed over the intertidal reef flat and forms low- relief ridges on the outer reef flat. The pavement is colonised by approximately 10% macroalgae, primarily *Sargassum*, and 20% coral colonies of the genera *Goniastrea, Acropora*, *Porites* and *Favites* (Figure 3, AR1-AR3). A broad 1-2 km wide intertidal coralgal pavement, completely exposed at MLWS, separates the sand cay from the outer reef flat.

Crustose coralline algae. Crustose coralline algae occur in a 100-1,000 m wide zone along the outer reef flat, which is broadest on the southern side of the platform and narrows on the eastern (leeward) side. This zone forms a broad low-relief reef crest and intergrades with the coralliths and rhodolith assemblage.

Mixed assemblage of coralliths and rhodoliths. Coralliths and rhodoliths with a maximum diameter of (respectively) approximately 8 and 5 cm accumulate in anastomosing ridges approximately 15-20 cm high towards the outer edge of the reef crest (Figure 3, AR4). They are sub-spherical and mobile, and appear to develop where seawater flows off the elevated reef at low tide. Soft and hard corals: On the SW side of the reef, the forereef slope gently dips seawards to a broad submerged terrace at 25-30 m depth, and then dips steeply to the surrounding shelf seafloor at 70-90 m depth. The upper few metres of forereef slope are colonised mainly by soft corals, branching *Acropora* and encrusting *Montipora* up to 1 m in diameter.

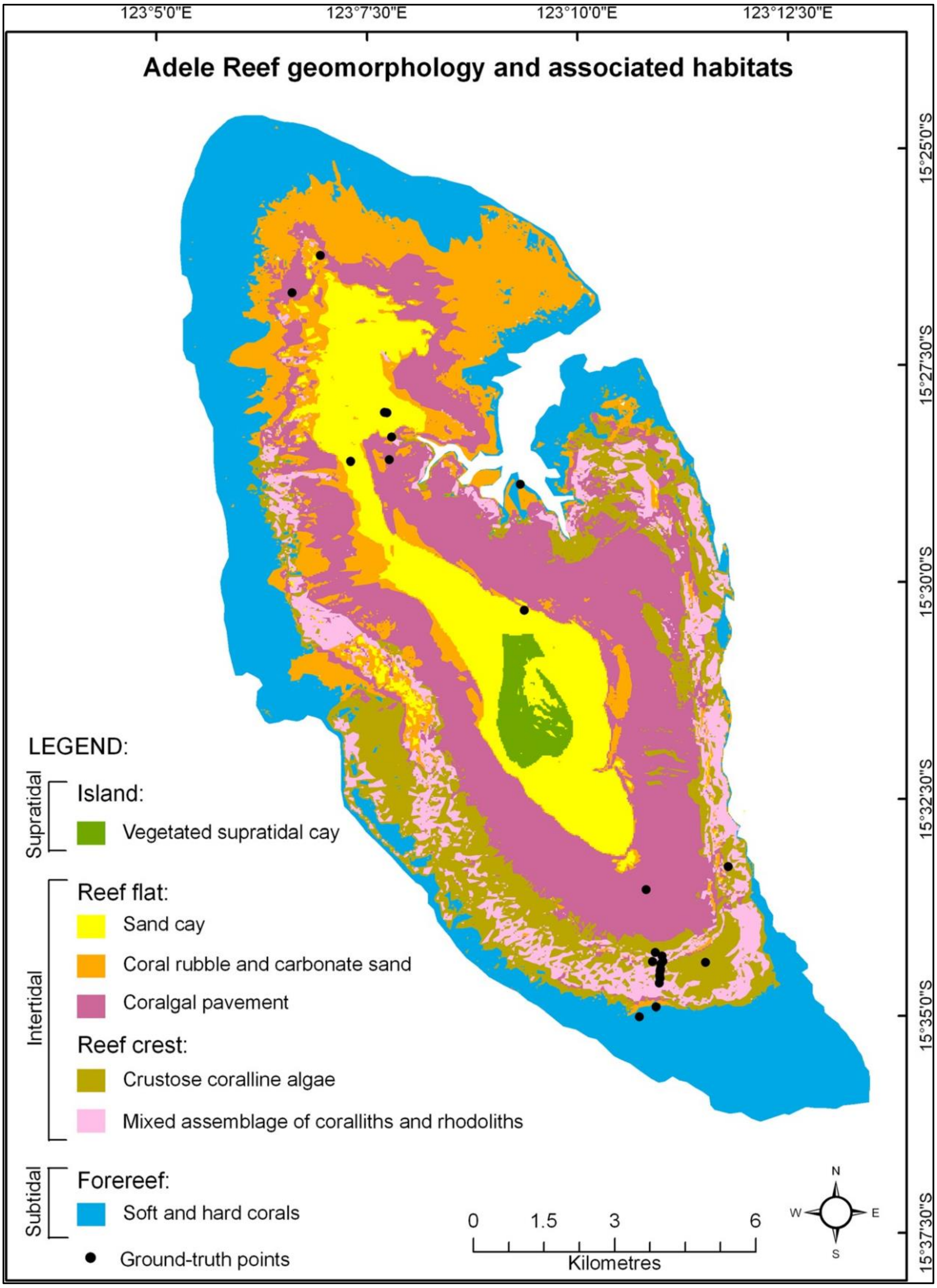


Figure 2. Map of Adele platform geomorphology and associated habitats, derived from Landsat 8, 23 May 2015.

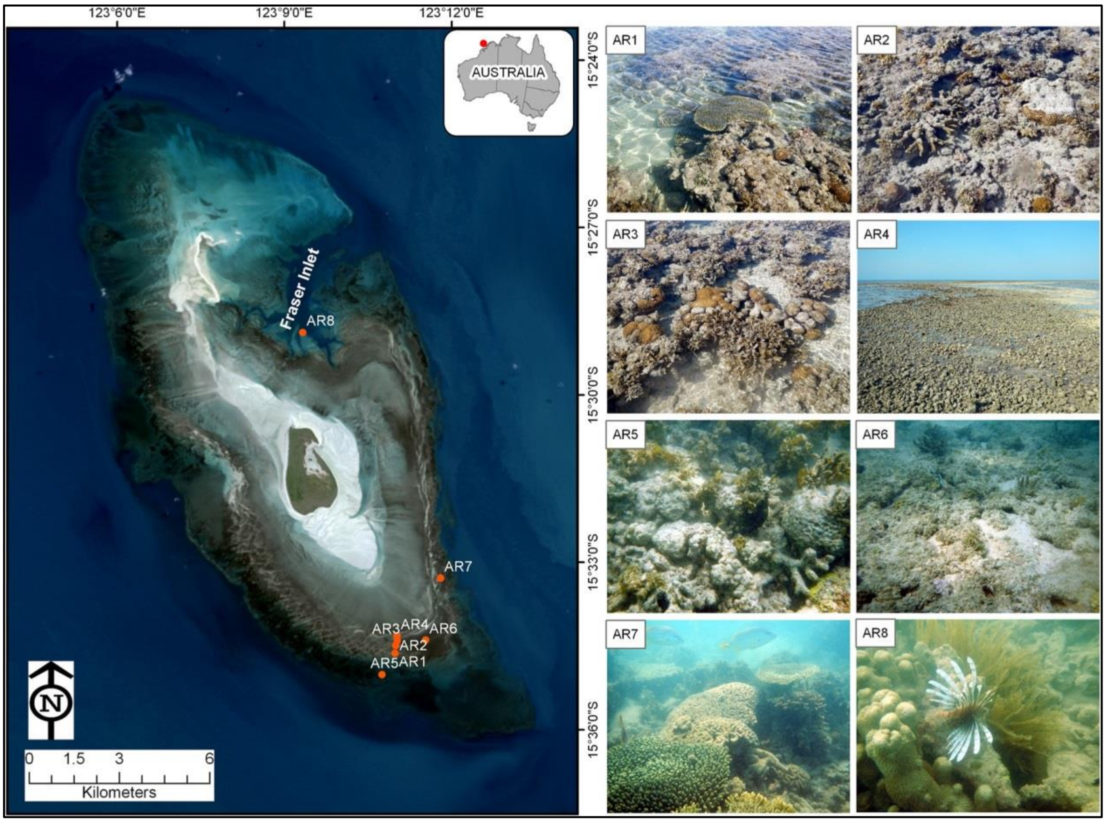


Figure 3. Contemporary reef habitats of the Adele Reef platform with ground-truth locations. AR1: crustose coralline algae with platy *Acropora*, *Favia*, *Goniastrea* and macroalgae (*Sargassum*). AR2: crustose coralline algae with branching *Porites*, *Goniastrea* and *Sargassum*. AR3: extensive shallow pool on reef flat colonised by *Sargassum*, *Favia* and crustose coralline algae. AR4: rhodolith banks exposed at low spring tides form low-relief reef crest on the SE reef flat. AR5: coral rubble and *Sargassum* on the SE outer reef flat. AR6: *Sargassum* on coral rubble and carbonate sand substrates. AR7: branching *Acropora* and *Lobophyllia* on the SE outer reef flat. AR8: robust branching coral near the narrow drainage channel of Fraser Inlet.

Reef architecture and seismic structure

Interpretation of the acoustic horizons across the Adele Reef platform suggests that there are at least three separate stages of reef accretion, bounded by seismic reflectors R1, R2 and R3 (Figure 4).

R1 reflector. R1 (Figure 4; depicted in green in Figure 5) is a high-energy reflector, typically expressed as a horizontal surface that parallels the modern surface morphology between 25 and 35 mbsl. The shallowest reef unit (unit 1, or U1) be- tween R1 and the modern reef surface is up to 30 m thick.

R2 reflector. R2 (Figure 4; depicted in yellow in Figure 5) is a low to medium amplitude reflector and was encountered in the northern portion of Adele Reef, around 40 mbsl. Unit 2 (U2), between R1 (-30 mbsl) and R2 (-40 mbsl), is mostly acoustically transparent and up to 10 m thick.

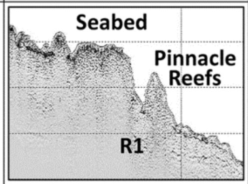
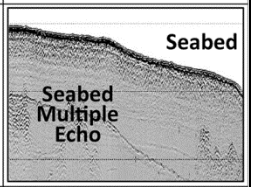
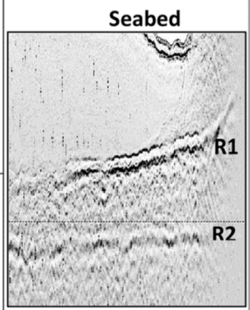
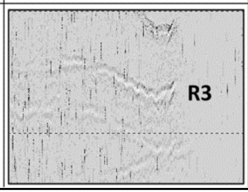
Seismic Unit	Thickness	Limits	Internal Structure	Morphology	Interpretation	Example
U1	Variable: 20-28 m	**Top:** seabed **Bottom:** unconformity R1	Moderate to low amplitude. Local discontinuous and sub-parallel reflectors (H1, H2 and H3)	Reef flat, crest forereef slope. Local pinnacle reefs	Reef facies	
			Well-defined, locally parallel to subparallel, prograding layers. Minor disconformities	Channel fill. Sediment mounds or drapes	Sediment Bodies	
U2	Variable: 5-10 m	**Top:** unconformity R1 **Bottom:** unconformity R2	Weak to moderate amplitude with discontinuous, subparallel minor reflectors	Reef flat, crest, forereef slope. Local pinnacle reef	Reef facies	
U3	~ 22 m	**Top:** unconformity R2 **Bottom:** unconformity R3	Low to medium amplitude, mostly acoustically transparent	Reef flat, crest, forereef slope	Reef facies	
U4	NA	**Top:** unconformity R3 **Bottom:** NA	Low amplitude	Reef flat	Reef facies	

Figure 4 Characteristics of the acoustic features identified in the seismic profiles of Adele Reef (after Bufarale et al., 2016).

R3 reflector. The low amplitude reflector R3 (Figure 4; depicted in pink in Figure 5) was detected only within Fraser Inlet, at a depth of about 65 mbsl. Since the bottom of this channel is relatively deep (~30 mbsl), the substrate that overlies this reflector is thinner than elsewhere, allowing deeper penetration of the acoustic signal. Seismic unit 3 (U3) is constrained between R2 and R3 and it is at least 20 m thick, with no recognisable internal architecture. Reflector R3 covers a deeper seismic unit, the lower limit of which cannot be detected within the acoustic profiles.

The forereef slopes are characterised by an irregular topography (Figure 5A) that likely represents pinnacle reefs, or perhaps linear ridges, rimming the reef platform. These features occur at various depths, typically rising from between 27 and12 mbsl. Most of these structures have an average relief of about 3 m and occur in small groups of three to five pinnacles/ridges. Larger pinnacles/ridges of up to 8 m in height occur in deeper water (>20 mbsl).

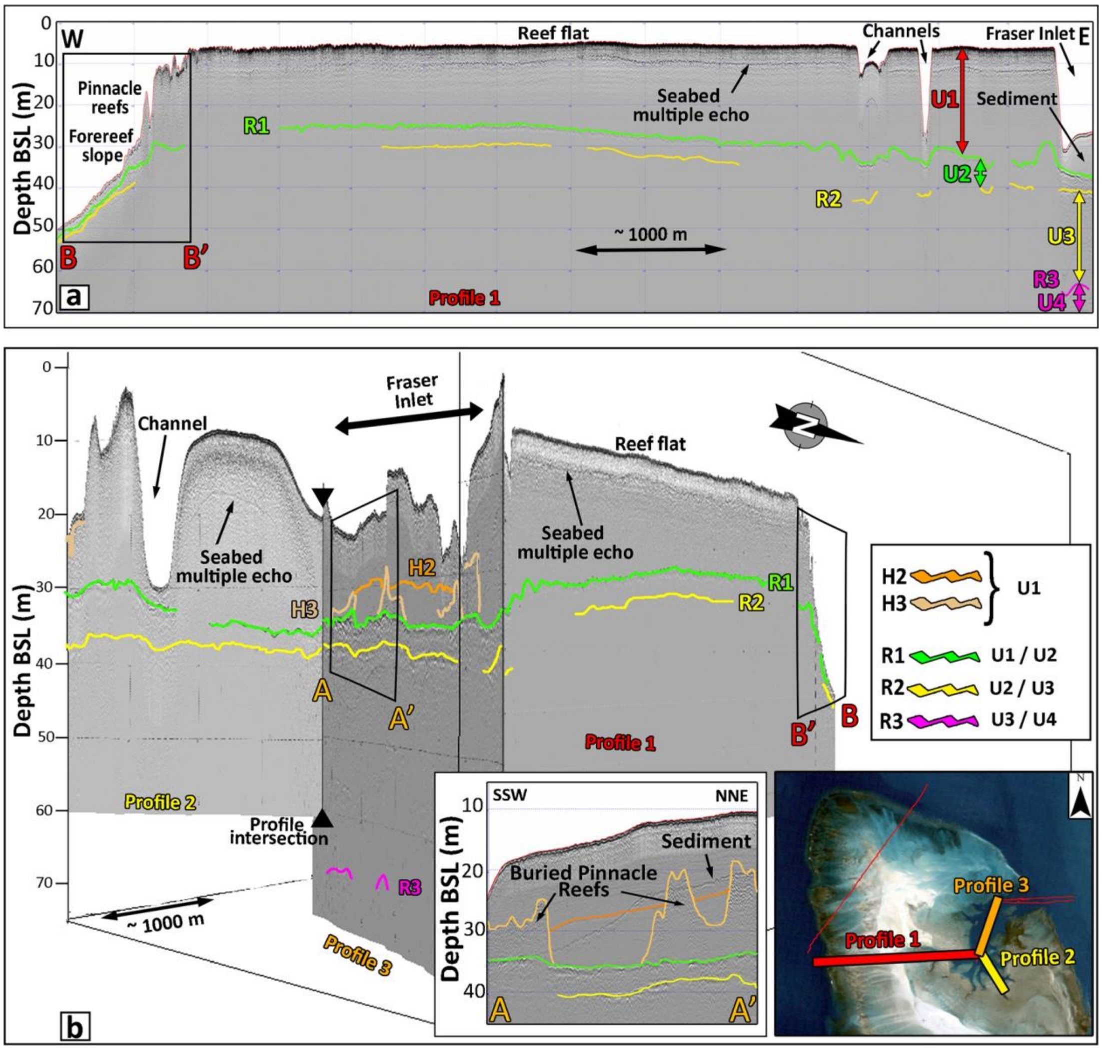


Figure 5. Cross-sections showing multiple stages of reef build-up (MIS 1, 5,7, 9 or 11 respectively). A) Profile 1, oriented W-E, intersects the northern portion of Adele Reef (modified after Collins et al., 2015). B) Profile 3 runs longitudinally through Fraser Inlet and profile 2 cuts the southern branch of the inlet. The Holocene reef is 25-35 m thick, with drowned pinnacle reefs on the western forereef slope. Along Fraser Inlet, a series of pinnacle reefs are buried within muddy sediments (left insert). The location of the profiles is shown in the insert at lower right.

Bathymetric and seismic profiles across the Adele group of platform reefs reveal a series of deeply incised channels separating the platforms. The channels are relatively broad (between 7 and 30 km) and are oriented in a north-south to northwest-southeast direction, aligning with the river channels along the mainland coast (Figure 6). The channel separating Adele and Churchill Reef platforms is around 6 km wide and more than 90 m deep. Based on seismic reflection data and the sediments collected with the pipe dredge, the base of this incised channel contains approximately 7 m of thinly bedded fine-grained sediments.

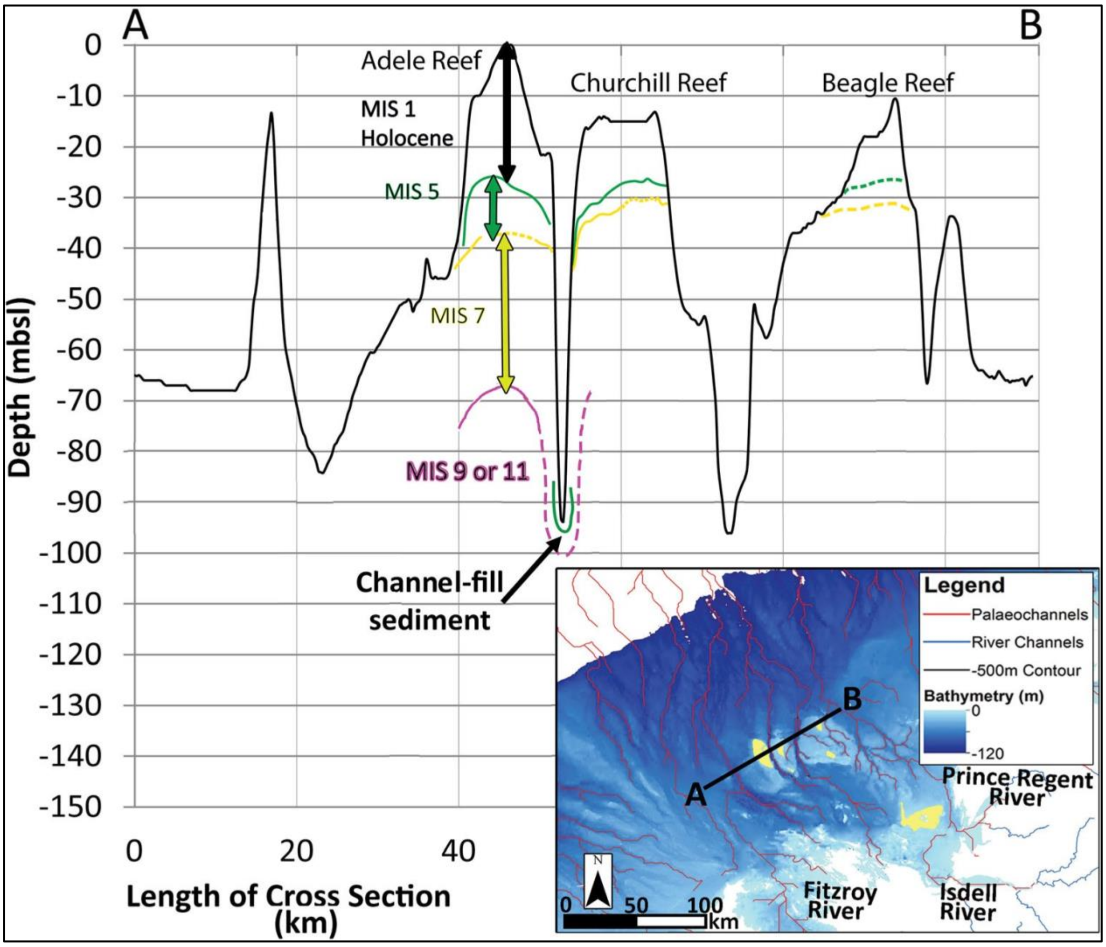
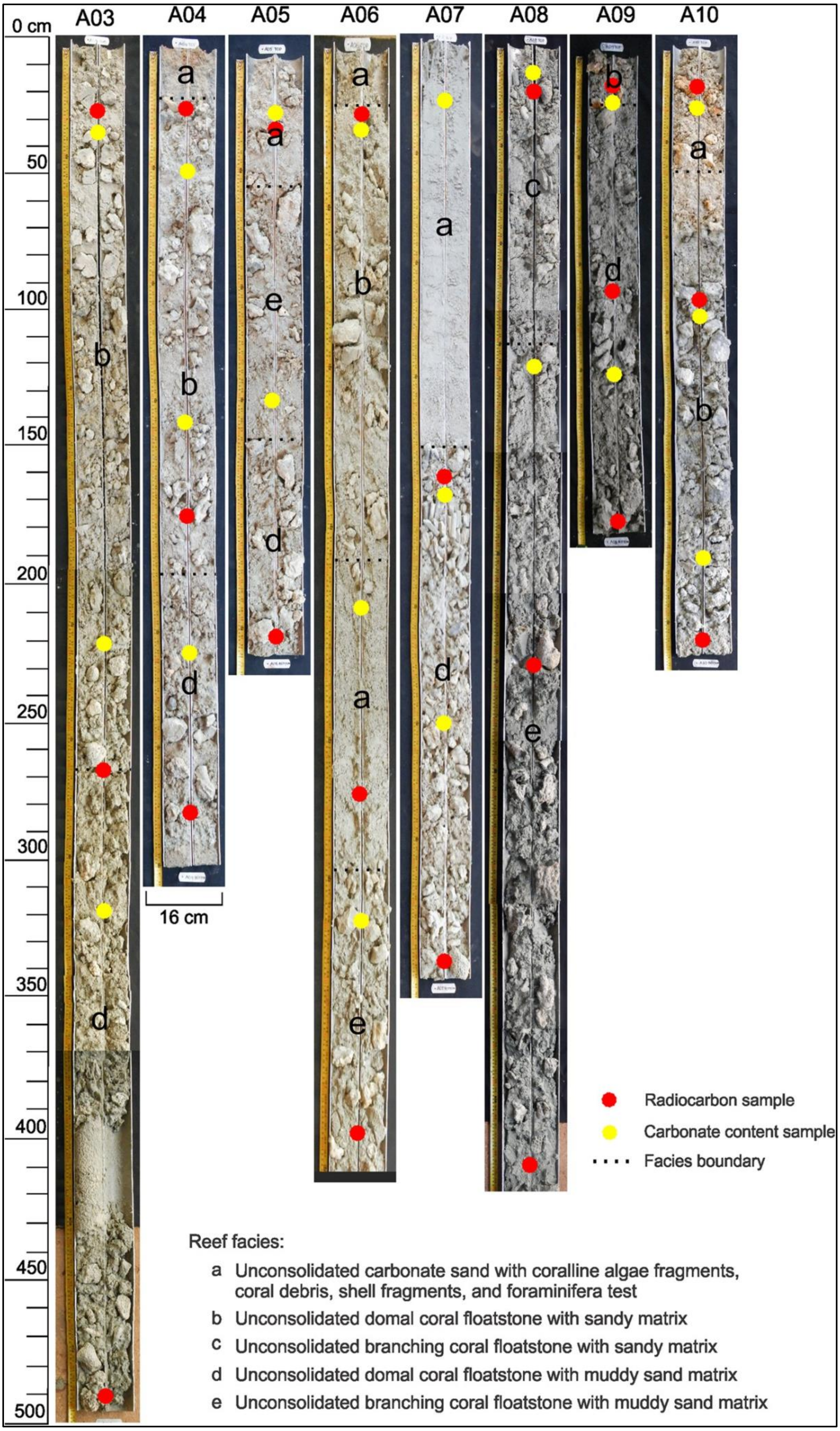


Figure 6. Bathymetric and seismic profile across Adele Reef and adjacent platforms (see inset for location). Bathymetry data were sourced from Geoscience Australia's 250 m DEM. Note the deep incisions between the platforms. Seismic units within the platforms are interpreted as stacked phases of reef accretion during sea-level highstands (MIS 1, 5, 7 and 9 or 11). Dashed lines are inferred.

Reef stratigraphy and geochronology

The eight percussion cores collected around Adele Reef com- prised five on the northwest and three on the southeast sides of the platform. Core penetration ranged from 1.84 to 5.06 m. The cored reef facies are primarily detrital; no reef framework was encountered and few colonies were unequivocally in growth position (Figure 7). However, the predominance of detrital facies is at least partly due to the selection of coring sites; coralline algal pavement was avoided because it could not be penetrated.

The coarser detrital clasts are predominantly coarse gravel to cobble-sized fragments of domal (dome-shaped) corals, with occasional branching coral fragments. Coral genera recorded include, in estimated order of abundance, *Favia*, *Goniopora*, *Porites*, *Galaxea*, *Acropora*, *Cyphastrea*, *Favites*, *Astreopora*, *Heliopora*, *Lobophyllia*, *Fungia* and *Pavona*. Matrix sediment is dominated by carbonate sand with an upward coarsening sequence from mud to coarse sand. The carbonate content ranges from 75% (A08) to 91% (A09), and generally increases up section. The non-carbonate materials are terrigenous mud and organics.



0 cm
A03
A04
A05
A06
A07
A08
A09
A10
50
100
150
200
250
300
350
400
450
500
16 cm
Radiocarbon sample
Carbonate content sample
Facies boundary
Reef facies:
a Unconsolidated carbonate sand with coralline algae fragments, coral debris, shell fragments, and foraminifera test
b Unconsolidated domal coral floatstone with sandy matrix
c Unconsolidated branching coral floatstone with sandy matrix
d Unconsolidated domal coral floatstone with muddy sand matrix
e Unconsolidated branching coral floatstone with muddy sand matrix

Figure 7 (previous page). Core photograph of Adele Reef showing representative Adele Reef facies where the cores were collected.

Twenty-two coral samples were collected from the cores for radiometric dating (Figure 8, Table 1). Due to the thick Holocene reef build-up (up to 30 m based on seismic data), the shallow reef coring (maximum core penetration of ~5 m) only penetrated the late Holocene. Therefore, the timing of reef initiation and the style and rates of reef aggradation over the full growth sequence is unknown. The oldest date, ~5,240-4,960 cal years BP, was obtained from the base of core A03 at 7 mbsl on the NW (seaward) side of the island. The reef sequence on the relatively sheltered SE side of the island is apparently younger, the oldest date there being ~3,155-2,940 cal years BP at 5 mbsl in core A08. At both sites, the reef accreted relatively rapidly (mean 4.2 and 3.3 mm/year respectively) until it attained present LAT level (Lowest Astronomical Tide) at approximately 4,000 cal years BP in core A03 and 2,000 cal years BP in core A08, and subsequently decelerated to approximately 1.0 and 2.0 mm/year respectively. Near-surface samples were dated to ~3,225-3,025 cal years BP at 2.9 mbsl in core A04 and ~360-245 cal years BP at 1 mbsl in core A08 (Figure 8, Table 1).

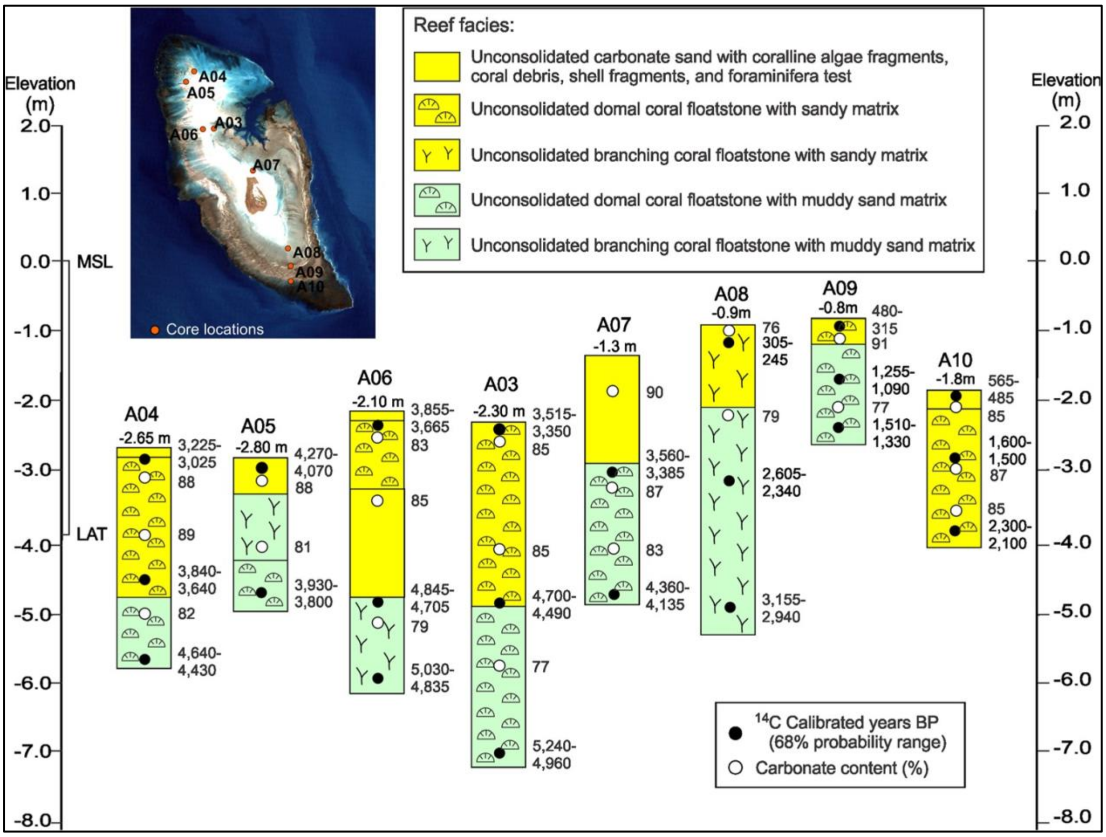


Figure 8. Lithostratigraphic and chronostratigraphic summary of Holocene reef facies for Adele Reef. The dominant facies was domal coral but the sections also contain fragments and colonies of branching coral.

Table 1. AMS Radiocarbon dates from selected samples across Adele Reef.

Sample code	Depth (mbsl)	Lab. code	Material	Measured age	$^{13}C/^{12}C$ (‰)	Conventional age (BP)	Calibrated (68% probability, cal yr BP)	Accretion (mm/year)
A03-43	−2.33	Beta-397758	*Favia*	3190±30	+0.3	3600 ±30	3515–3350	
A03-269	−4.59	Beta-397759	*Goniopora*	4100±30	−2.1	4480±30	4700–4490	1.94
A03-492	−6.82	Beta-397760	*Galaxea*	4500±30	−2.9	4860±30	5240–4960	4.42
A04-25	−2.75	Beta-425803	*Favia*	2930±30	+0.4	3350±30	3225–3025	
A04-175	−4.25	Beta-425791	*Acropora*	3490±30	−2.6	3860±30	3840–3640	0.4
A04-284	−5.34	Beta-425792	*Lobophyllia*	4040±30	−0.2	4450±30	4640–4430	1.3
A05-29	−2.89	Beta-425793	*Acropora*	3780±30	−1.2	4170±30	4270–4070	
A05-217	−4.77	Beta-425794	*Favites*	4270±30	+0.7	4690±30	4930–4800	2.7
A06-25	−2.25	Beta-425795	*Favid*	3460±30	+0.1	3870±30	3855–3665	
A06-278	−4.78	Beta-425796	*Acropora*	4210±30	+0.4	4630±30	4845–4705	2.5
A06-400	−6.00	Beta-425797	*Acropora*	4370±30	−1.1	4760±30	5030–4835	7.7
A07-180	−1.80	Beta-425798	*Lobophyllia*	3250±30	−1.0	3640±30	3560–3385	
A07-341	−3.41	Beta-425799	*Favia*	3820±30	−0.5	4220±30	4360–4135	2.1
A08-18	−1.68	Beta-397761	*Favia*	250±30	+2.5	700±30	360–245	
A08-226	−3.76	Beta-397762	*Lobophyllia*	2450±30	−3.8	2800±30	2605–2340	0.9
A08-416	−5.66	Beta-397763	Coralline algae	2880±30	−0.3	3290±30	3155–2940	3.3
A09-26	−2.36	Beta-425800	*Chypastrea*	440±30	−1.4	830±30	480–315	
A09-100	−3.10	Beta-425801	Coralline algae	1240±30	+1.0	1670±30	1255–1090	0.9
A09-177	−3.87	Beta-425802	*Porites*	1530±30	−0.4	1930±30	1510–1330	3.1
A10-14	−2.84	Beta-425804	*Rhodoliths*	580±30	−0.5	980±30	565–485	
A10-128	−3.98	Beta-425806	*Porites*	1650±30	−0.3	2060±30	1655–1500	1.1
A10-211	−4.81	Beta-425805	*Galaxea*	2190±30	−0.8	2590±30	2300–2110	1.3
A03-43	−2.33	Beta-397758	*Favia*	3190± 30	+0.3	3600±30	3515–3350	
A03-269	−4.59	Beta-397759	*Goniopora*	4100±30	−2.1	4480±30	4700–4490	1.94
A03-492	−6.82	Beta-397760	*Galaxea*	4500±30	−2.9	4860±30	5240–4960	4.42
A04-25	−2.75	Beta-425803	*Favia*	2930±30	+0.4	3350±30	3225–3025	
A04-175	−4.25	Beta-425791	*Acropora*	3490±30	−2.6	3860±30	3840–3640	0.4

Discussion

Reef stratigraphy and sea-level changes

Seismic surveys across Adele Reef reveal multiple stacked seismic units that likely represent distinct phases of reef accretion during sea-level highstands. The seafloor and seismic reflectors R1, R2 and R3 correspond to the top of each seismic unit. Although it is not possible to establish the age of each seismic unit due to the limitations in core penetration (max. depth 5 m), the age can be inferred based on a comparison with seismic, stratigraphic and chronological data from the outer-shelf Scott Reefs, 200 km NW of Adele Reef (Collins et al., 2011), and the inner-shelf Kimberley reefs 70 km SW of Adele Reef (Solihuddin et al., 2015).

Reflector R1, identified at a depth of 25-35 mbsl on Adele Reef (Figure 5), was also recorded on the inner shelf of Cockatoo Island and the shelf-edge Scott Reefs (see Figure 1 for location). On Cockatoo Island, an open cut iron ore pit has exposed a complete Holocene section, allowing the R1 reflector to be directly correlated with the logged stratigraphic contact. Solihuddin et al. (2015) found that the depth of the R1 reflector at 15 to 20 mbsl corresponded closely with the Holocene/Last Interglacial (LIG) stratigraphic contact in the mine pit, measured at 15 to 18 mbsl. At Scott Reefs, the R1 reflector occurs from 26 mbsl (interpreted as a palaeoreef crest; Collins et al., 2011), a similar depth to Adele, down to 58 mbsl (interpreted as a palaeoreef lagoon; Collins et al., 2011). Shallow boreholes made by Woodside Energy Ltd in 2006/07, and analysed by Collins et al. (2011), found that the Scott Reefs Holocene sequence rested unconformably on a karstified LIG reef exposure surface. U-series analysis of corals beneath the R1 reflector at Scott Reefs returned ages of 125,000 and 130,000 cal years BP. Therefore, it is inferred that R1 on Adele Reef also marks the LIG unconformity surface, and seismic unit U1 is a Holocene reef sequence up to 30 m thick.

Reflector R2 occurs at a depth of 30-40 mbsl on Adele Reef. A similar second reflector was identified on Scott Reefs at a depth of 58 m, and was interpreted as a marine isotope stage (MIS) 7 exposure surface, based on a U-series age of 208,000 cal years BP (Collins et al., 2011). Based on the Scott Reefs observations, R2 at Adele Reef is also interpreted as representing the MIS 7 exposure surface. R2 was not observed in any of the inner shelf seismic surveys (Bufarale et al., 2016) or in the mine pit stratigraphic section of Cockatoo Island (Solihuddin et al., 2015), perhaps indicating that this area remained above sea level during MIS 7.

Reflector R3 is the lowermost unconformity at 65 mbsl (Figure 5). R3 was only observed along seismic lines within the 30 m deep Fraser Inlet. Its apparent absence along the main Adele Reef platform may be due to energy loss with increasing depth, i.e. R3 may be more extensive but not detected. The Adele Island 1 stratigraphic log shows limestone to a depth of 160 mbsl, so it is likely that R3 is a middle to late Pleistocene unconformity surface. It may correlate to the third stratigraphic unconformity at 90 mbsl in Scott Reefs (Collins et al., 2011). A coral sample immediately below this unconformity returned a U-series age of 313,000 cal years BP (Collins et al., 2011), suggesting that the R3 reflector at Scott Reefs, and potentially also at Adele Reef, is the MIS 9 exposure surface.

Fraser Inlet presently has a broad flat sandy mud floor; however, seismic profiling along and across the axis of the channel reveals a buried complex of pinnacle reefs. The pinnacle reefs are considered to be of early Holocene age as they sit atop the R1 reflector. Sedimentation was probably minimal during the early-middle Holocene catch-up phase; however, as the reef platform reached sea level around 3,000 years BP, sediment delivery into Fraser Inlet probably increased, eventually burying the pinnacles.

There is evidence of cross-shelf fluvial incision as seen in a series of deep channels that dissect the main platforms of Adele, Churchill and Beagle reefs. The channel floors have depths of more than 65 mbsl and likely represent glacial lowstand palaeoriver channels, possibly tributaries of the Fitzroy, Isdell and Prince Regent rivers (Figure 6).

Mode of Holocene growth

The early to mid-Holocene history of Adele Reef remains unknown due to the limited core penetration. Holocene sea level reconstructions (Collins et al., 2006, 2011) suggest that the subaerial LIG surface of Adele Reef would have been transgressed at ~10,000 years BP. Subsequent colonisation and accretion was relatively rapid, as the reef was already up to 20 m thick at the time of the earliest core dates (~5,000 years BP). The internal seismic structure of the Holocene reef appears uniform, consistent with simple vertical aggradation of an extensive low-relief cover of coral and sediment, as inferred for Cockatoo Island where the complete Holocene section was sampled (Solihuddin et al., 2015). Adele Reef at this time may have resembled the coral-rich submerged banks re- ported from the Timor Sea by Heyward et al., (1997). The flanks of the platform are topographically complex and appear to be slowly prograding through pinnacle reef growth and platform-derived sedimentation.

The cores indicate a 'catch-up' growth pattern in the late Holocene, with the reef surface being approximately 5-10 m deep when sea level stabilised at its present elevation 6,500 years BP (Collins et al., 2006). The 'catch-up' pattern on Adele Reef coincides with a 'catch-up' phase from 5,500 years BP at Cockatoo Island, after a short initial period of 'keep-up' growth followed by deeper submergence (Solihuddin et al., 2015). Accretion slowed as Adele Reef reached the intertidal zone, probably due to increasing wave energy and periodic emergence at spring low tides, as inferred for Scott Reefs (Collins et al., 2011). The central and northern parts of the platform reached sea level around 3,000 years BP, whereas the southern part of the platform reached sea level only very recently.

Comparison with other reef systems

The Kimberley Bioregion has abundant inner-shelf fringing reefs but relatively few mid- and outer-shelf reefs. This contrasts with the Great Barrier Reef (GBR), which has more mid- and outer-shelf reefs than inner-shelf reefs. The Kimberley and the GBR reefs also differ in that the Kimberley reefs are generally flat-topped platforms (Brooke 1997; Wilson 2013; Kordi et al., 2016) whereas most GBR reefs have a raised marginal rim surrounding a deeper lagoon (Maxwell 1968; Hopley et al., 2007).

Adele Reef differs from the inshore Buccaneer Archipelago in its relatively exposed oceanic setting, smaller tidal range (7 vs. 11 m), deeper surrounding bathymetry, lower freshwater input and lower turbidity. These contrasts result in obvious differences in the surface features of Adele, including the presence of a sand cay and the absence of mangroves. However, there are also similarities between the mid-shelf and inshore reefs, particularly the abundance of coralline algae and the development of coralline algal ridges, although these consist largely of uncemented rhodoliths on Adele whereas they are often strongly cemented framework structures on the inshore platform (Richards and O'Leary 2015; Solihuddin et al., 2016).

Subsurface facies of Adele Reef differ from those inshore, consisting predominantly of matrix-supported transported domal coral fragments and sand at Adele versus in-situ branching Acropora-rich muddy units inshore (Solihuddin et al., 2015, 2016). This difference is probably due to the greater exposure of Adele to wave action and cyclones. Reef accretion patterns and rates appear broadly similar between Adele and the inshore reefs, with 'catch-up' growth predominating at both sites and accretion rates averaging <5 mm/year, although some more rapid intervals (up to 27 mm/year) were recorded in the intensively sampled Cockatoo Island sequence (Solihuddin et al., 2015).

Cross-shelf profile of Holocene reef accretion

Figure 9 portrays a schematic cross-shelf profile of Holocene reef accretion from Cockatoo Island (inner shelf) to Adele Reef (mid-shelf) and Scott Reefs on the edge of the continental shelf (outer shelf). Stratigraphic data from Cockatoo Island and other inner-shelf reefs suggest that the LIG reef beneath the Holocene reef is 15 to 20 mbsl, corresponding to a maximum subsidence rate of 0.12 mm/year (Solihuddin et al., 2015). Collins et al., (2011) reported the upper LIG reef surface of 26 m Scott Reefs, estimating the post-LIG subsidence rate of Scott Reefs to be ~0.2 mm/year. Similarly, seismic profiles at Adele Reef indicate that the upper LIG reef surface is 25 mbsl (Figure 5), giving an inferred subsidence rate of ~0.2 mm/year. So while the subsidence of the NW is well documented, particularly in the petroleum well (Ingram, 1982; Marshall, 1995) and seismic data (Bufarale et al., 2016), this study is able to constrain rates based on the elevation of the Holocene/LIG unconformity surface.

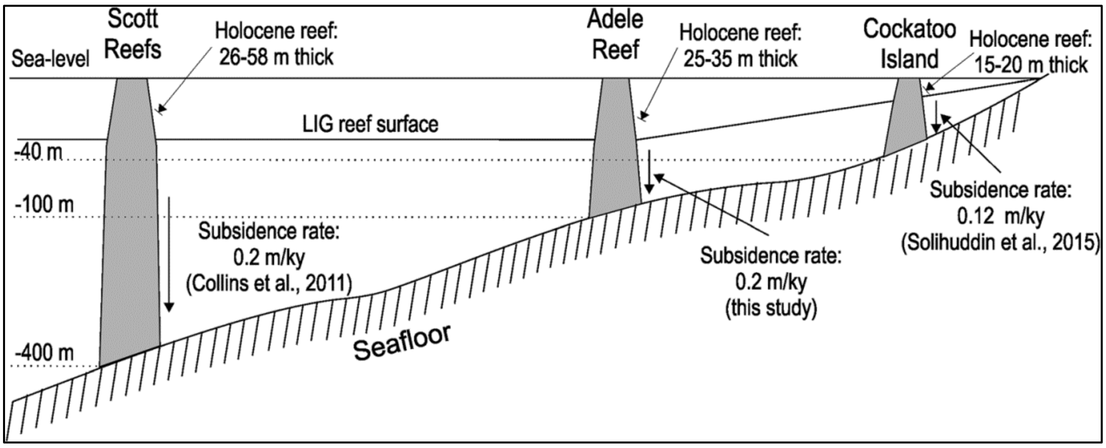


Figure 9. Diagrammatic cross-shelf profile of Holocene reef growth from Cockatoo Island on the inner shelf to Adele Reef on the mid- shelf and Scott Reefs on the outer shelf, showing estimated post- LIG subsidence rates of 0.12 mm/ year at Cockatoo Island, 0.2 mm/ year at Adele Reef and 0.2 mm/ year at Scott Reefs.

This cross-shelf dataset of LIG reef elevations provides the first quantitative estimate of neotectonic subsidence rates across the NW shelf of Australia, spanning the last 120,000 years. Interestingly, subsidence appears to change at a relatively uniform rate of 0.2 m across the mid to outer shelf, with a lower rate of 0.12 along the inner shelf. This difference may be a function of the underlying structural geology bordering the Proterozoic Kimberley basement rocks, and the offshore Browse Basin sediments on which both the Adele and Scott reefs are situated. The higher rate of subsidence across the middle and outer shelf relative to the inner shelf has provided additional accommodation space to build thicker Holocene sequences, as has been recorded on the GBR (Browne et al., 2012).

Conclusions

This is the first investigation of the Holocene geomorphology and accretion history of a mid-shelf platform reef of the Kimberley Bioregion. Sub-bottom profiles of Adele Reef show at least three stages of reef accretion bounded by reflectors. The shallowest reflector at 25-35 mbsl is interpreted as the Holocene/LIG (MIS 5) contact. Deeper reflectors are interpreted as boundaries between MIS 5 and MIS 7 at depths of 30-40 mbsl, and between MIS 7 and MIS 9 at 65 mbsl.

The Holocene sequence is up to 30 m thick. Cores from the uppermost 5 m of the sequence indicate that the reef accreted in a 'catch-up' mode, with accretion rates decreasing as the reef platform approached sea level. The cores were dominated by detrital domal coral colonies and fragments in a sandy matrix, in contrast with the in-situ branching Acropora and mud-rich subsurface facies of inshore reefs. These differences likely reflect Adele's higher-energy setting and greater exposure to cyclones. Coralline algae are a significant component of the contemporary intertidal and shallow subtidal reef sur- face but were underrepresented in the cores due to the difficulty of percussion coring in this habitat.

The mean post-LIG subsidence rate of the Adele Reef platform was estimated from seismic records to be 0.2 mm/year. This supports a hinge subsidence hypothesis for the Kimberley coast and adjacent shelf, with greater subsidence on the outer shelf (Scott Reefs) and mid-shelf (Adele Reef) than inshore (Cockatoo Island).

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Compliance with ethical standards

Conflict of interest. The authors declare that there is no conflict of interest with third parties.

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