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# Development of an inshore fringing coral reef using textural, compositional and stratigraphic data from Magnetic Island, Great Barrier Reef, Australia

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ABSTRACT

The stratigraphy of fringing coral reef environments and platforms provides unique insights into reef development and evolution. This study used twelve sediment cores from three transects across a reef flat in Nelly Bay, Magnetic Island (NE Australia), to examine its development over the Holocene. The maximum thickness of the Holocene reefal material based on seismic and bore log data was around 5 m and comparable to other fringing reefs in the Great Barrier Reef (GBR). Six different sedimentary facies were identified in the cores and two coincided with reef accretion: the lower muddy sand with coral rubble and the upper siliciclastic sand with coral rubble. Radiocarbon and U-series dates show that the Nelly Bay fringing reef initiated around 6300 yr BP on a gently sloping, unconsolidated or weakly cemented Pleistocene alluvial sedimentary facies. The ages of four massive coral heads (range between 5790 and 6290 calibrated C-14 yr BP) were almost contemporaneous with reefal initiation indicating that conditions were favourable for reef growth around this time. Vertical accretion rates for the Nelly Bay fringing reef were, on average about 0.5 mm/yr over the last 6000 yr, although rates were as high as 5 mm/yr during initiation. Average lateral accretion rates varied from 98 to 120 mm/yr, which are comparable to rates of other fringing reefs in the region. The age structure of the lower muddy sedimentary facies was consistent with the classic seaward prograding model of fringing reef development. In contrast, the upper siliciclastic sand with coral rubble facies was much younger in age (<1100 yr BP) than the models and appears to represent an erosional unconformity between the upper and lower reefal facies possibly linked to late Holocene sea-level fall. This younger facies extends laterally across the reef flat and has no obvious prograding symmetry. Our integrated approach, using multi-proxy analyses of sediment cores from the Nelly Bay reef flat, highlights the complex development of this reef which include changes in coral composition and rubble preservation, reef evolution in response to sea-level change and changes in reef accretion rates.



## 1. Introduction

Our understanding of initiation and development of fringing coral reefs during the Holocene has increased considerably over the last 30 yr particularly on the Great Barrier Reef (GBR) of Australia (see Kennedy and Woodroffe, 2002; Smithers et al., 2006; Hopley et al., 2007; Montaggioni and Braithwaite, 2009). In particular new investigations and improved dating methods have led to more detailed reef models where the complexities of the internal reef structure are better outlined (Smithers et al., 2006; Hopley et al., 2007; Perry and Smithers, 2011; Roche et al., 2011). Understanding the evolution of fringing and nearshore coral reefs in response to sea-level and environmental changes provide an important, long-term perspective of coral reef development as well as establishing a context for predicting the response of inshore coral reefs to future changes.

Most environmental studies of reef and coral health over the past 40 yr have focused on changes in coral coverage, water composition and fish abundance. Recent declines in coral cover, diversity and health in the GBR (Fabricius and De'ath, 2001; Bellwood et al., 2004; Fabricius et al., 2005; DeVantier et al., 2006; Hughes et al., 2011; Sweatman et al., 2011) have been linked to increased exposure to

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terrestrial runoff (McCulloch et al., 2003; Lewis et al., 2007, 2009), declining water quality (Fabricius et al., 2005), over-fishing (Pandolfi et al., 2003), more frequent crown of thorns starfish outbreaks (Brodie et al., 2005; Fabricius et al., 2010) and coral bleaching events (Berkelmans et al., 2004). However, the sparse long-term geomorphological and stratigraphic evidence from fringing reefs in the GBR shows that many reefs have ceased accreting or have 'turned off' over the last few thousand years, long before Europeans arrived (Smithers et al., 2006; Hopley et al., 2007; Perry and Smithers, 2010, 2011). This finding has implications for the interpretation of the current condition of fringing reefs and highlights the potential difficulties of separating changes caused by natural or anthropogenic factors.

Nelly Bay on Magnetic Island in northeastern Queensland, Australia (Fig. 1), is an ideal site to study the development of fringing reefs in the GBR. The fringing reefs on the south-eastern side of Magnetic Island are among the few known fringing reefs in the GBR still laterally accreting (Smithers et al., 2006) and have developed and evolved through markedly turbid water conditions. In Geoffrey Bay (Fig. 1A), for example, suspended sediment concentrations around the fringing reef may reach 20 mg/L for >24 h (Larcombe et al., 1995). Nearshore incipient reefs in the vicinity of Townsville, such as the Paluma Shoals, experience even higher turbidity levels (Larcombe et al., 2001). However, these turbid reef ecosystems originated much later ~1200 to 1500 yr ago (Smithers and Larcombe, 2003; Perry and Smithers, 2006; Perry et al., 2008) compared to the fringing reefs around Queensland's offshore islands (e.g. Palm Island Group, Rattlesnake Island, Cumberland Island Group) that initiated during the mid-Holocene (~6–8 ka) (Hopley et al., 1983; Kleypas, 1996; Smithers et al., 2006).

This contribution seeks to understand the initiation, structure, and evolution of the fringing reef off Nelly Bay using multi-proxy geochemical, sedimentological and taxonomical analyses of radiocarbon-dated sediment cores from three transects across the reef flat. We show that this novel approach provides key insights into reef development that allows for a detailed palaeo-environmental reconstruction of fringing reef evolution and possible disturbance regimes over the Holocene. Moreover, we re-examine the reliability of dating different carbonate materials (coral and shell fragments) to obtain robust age constraints on the stratigraphy of fringing coral reefs. We present our interpretations in the form of a stratigraphic model which outlines the development of the Nelly Bay fringing reef in the context of the latest sea-level reconstructions for the GBR (Lewis et al., 2008; Woodroffe, 2009). The incorporation of the latest and calibrated sea level data into our analysis shows that late Holocene sea-level changes may have considerably influenced the development and evolution of the Nelly Bay reef as well as other fringing reefs across the broader GBR.

## 2. Regional setting

Magnetic Island is an inshore continental island (52 $km^2$) of the GBR located about 8 km offshore from Townsville, in NE Queensland, Australia (Fig. 1). It is situated in the north-western part of the shallow (< 10 m), north-facing Cleveland Bay which is largely protected from the south-easterly trade winds that dominate the dry season from April to November. The Ross and Burdekin Rivers are the main contributors of terrigenous sediment into Cleveland Bay (Carter et al., 1993; Orpin et al., 2004; Lambrechts et al., 2010) and during flood periods salinity conditions vary markedly in the waters off Magnetic Island/Cleveland Bay (Walker, 1981; King et al., 2001). The sandy coastlines of the small pocket beaches on Magnetic Island are largely replenished from local catchments draining the adjacent headlands (Hopley, 1986), although at least some of the fine sediment fraction (mud size) deposited within the reef flats/slopes is derived from the Ross and/or Burdekin Rivers (Lewis, 2005). Negligible sediment transport occurs within the Magnetic Island embayments except during high energy storms or tropical cyclones. Aerial photographs show that Nelly Bay has been highly stable with little geomorphological change over the past 50 yr (Hopley, 1986).

Magnetic Island hosts several fringing reefs that contain a diverse (over 100 species) range of corals which exist in varying levels of wind and wave exposure, ranging from highly protected to moderately exposed sites (Collins, 1987). Some of the best developed reefs of Magnetic Island occur on the windward south-eastern side off Nelly and Geoffrey Bays (reef areas of 43 and 31 ha, respectively) which have sizable reef flats up to ~500 m wide (Collins, 1987) (Fig. 1). These "bayhead" fringing reefs have been examined by

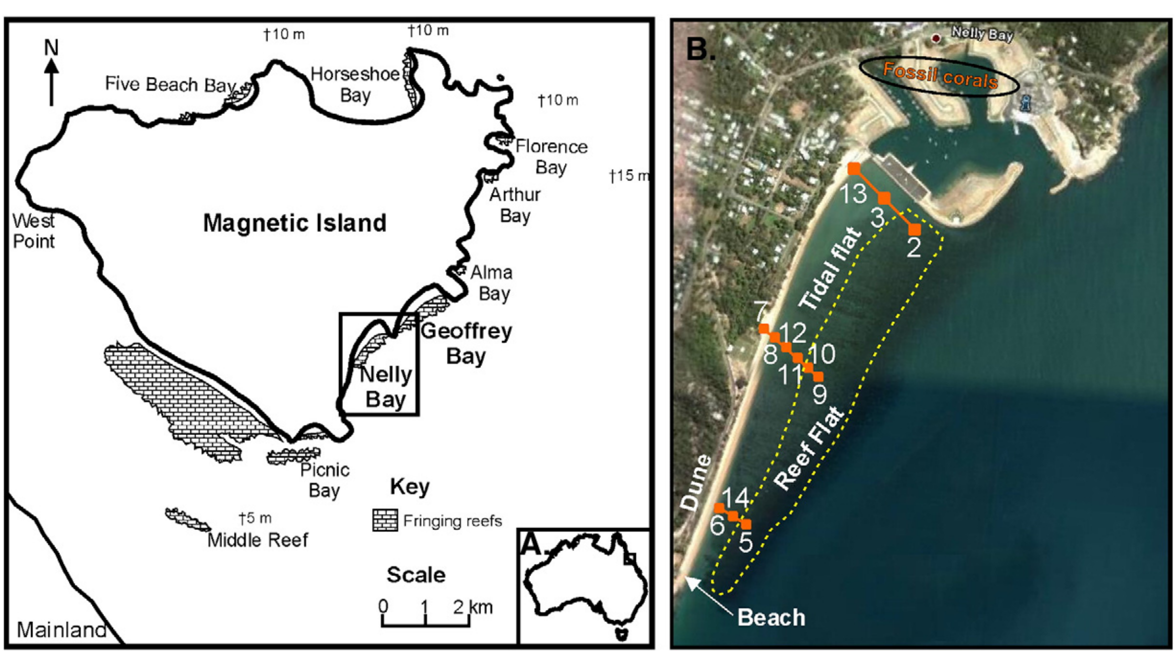


**Fig. 1.** Map of the fringing reefs of Magnetic Island. Note the well developed fringing reefs of Nelly and Geoffrey Bays. Magnetic Island is located in north Queensland, Australia (inset A). The sediment coring locations are shown in inset B. Selected bathymetry points around Magnetic Island are marked. Note Nelly Bay Harbour in inset B shows the approximate location where the fossil *Porites* corals were recovered.

**Table 1**
Sediment cores from Nelly Bay: core length, penetration and % compaction.

| Core | Core length (cm) | Penetration (cm) | Compaction (%) |
|---|---|---|---|
| 2 | 127 | 260 | 51% |
| 3 | 56 | 281 | 80% |
| 5 | 0 | 0 | N/A |
| 6 | 95 | 230 | 59% |
| 7 | 83 | 93 | 11% |
| 8 | 110 | 177 | 38% |
| 9 | 24 | 30 | 20% |
| 10 | 93 | 274 | 66% |
| 11 | 45 | 140 | 68% |
| 12 | 67 | 124 | 46% |
| 13 | 200 | 300 | 33% |
| 14 | 32 | 50 | 36% |

several researchers, although published studies are restricted mainly to the surficial deposits on these reef flats. Smith (1978) identified three major geomorphological zones in Nelly Bay, including the upper beach, the lower beach and the reef flat, each with its own sedimentary characteristics. Chappell et al. (1983) dated seven fossil coral microatolls found on the reef flat in Geoffrey Bay as part of a regional study to investigate the sea-level history of the GBR. The age of these microatolls ranged between 6150 and 410 calibrated yr BP from inshore to offshore sites on the reef flat. These data show that the Geoffrey Bay reef is among the few known fringing reefs still laterally accreting in the GBR (Smithers et al., 2006).

The internal structure of the fringing reef in Geoffrey Bay was examined by jet probes that revealed that the reef flat is largely comprised of sand and coral shingle with, potentially, a buried reef ridge near the current reef front running parallel to the shoreline (Hopley et al., 1983). This ridge may have provided the foundation structure for the present reef. A similar feature was also discovered in Nelly Bay (Hopley, 1986), although unpublished seismic surveys in the embayment have failed to reveal this "structure" (Carter and Johnson, 1989; Sinclair Knight Merz, 1998). Seismic surveys of Nelly Bay clearly depict the Pleistocene–Holocene boundary ('Reflector A') at ~4 to 5 m below the surface sediments whilst another strong reflector, between 10 and 13 m depth, was interpreted as granitic basement (Carter and Johnson, 1989; Sinclair Knight Merz, 1998). Coring for the Nelly Bay Harbour construction identified the Pleistocene–Holocene boundary at between 2 and 5.5 m below the surface across the Nelly Bay reef flat (McIntyre and Associates, 1986, 1989; Golder Associates, 2000).

## 3. Materials and methods

### 3.1. Sediment core location and collection

Topographic profiles were performed along three transects in Nelly Bay where 14 percussion cores were taken (Fig. 1B). The surveys were corrected to mean Australian sea-level height datum for Magnetic Island (AHD = +1.91 m above lowest astronomical spring tide) using the previous high tide mark as well as the tidal level at the time of the survey. Along these transects, the key morphological zones as identified by Smith (1978) were noted. These included dune, beach, tidal flat and reef flat facies each of which has specific characteristics which are described in our study.

Up to four metre long aluminium pipes (7.5 cm diameter) were driven into the ground surface along our three transects using a star-picket driver. The cores were winched to the surface with a tripod. Typical penetration was approximately 2 m with a maximum of 3 m for core 13. The amount of sediment compaction in the coring process ranged between 11% and 80% with a median of 40% (Table 1). Each core was corrected to account for the total penetration assuming uniform compaction rates throughout the core.

### 3.2. Sediment core texture and composition

Six sedimentary facies were identified within the cores based on a visual analysis on the amount of coral rubble preserved, the particle size composition of the matrix and the amount of carbonate versus terrigenous material. This approach allowed the facies to be correlated between cores and sample intervals for more quantitative investigations to be identified.

Particle size analysis of 54 samples evenly distributed throughout six selected cores (representing the best recovery) was conducted using a *Malvern Mastersizer 2000* to characterise the texture of the sedimentary facies within Nelly Bay throughout the Holocene. The coarse (>2 mm) fraction was sieved out and these particles were described visually. Each sample was analysed at least twice and a mean was taken. The results were grouped into the Wentworth classes of sand (63–2000 μm), silt (4–63 μm), and clay (<4 μm).

The mineralogical composition of six samples from core 13 were analysed to examine the proportions of terrigenous to carbonate sediments. These samples were analysed using a *Siemens D5000* powder X-ray Diffractometer (XRD) at the Advanced Analytical Centre at James Cook University. Samples were taken at increments of 5 cm, 54 cm, 140 cm, 159 cm, 263 cm and 293 cm from the top of the core (compaction corrected). The samples were pulverised in a zirconium mill and mixed to a paste with water, smeared onto a glass disc and analysed (3–70° 2Theta). Mineralogical phases were identified using the Eva© software and quantitative Rietveld phase analysis was undertaken using SIROQUANT© V. 2.0 (see Taylor, 1991; Webb et al., 2003). Total carbon contents were also determined on 27 samples using an *Elementar VarioMax* CNS Analyser to similarly determine the proportions of terrigenous to carbonate sediments. The $CaCO_3$ contents of the samples were calculated using the obtained C total (assuming the organic C fraction to be minimal).

The composition of coral rubble assemblages in cores 2, 3, 6, 8, 10 and 13 were identified to examine changes in reef structure and development over the Holocene. The rubble composition description included information on fragment size, coral genus, preservation status of fragments (level of abrasion, bio-erosion, discoloration etc.) and the characteristics of the coralline algae crusts that coated some fragments. Based on this information, six different assemblages were established (Fig. 2). These include Acropora Group 1 which was composed of moderate- to well-preserved delicate (<1 cm diameter) branching *Acropora* with some branching Pocilloporid (*Seriatopora* sp.) fragments; Acropora Group 2 consisted of larger (>1.5 cm diameter) staghorn *Acropora* fragments with coral pieces containing partial covers of crustose coralline algae; Acropora Group 1.5 was a mix of Groups 1 and 2; Acropora Group 3 contained dense coral fragments of single and multiple branching bifurcating and markedly abraded *Acropora* and Acroporid fragments. These fragments were coated with thick crusts of crustose coralline algae and several corals also had dark coatings of unknown origin. Many fragments were heavily bio-eroded, coated by fruitocose coralline algae and formed well-developed coralgal nodules; Montipora Group 1 was characterised by plate-like *Montipora* sp. and moderately to heavily abraded *Acropora* fragments which commonly contained coralline algal crusts; Porites Group 1 contained *Porites* and some fragments from the Mussid Family and all coral fragments were abraded; Pavona Group 1 contained well-preserved foliose agaricid fragments of *Pavona* sp.

**Fig. 2.** Sedimentological analyses on six selected cores from Nelly Bay including C-14 ages, particle size, carbonate content and coral rubble assemblages. The legend for the core facies is provided in Fig. 3.

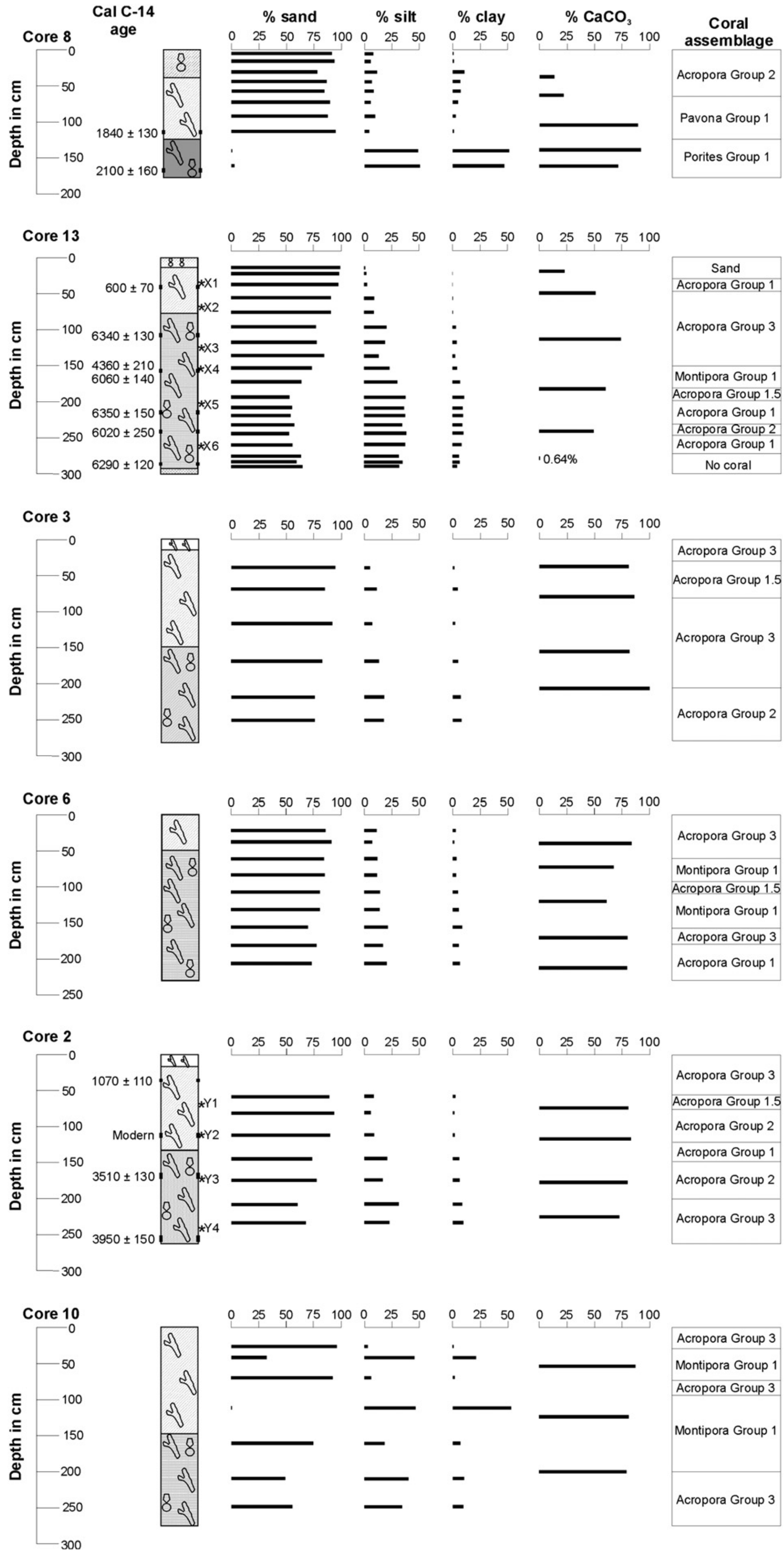
Core 8
Cal C-14 age
% sand
% silt
% clay
% CaCO3
Coral assemblage
Depth in cm
1840 ± 130
2100 ± 160
Acropora Group 2
Pavona Group 1
Porites Group 1
Core 13
600 ± 70
6340 ± 130
4360 ± 210
6060 ± 140
6350 ± 150
6020 ± 250
6290 ± 120
X1
X2
X3
X4
X5
X6
0.64%
Sand
Acropora Group 1
Acropora Group 3
Montipora Group 1
Acropora Group 1.5
Acropora Group 1
Acropora Group 2
Acropora Group 1
No coral
Core 3
Acropora Group 3
Acropora Group 1.5
Acropora Group 3
Acropora Group 2
Core 6
Acropora Group 3
Montipora Group 1
Acropora Group 1.5
Montipora Group 1
Acropora Group 3
Acropora Group 1
Core 2
1070 ± 110
Modern
3510 ± 130
3950 ± 150
Y1
Y2
Y3
Y4
Acropora Group 3
Acropora Group 1.5
Acropora Group 2
Acropora Group 1
Acropora Group 2
Acropora Group 3
Core 10
Acropora Group 3
Montipora Group 1
Acropora Group 3
Montipora Group 1
Acropora Group 3

**Table 2**
Dates of the fossil *Porites* corals and from the sediment cores taken in Nelly Bay.

| Lab code | Material | Location | Sedimentary facies | Method | Uncorrected age | ± | Calibrated (C-14) or Corrected (U–Th) age | ± |
|---|---|---|---|---|---|---|---|---|
| ANU-11580 | Coral head | Outer layer NEL-07 | – | Conventional 14-C | 5630 | 90 | 6040 | 210 |
| ANU-11581 | Coral head | Outer layer NEL-08 | – | Conventional 14-C | 5620 | 90 | 6010 | 220 |
| OZH-574 | Coral head | Basal layer NEL-03 | – | AMS 14-C | 5870 | 50 | 6280 | 110 |
| OZH-575 | Coral head | Outer layer NEL-03 | – | AMS 14-C | 5740 | 60 | 6130 | 140 |
| | Coral head | Basal layer NEL-03 | – | TIMS U–Th | 6210 | 30 | 6180 | 40 |
| | Coral head | Outer layer NEL-03 | – | TIMS U–Th | 6200 | 60 | 6060 | 90 |
| | Coral head | Basal layer NEL-01 | – | TIMS U–Th | 6100 | 40 | 6090 | 40 |
| | Coral head | Outer layer NEL-01 | – | TIMS U–Th | 5830 | 20 | 5790 | 30 |
| OZH-561 | Shell | Core 13 (0.41–0.45 m) | Silic. sand w/coral rubb. | AMS 14-C | 1040 | 40 | 600 | 70 |
| OZH-562 | Shell | Core 13 (1.08–1.14 m) | Muddy sand w/coral rubb. | AMS 14-C | 5930 | 60 | 6340 | 130 |
| OZH-563 | Shell | Core 13 (1.61–1.67 m) | Muddy sand w/coral rubb. | AMS 14-C | 4280 | 70 | 4360 | 210 |
| OZH-564 | Coral | Core 13 (1.61–1.67 m) | Muddy sand w/coral rubb. | AMS 14-C | 5670 | 60 | 6060 | 140 |
| OZH-565 | Shell | Core 13 (2.19–2.25 m) | Muddy sand w/coral rubb. | AMS 14-C | 5940 | 70 | 6350 | 150 |
| OZH-566 | Coral | Core 13 (2.66–2.70 m) | Muddy sand w/coral rubb. | AMS 14-C | 5640 | 110 | 6020 | 250 |
| OZH-567 | Coral | Core 13 (2.88–2.93 m) | Muddy sand w/coral rubb. | AMS 14-C | 5880 | 60 | 6290 | 120 |
| OZH-568 | Coral | Core 2 (0.33–0.39 m) | Silic. sand w/coral rubb. | AMS 14-C | 1530 | 40 | 1070 | 110 |
| OZH-569 | Shell | Core 2 (1.09–1.17 m) | Silic. sand w/coral rubb. | AMS 14-C | Modern | | | |
| OZH-570 | Coral | Core 2 (1.64–1.72 m) | Muddy sand w/coral rubb. | AMS 14-C | 3630 | 50 | 3510 | 130 |
| OZH-571 | Coral | Core 2 (2.50–2.58 m) | Muddy sand w/coral rubb. | AMS 14-C | 3960 | 50 | 3950 | 150 |
| OZH-572 | Shell | Core 8 (1.13–1.17 m) | Silic. sand w/coral rubb. | AMS 14-C | 2250 | 50 | 1840 | 130 |
| OZH-573 | Shell | Core 8 (1.66–1.72 m) | Mud w/coral rubb. | AMS 14-C | 2450 | 50 | 2100 | 160 |

with minor *Acropora* and *Porites* fragments. We note that these coral rubble assemblages did not always change or correspond to the broader sedimentary facies indentified in the sediment cores.

Benthic foraminifera were identified in two representative cores (13 and 2), one from the inner reef and one from the outer reef flat. The benthic foraminifera assemblages provided additional information in support of our palaeoenvironmental interpretations. Samples were sieved into >500 µm and 125–500 µm fractions. From the >500 µm fraction at least 200 specimens were picked and identified. The 125–500 µm fraction was only used for qualitative analysis to check whether important species were missed.

### 3.3. Dating

Samples from cores 2, 8 and 13 were dated using AMS radiocarbon methods to establish an age control for the stratigraphy in Nelly Bay (Fig. 1B). Seven shell and six coral fragments were selected (Table 2) and prepared and analysed at the Australian Nuclear Science and Technology Organisation (ANSTO) in Lucas Heights, Sydney, according to the method described by Fink et al. (2004). The rationale behind choosing shell and coral fragments for age control in our cores was to identify the reliability of these materials since age inversions from coral fragments have been noted from other studies (e.g. Johnson and Risk, 1987).

During the construction of Nelly Bay Harbour in 2001, eight massive fossil *Porites* coral colonies approximately 2–3 m in diameter were unearthed (Fig. 1B) and transported to the Australian Institute of Marine Science (AIMS). These coral "bommies" were cored and four coral heads were dated by three separate laboratories including the Australian National University (ANU) (two samples from the upper growth layers of NEL07 and NEL08: conventional radiocarbon), ANSTO (two samples from the upper and lower growth layers of NEL03: AMS radiocarbon) and the Centre for Microscopy and Microanalysis (CMM) Laboratory, University of Queensland (UQ) (four samples from the upper and lower growth layers of NEL01 and NEL03, respectively: TIMS U–Th) (Table 2). Unfortunately, the precise locations and depths of the fossil corals recovered in Nelly Bay Harbour are unknown. All radiocarbon ages (including the fossil coral ages) were calibrated using the *IntCal04 Marine04* C-14 "global" marine calibration dataset (Hughen et al., 2004) in the Calib 5.1 *beta* program (Stuiver et al., 2005). The program corrects for a 400-year global marine reservoir effect as well as for the regional marine reservoir effect (ΔR) of 12 ± 6 yr for marine carbonates from the central GBR (Hughen et al., 2004). We note, however, that estimation of the ΔR varies widely from site to site on the GBR (Stuiver et al., 2005) as well as over time (see Yu et al., 2007; McGregor et al., 2008) but we have used the suggested 12 ± 6 yr to calibrate the C-14 ages for this study. U–Th ages were calibrated using the Isoplot Excel program at the CMM laboratory. All dates are presented with a 2σ standard deviation.

## 4. Results

### 4.1. Nelly Bay surface morphology

Four major morphological zones: dune, beach, tidal flat, and reef flat, were identified in the three topographic profiles along the southern, central and northern sections of Nelly Bay (Fig. 1B). These were consistent with the zones described by Smith (1978). The dune zone ranged between +2 to 3 m AHD and consisted of well-sorted fine to medium sized quartz-rich sands; the beach zone ranged between −1 m to +2 m AHD and contained poorly sorted medium to coarse quartz-rich sands with some coral and shell fragments; the tidal flat was around −1 m AHD and contained moderately sorted medium to coarse quartz-rich sands with some coral rubble, and the reef flat zone (at −1.5 m AHD) contained coral fragments with some live corals (*Gonastrea* and *Porites* sp.) and microatolls (predominately *Porites* sp.). An extensive sand body was observed on the southern transect landward of the Nelly Bay road and its height (range between +3 and 4.5 m AHD) is consistent with higher sea levels during the mid-Holocene where it was most likely an active beach ridge. Elevated dunes and chenier ridges at similar heights that run adjacent to the modern beach are commonplace in the Townsville region and are of early to mid-Holocene age (see Belperio, 1979; Carter et al., 1993).

### 4.2. Basic sedimentary facies descriptions

Visual analysis of the sediment cores, such as colour, texture, particle size, and composition, revealed six sedimentary facies. The first was composed of medium to coarse grained siliciclastic sands with variable amounts of shell fragments and was termed siliciclastic sand facies. The second facies was made up exclusively of branching coral rubble and was named clast supported coral rubble facies. The third, fourth and fifth facies contained abundant coral rubble, with differing matrices such as (3) medium siliciclastic sand, (4) muddy sand and (5) mud. The coral rubble of these three facies contained variations in taxonomic composition, size and preservation state (see Section 3.2). These facies were named siliciclastic sand with coral rubble facies, muddy sand with coral rubble facies and mud with coral rubble facies, respectively. Facies six was composed of weathered muddy sand with no coral or shell fragments and termed Pleistocene sediment facies. Previous drilling records from the geotechnical investigations (McIntyre and Associates, 1986, 1989; Golder Associates, 2000) closely match the facies observed in the sediment cores collected in this study which describe facies such as 'weathered mottled clays' (i.e. Pleistocene sediment facies), 'muddy sandy coral' (i.e. muddy sand with coral rubble facies) and 'sandy coral' (i.e. siliciclastic sand with coral rubble facies). Additional quantitative textural and compositional analyses that were performed on six representative sediment cores (cores 13, 3, 2, 8, 10 and 6) from the three transects within each geomorphological zone (Fig. 2) are described below, along with the distribution of the facies.

### 4.3. Beach zone

Core 8 (total penetration of 177 cm) contained a shell fragment which constrained a basal age of 2100 ± 160 cal yr BP while another shell fragment ~50 cm higher yielded an age of 1840 ± 130 cal yr BP. The bottom 53 cm of the core contained mud with coral rubble facies, followed by 85.5 cm of siliciclastic sand with coral rubble facies and the top 38.5 cm of siliciclastic sand facies. The core had a coarsening upwards sequence, although sand content at the bottom of the core was much lower (<3%) than in the other cores (Fig. 2). Between 138 cm and 113 cm depth, sand-size contents increased rapidly from <1% to 95% and remained >80% towards the top of the core. The silt and clay fractions each comprised ~50% in the bottom section of the core. Carbonate contents were 70–90% in the bottom half of the core before decreasing to <20% towards the top. The basal (124–177 cm) coral rubble assemblage was composed of abraded fragments of *Porites* and Mussids (Porites Group 1) and the assemblage changed to well-preserved foliose agaricid fragments of *Pavona* sp. with some *Acropora* and *Porites* (Pavona Group 1) between 64 and 124 cm depth (Fig. 2). The top 64 cm was composed of heavily abraded large staghorn (>1.5 cm diameter) *Acropora* fragments with partial covers of crustose coralline algae (Acropora Group 2).

### 4.4. Tidal flat zone

Core 13 was 3 m long and penetrated into mottled orange-grey sediments of the Pleistocene–early Holocene surface (bottom 7.5 cm of core). This basal Pleistocene sediment facies contained no coral fragments, very low carbonate contents (0.64%) and the particle size distribution was composed of 64% sand, 32% silt, and 4% clay (Fig. 2). This facies was followed by 226.5 cm of muddy sand with coral rubble facies, 51 cm of siliciclastic sand with coral rubble facies with the top 15 cm of the core composed of siliciclastic sand facies. Shell and coral fragments from the bottom 200 cm of core 13 had C-14 ages between 6000 and 6400 cal yr BP, with a shell fragment at 161–167 cm depth the only exception (4360 ± 210 cal yr BP). A coral fragment from 288 to 293 cm (the zone where corals first appeared in the core) yielded an age of 6290 ± 210 cal yr BP. A large time gap was apparent in core 13 between 50 and 100 cm depth; a shell fragment from 41 to 45 cm had an age of 600 ± 70 cal yr BP while a shell fragment taken from 108 to 114 cm was dated at 6340 ± 130 cal yr BP (Fig. 2).

Core 13 had a characteristic coarsening upwards sequence with sand size contents increasing from ~50% at the bottom to ~100% at the core top (Fig. 2). Silt contents were 35–40% at the bottom and decreased to <1% at the core top and likewise, clay fractions were highest at the bottom (~10%) and absent at the core top. At three depths, ~200 cm, ~150 cm and ~80 cm, marked shifts of particle sizes towards coarser fractions were evident (Fig. 2). Carbonate contents in core 13 were typically >50%, with the largest amount (75%) at 116 cm depth coinciding with the area of highest reef-associated benthic foraminifera diversity.

The coral rubble assemblage in core 13 from bottom to top included well preserved delicate *Acropora* and some branching Pocilloporid fragments of Acropora Group 1 (246–293 cm), crustose coralline algae encrusted and abraded large staghorn *Acropora* fragments of Acropora Group 2 (231–246 cm), Acropora Group 1 (198–231 cm), a mixed layer of Acropora Groups 1 and 2 (Acropora Group 1.5, 180–198 cm), plate-like *Montipora* and moderately-heavily abraded *Acropora* fragments of Montipora Group 1 (150–180 cm), dense coral fragments of single and multiple branching bifurcating and abraded *Acropora* and Acroporid fragments with thick crusts of crustose coralline algae and dark coatings (Acropora Group 3, 47–150 cm) and Acropora Group 1 (29–47 cm, Fig. 2). The top part of the core contained few coral fragments.

The benthic foraminifera in core 13 showed a low diversity within the >500 μm size fraction including species of the genera *Elphidium*, *Peneroplis*, *Amphistegina* and *Operculina* (Table 3). The sample at 126 cm depth (X3) contained the most reef-associated taxa. *Elphidium* sp. dominated the samples below 155 cm (X4) and 204 cm (X5) depth (Fig. 2). The samples at 69 and 35 cm depth

**Table 3**
Benthic foraminifera composition and environmental interpretation of cores 13 and 2.

| Sample | Core | Depth | Species | Environmental interpretation |
|---|---|---|---|---|
| X1 | 13 | 35 cm | *Elphidium*, *Peneroplis* and *Amphistegina* | Less diversity, higher turbidity, sandy environment at the lowest part of the reef slope to reef base, turbid waters 5–10 m water depth |
| X2 | 13 | 69 cm | *Elphidium*, *Peneroplis* and *Amphistegina* | Sandy environment at the lowest part of the reef slope to reef base, turbid waters 5–10 m water depth |
| X3 | 13 | 126 cm | *Elphidium*, *Peneroplis*, *Amphistegina* and *Operculina* | Most reef associated taxa, sandy environment at the lowest part of the reef slope to reef base, decrease in water depth and/or turbidity, turbid waters 5–10 m water depth |
| X4 | 13 | 155 cm | *Elphidium*, *Peneroplis*, *Amphistegina* and *Operculina* | Sandy environment at the lowest part of the reef slope to reef base, dominance of *Elphidium* sp., turbid waters 5–10 m water depth |
| X5 | 13 | 204 cm | *Elphidium*, *Peneroplis*, *Amphistegina* and *Operculina* | Sandy environment at the lowest part of the reef slope to reef base, dominance of *Elphidium* sp., turbid waters 5–10 m water depth |
| X6 | 13 | 263 cm | *Elphidium*, *Peneroplis*, *Amphistegina* and *Operculina* | Sandy environment at the lowest part of the reef slope to reef base, turbid waters 5–10 m water depth |
| Y1 | 2 | 68 cm | *Elphidium?* | Very low diversity and very few photosymbiotic and chloroplast retaining species, water depth 8–12 m |
| Y2 | 2 | 111 cm | *Elphidium*, *Peneroplis* and *Amphistegina* | *Elphidium* becomes abundant, water depth 8–12 m — slight increase in water depth |
| Y3 | 2 | 172 cm | *Elphidium*, *Peneroplis* and *Amphistegina* | *Elphidium* becomes abundant, water depth 8–12 m — slight increase in water depth |
| Y4 | 2 | 240 cm | *Elphidium*, *Peneroplis* and *Amphistegina* | Water depth 8–12 m |

were less diverse and dominated by *Elphidium*, *Peneroplis* and *Amphistegina* (Table 3).

Core 3 penetrated 281 cm into the reef flat but was highly compacted (80%, Table 1). The bottom 91 cm of the core contained muddy sand with coral rubble facies followed by 175 cm of siliciclastic sand with coral rubble facies and the top 15 cm of clast supported coral rubble facies. Similarly to core 13, it had a general coarsening upwards sequence with sand-sized particles increasing from ~75% at the bottom to >90% at the top. Carbonate contents of ~100% occurred at the bottom of the core and were high (>80%) throughout the core. The coral rubble assemblages from bottom to top included the crustose coralline algae encrusted and abraded large staghorn *Acropora* fragments of Acropora Group 2 (206–281 cm depth), the bifurcating, abraded *Acropora* and Acroporid fragments with thick crusts of crustose coralline algae (some fruitocose) and some dark coatings forming Acropora Group 3 (80–206 cm depth), mixed well-preserved delicate and larger staghorn *Acropora* fragments of Acropora Group 1.5 (30–80 cm depth), and Acropora Group 3 (top-30 cm depth) (Fig. 2).

Core 6 (penetration 230 cm) was the only core recovered along the southern transect and contained muddy sand with coral rubble facies in the bottom 97 cm with 133 cm of siliciclastic sand with coral rubble facies in the core top. A general coarsening upward trend was also evident in this core, although sand contents in the bottom of the core (70–75%) were much higher compared to basal sections of other cores except possibly for core 3. Carbonate contents showed no apparent trend and ranged between 60 and 80%. The coral rubble assemblages in this core consisted upwards from the base of: Acropora Group 1 (179–230 cm depth), Group 3 (157–179 cm depth), Montipora Group 1 (109–157 cm depth), Acropora Group 1.5 (92–109 cm depth), Montipora Group 1 (61–92 cm depth) and Acropora Group 3 (top-61 cm depth; Fig. 2).

### 4.5. Reef flat zone

Core 2, with a penetration of 260 cm, had a basal age of 3950 ± 150 cal yr BP (Fig. 2). The two other coral fragments dated in this core were progressively younger (3510 ± 130 cal yr BP at ~210 cm and 1070 ± 110 cal yr BP at ~80 cm depth), whilst the only dated shell fragment taken at 109–117 cm depth returned a modern age. The core contained a sequence of muddy sand with coral rubble facies in the bottom 129 cm of the core followed by 114.5 cm of siliciclastic sand with coral rubble facies and 16.5 cm of clast supported coral rubble facies in the top of the core. This core had a typical coarsening upwards sequence with 60–77% sand-size particles at the bottom (141–240 cm) and ~90% at the top ~140 cm (Fig. 2). A corresponding decrease of silt and clay fractions with reductions from ~20–30% to ~8% and from 5–10% to ~1–2%, respectively, was observed. Carbonate contents were ~80% throughout the core. The coral rubble assemblages in core 2 from bottom to top included bifurcating, abraded *Acropora* and Acroporid fragments with thick crusts of crustose coralline algae, some dark coatings and fruiticose algae crusts forming Acropora Group 3 (199–260 cm depth), abraded *Acropora* fragments partially encrusted with crustose coralline algae of Acropora Group 2 (147–199 cm depth), well-preserved delicate *Acropora* fragments of Acropora Group 1 (121–147 cm depth), with further changes to Acropora Group 2 (76–121 cm depth), Group 1.5 (55–76 cm depth) and Group 3 (top-55 cm depth) (Fig. 2). The benthic foraminifera assemblage in this core included species of *Elphidium*, *Peneroplis*, and *Amphistegina*. An assemblage change occurred over the interval between 240 cm and 111 cm depth (Y4–Y2) where *Peneroplis* and *Amphistegina* became less abundant, and *Elphidium* became more abundant. In the sample collected at 68 cm (Y1), very few photosymbiotic and chloroplast retaining species occurred.

Core 10 also showed a coarsening upwards trend, although one sample just below the surface (115 cm depth) was mud-rich (Fig. 2). The bottom 127 cm of the core contained muddy sand with coral rubble facies with the top 147 cm containing siliciclastic sand with coral rubble facies. Sand-size contents were 50–56% in the basal samples and then, typically, increased to >90% towards the core top. Silt and clay contents in the core typically decreased from 34–40% to 3–6% and from 10% to <2%, respectively. Carbonate contents were high with values between 80 and 90% throughout the core. An alternating pattern of coral rubble assemblages Acropora Group 3 (200–274 cm, 74–94 cm and top-29 cm depth) and plate-like *Montipora* and moderately heavily abraded *Acropora* fragments of Montipora Group 1 (94–200 cm and 29–74 cm depth) was found in this core.

### 4.6. Reef flat chronology, vertical and lateral accumulation rates

The radiocarbon dates from the cores typically show trends of decreasing age, both upward and seaward, with the exceptions of a few apparent age reversals. These reversals are exclusively linked to the shell material (Fig. 2). The coral fragment data show no reversals and were used to estimate vertical and lateral accretion rates for the Nelly Bay fringing reef. The vertical accretion rates in core 13 ranged approximately between 0.8 and 5.5 mm/yr (Table 2). A similar estimate was calculated (2.0 mm/yr) using two dated coral fragments in core 2 (3950 cal yr BP at 2.54 m and 3510 cal yr BP at 1.68 m depth, Table 2). Although shell fragment data have been excluded from the accretion rate calculations, the two fragments in core 8 also yield an accumulation rate of 2.0 mm/yr. Using each individual datapoint to calculate overall accumulation rate (i.e. to the core top), the range is between 0.3 and 0.6 mm/yr (coral fragments only).

Lateral accretion rates between core 13 and core 2 (250 m distance) in the northern transect were estimated based on the ages of coral fragments from the basal (muddy sand with coral rubble) facies which displayed a seaward progradation, unlike the upper muddy sand with coral rubble facies. The coral rubble produced an estimate of lateral accretion between 98 and 120 mm/yr (see Fig. 3).

### 4.7. Radiocarbon reservoir estimation

The coupled radiocarbon and U–Th ages from a single year's growth in the NEL03 fossil coral provide an independent measure of the local C-14 reservoir effect (ΔR) at that time. The basal and outer C-14 ages (uncalibrated) for the NEL03 coral are 5870 ± 50; 5740 ± 60 yr BP, with corresponding U–Th dates of 6180 ± 40; 6060 ± 90 yr BP (Table 2). ΔR for Magnetic Island was determined using the method described by Wiesler et al. (2009) where ΔR is the difference between the radiocarbon age and the model marine age (determined from the Marine09 data set of Reimer et al., 2009). The ΔR calculated for NEL03 (basal) of 167 ± 53 $^{14}$C yr, and NEL03 (outer) of 120 ± 95 $^{14}$C yr is considerably higher than that recommended for the east-central Australia region by IntCal04 (12 ± 6 yr, Hughen et al., 2004).

## 5. Discussion

The textural, compositional and chronological data from the Nelly Bay fringing reef highlight the complex nature of its formation and development. The findings from the Nelly Bay fringing reef may help better understand other fringing coral reefs along the GBR. Our key findings include:

1. Reef initiation at Nelly Bay occurred by 6300 yr BP on top of weathered, compacted muddy sand sediments (i.e. Pleistocene coastal sediments);
2. The different stratigraphic facies in the cores and changing faunal assemblages suggest that environmental changes occurred across

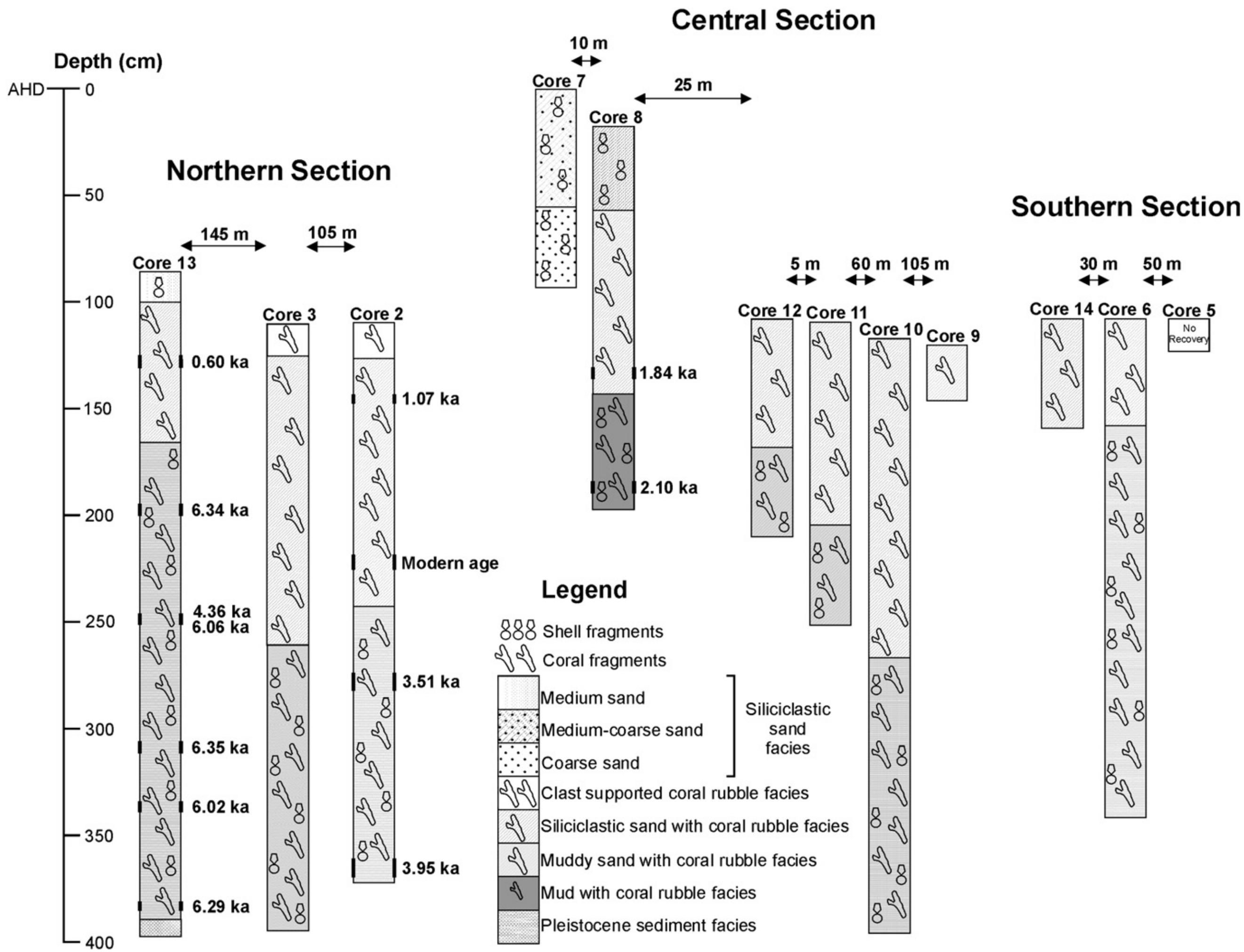


**Fig. 3.** Schematic logs of the sediment cores taken along the northern, central and southern transects of the Nelly Bay reef flat reveal several sedimentary facies within the reef flat. The calibrated C-14 ages and sampling locations are marked.

the reef over the last 6000 yr including possible depositional hiatuses or erosional nonconformities; and
3. The uppermost facies of the fringing reef drapes across the entire reef flat and is a relatively young deposit (<1100 yr BP) that is probably an erosional feature that corresponds to late Holocene sea-level fall.

We discuss these findings in the context of a new stratigraphic model that illustrates fringing reef initiation and development in Nelly Bay during the Holocene as well as comparisons with other studied fringing reefs in the GBR. We also discuss key environmental changes that are recorded in the sediment cores and associated biotic assemblages.

### 5.1. Stratigraphic model of evolution and environmental changes

The relative position of each sediment core in Nelly Bay was compiled along topographic profiles to develop the stratigraphic model of the embayment (Fig. 4). Previous borehole and seismic results (McIntyre and Associates, 1986, 1989; Carter and Johnson, 1989; Sinclair Knight Merz, 1998; Golder Associates, 2000) were used to construct the depths of both the Pleistocene and granitic bedrock units. The Pleistocene/early Holocene facies occurs at 2.0 to 5.5 m below the surface sediments (Carter and Johnson, 1989; Sinclair Knight Merz, 1998), which was also the case in core 13 where alluvial sediments were encountered at the base of the core at 3 m below the surface sediments. Based on the age control of our cores, the delineated stratigraphic facies and published sea level curves, we have constructed a stratigraphic model for Nelly Bay over the Holocene focusing on four major time periods: 10–7 ka, 7.0–6.0 ka, 6.0–1.5 ka, and 1.5 ka to present.

### 5.2. Chronology of reef flat development

In this study six coral and seven mollusc shell fragments were dated to produce a chronology on the development of the Nelly Bay fringing reef. In two cores distinct age reversals were recorded but these were confined to the shell material. Dating of reefal deposits is well known to be problematic as most material can remain in the system for long periods before burial or easily be bioturbated and reworked (Kosnik et al., 2009). Such processes can produce inverse and thus difficult to interpret age data and as a result most studies generally focus on a single carbonate fraction (e.g. corals, shells, foraminifera, etc.). No consensus has been reached so far on the most appropriate material to determine the exact age of carbonate reefs. However, the majority of studies in the GBR have focused on establishing the age of reefs using coral rubble (Johnson and Risk, 1987; Smithers and Larcombe, 2003; Perry et al., 2008; 2009; Perry and Smithers, 2010) and one study has used benthic foraminifera (Frank, 2008).

In our study, the six coral data in the two cores show no age reversals although two fragments in core 13 have identical ages (6020 ± 250 and 6060 ± 140) but are over 1 m apart (Table 2). These ages may suggest contemporaneous deposition but the coral assemblage data show clear stratigraphic layering between the two samples and thus it is more likely that the fragments were buried at different times but originated from a similar source. A possible scenario would be the incorporation of loose coral fragments into reef sediments due to storm activity as suggested by Johnson and Risk (1987) which is a common process on fringing reef environments. Our coral age data suggest that there were marked hiatuses or even erosional events between some of our identified stratigraphic facies. High resolution dating would be able to resolve details of any such time breaks

In contrast, the shell data of our cores imply marked age inversions with the exception of core 8. Unfortunately, we did not examine the taxonomical composition of the shell fragments which have previously been shown to influence the establishment of a reliable age control, as well as the possibility for bioturbation and preservation (see Kosnik et al., 2009).

Based on our findings, we recommend that coral fragments provide a better chronology of fringing reefs than shell fragments and all our interpretations are based on the coral data and not shell material. However, future research that examines the reliability of different materials available for dating of reef flats (e.g. coral, shell, benthic foraminifera) with a particular emphasis on species composition is warranted.

### 5.3. The early Holocene (10–7.0 ka)

During the early Holocene, sea level was still rising rapidly following the last glacial termination and was approximately 5 m below present sea level by 7590 ± 190 cal yr BP based on the C-14 ages of relict mangrove mud deposits in Cleveland Bay (Carter et al., 1993). The early Holocene 'beach' possibly stretched from the tip of Bright Point across Nelly Bay following the modern −5 m isobath (Fig. 4). Pleistocene and early Holocene clay soils and alluvial sediments underlie most areas where the modern fringing reef is located. The Pleistocene–Holocene boundary in core 13 and the sediments described in the core logs from geotechnical investigations suggest that the Pleistocene/early Holocene sediments were weathered, poorly sorted muddy-sands. These reefal foundations are consistent with many previous studies on fringing reefs of the GBR (see Johnson and Risk, 1987; Smithers et al., 2006; Perry et al., 2011).

### 5.4. The Mid-Holocene period and sea-level highstand (7.0–6.0 ka): reef initiation

The mid-Holocene period, ~7.0–6.0 ka ago, was critical for the evolution of Nelly Bay as reef growth initiated across the modern day reef flat area and quickly blossomed following the slow-down of sea-level rise as the mid-Holocene sea-level highstand was reached (Lewis et al., 2008; Woodroffe, 2009). In fact, the basal age of the sediment cores (6350 ± 150 cal yr BP) is very similar to the oldest age of the fossil *Porites* coral heads (6280 ± 110 cal yr BP) and, more importantly, very close to the age of the oldest coral microatoll (6150 ± 170 cal yr BP: Chappell et al., 1983) that sits on top of the reef flat in neighbouring Geoffrey Bay. The data suggest that the Nelly Bay fringing coral reef system developed before 6300 cal yr BP and significant amounts of both coral and terrestrial material were deposited and built up a "reef flat" on top of which coral microatolls developed. The GBR sea level was 1.0 to 1.5 m above present by 7000 yr BP (Lewis et al., 2008; Woodroffe, 2009; Yu and Zhao, 2010), which is ~600 yr before the suggested initiation for the Nelly Bay fringing reef. However, it is assumed that it may take several hundred years from the time of the first coral recruits to coral debris build-ups (see Hopley et al., 2007) and as such our reported time of reef initiation may be earlier than 6300 yr BP. Moreover, the earliest oyster bed date (6280 ± 100 cal. yr BP) for the GBR (Balding Bay, Magnetic Island) coincides closely with the timing of reef initiation in Nelly Bay and also is the earliest date which confines the beginning of the mid-Holocene highstand at 1.65 m above present sea level (Lewis et al., 2008). Several coral rubble fragments (Acropora Group 1) in core 13 have ages that coincide with the suggested timing of reef initiation implying rapid development and growth within Nelly Bay. Once reef growth was initiated, carbonate production was high signalled by the elevated carbonate levels in this section of the sediment cores (generally > 70%) and by the rapid reef accretion inherent in the chronology of the sediment cores (Table 4). In addition, the supply of terrigenous sediment was also considerable with quartz, feldspar and clay minerals comprising up to 20–30% of the sediment composition (Table 4). The distinct coarsening upward sequences,

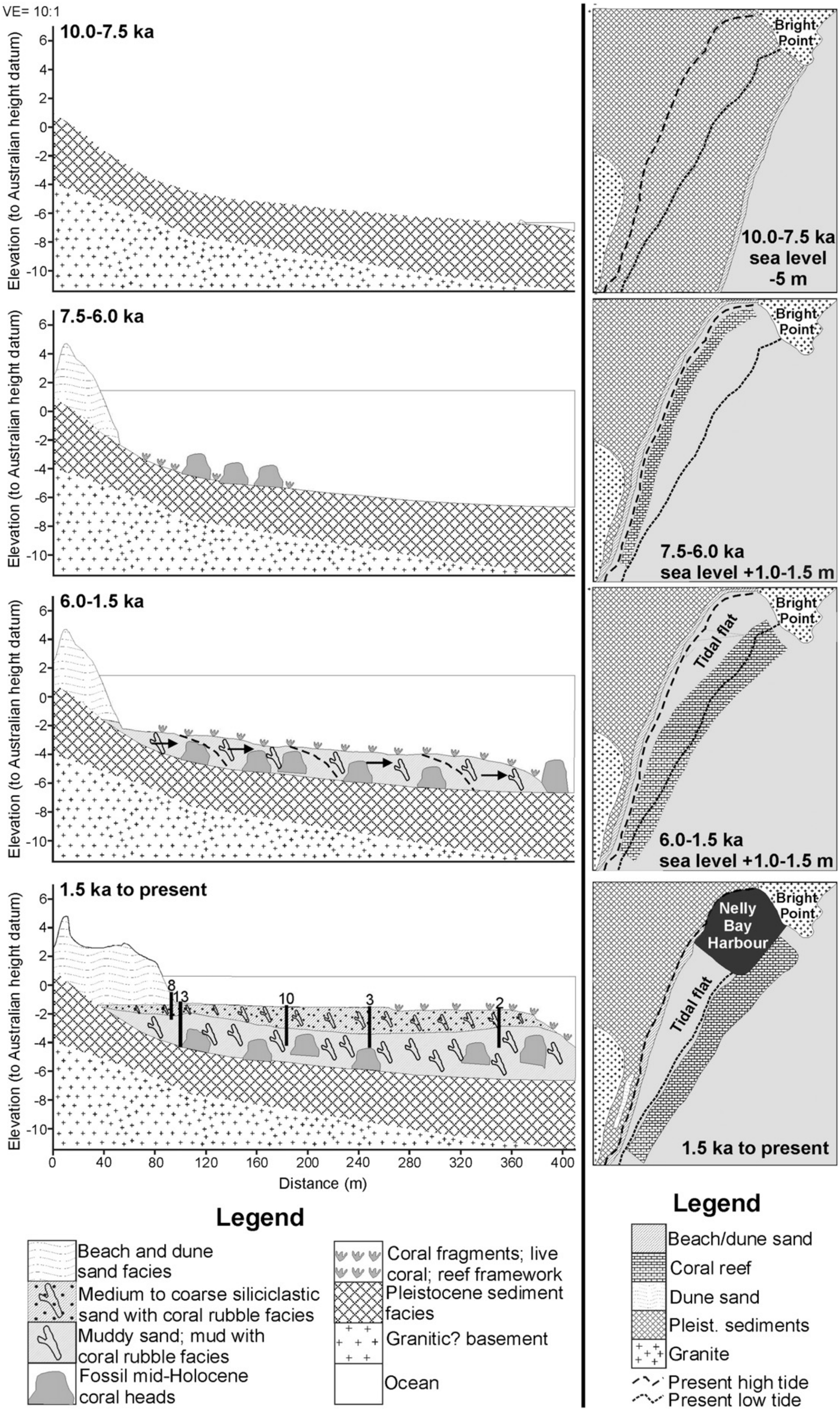


**Fig. 4.** Stratigraphic sketch and plan view profiles showing the development of the fringing reef and beach/dune deposits in Nelly Bay during the Holocene.

**Table 4**
Mineralogy of the sedimentary facies in Nelly Bay from core 13.

| Sedimentary facies | Interval | Quartz | Feldspars | Clays | Aragonite | Calcite | High Mg-calcite |
|---|---|---|---|---|---|---|---|
| Siliciclastic sand | 5 cm | 52.0 | 45.0 | 3 | | | |
| Siliciclastic sand with coral rubble | 54 cm | 23.2 | 9.6 | 2.9 | 45.3 | 4.1 | 15.1 |
| Muddy sand with coral rubble | 140 cm | 11.4 | 0.0 | | 59.2 | 2.6 | 27.1 |
| Muddy sand with coral rubble | 159 cm | 20.5 | 25.1 | | 40.9 | 1.0 | 12.8 |
| Muddy sand with coral rubble | 263 cm | 37.9 | 36.1 | | 22.6 | | 3.8 |
| Muddy sand with coral rubble | 293 cm | 10.5 | 16.9 | | 42.9 | 1.4 | 28.5 |

apparent in all of the sediment cores, suggest that energy conditions increased as a result of water depth shallowing due to vertical reef growth.

Reef initiation around the emerging islands was largely controlled by bathymetry and location of the reef system. For example, reef initiation around Fantome Island was contemporaneous (6320 ± 260 cal yr BP; Johnson and Risk, 1987) to Nelly Bay whilst older ages are known from Rattlesnake Island (7500 ± 340 cal yr BP) and Pioneer Bay on Orpheus Island (7050 ± 520 cal yr BP) (Hopley et al., 1983). These data demonstrate that modern fringing reefs around coastal islands in the GBR region existed before the mid-Holocene sea-level highstand was reached. Hopley et al. (1983) suggest that coral reef growth in inshore environments during the early Holocene may have been restricted because of highly turbid conditions from Pleistocene soil surfaces and terrestrial runoff but that some locations, such as the much smaller Rattlesnake Island, may have had conditions more favourable for reef growth. The basal facies of the sediment cores from Nelly Bay contained a large proportion (~50%) of terrigenous sediment and together with the benthic foraminifera assemblage suggest that the reef developed under considerable levels of turbidity and sedimentation. Indeed, muddy substrates and mud-rich fringing reefs were common features during the mid-Holocene in north Queensland. For example, the fringing reef off Fantome Island, located approximately 50 km north of Magnetic Island, contains a basal Holocene facies characterised as a 'very muddy coral floatstone and rudstone' which developed on a lower seaward slope of the initiated fringing reef (Johnson and Risk, 1987). This basal reefal deposit appears comparable to the basal muddy sand with coral rubble facies in Nelly Bay.

The massive and large *Porites* colonies in Nelly Bay have outer growth layers aged around 6000–6150 yr BP, with the exception of the U–Th age of the NEL01 coral (5790 ± 30 yr BP; Table 1). X-ray records of annual density bands in core slices from these fossil corals reveal relatively fast vertical growth rates of approximately 10–20 mm/yr (Lewis, 2005). The abundant fossil bommies excavated during the Nelly Bay Harbour construction demonstrates that massive *Porites* colonies flourished during at least a short period (~500 yr) of the mid-Holocene. Importantly, modern live colonies of similar size are found on the present reef front.

The coral rubble assemblages in the cores reveal distinct variations from well-preserved delicate branching *Acropora* fragments (Acropora Group 1) to larger branching *Acropora* fragments with crusts of coralline algae (Acropora Group 2) to heavily abraded Acroporid fragments (Acropora Group 3) and in some cores, an assemblage of *Montipora* sp. plate fragments (Montipora Group 1). The complex and changing coral assemblages in the cores are evidence of changing environments and recurring disturbances. The delicate well-preserved fragments suggest rapid deposition and burial, while heavily abraded fragments indicate a much longer period of surface exposure and storm reworking. Evidence of storm reworking was also observed in age reversals found in sediment cores from Fantome Island (Johnson and Risk, 1987) and well as other locations around the world (e.g. Easton and Olson, 1976). In contrast, Roche et al. (2011) found that changing coral assemblages in sediment cores from King Reef were related to shallowing water conditions due to vertical reef accretion. Clearly, our study and that of Roche et al. (2011) highlight the importance of examining the changes in coral assemblages in sediment cores from fringing coral reefs for palaeo-environmental reconstructions.

Storm-derived coarse terrigenous sediments were observed on the Nelly Bay reef flat after Tropical Cyclone Althea in 1971 (Hopley, 1986) and it is assumed that storms were more intense during the mid Holocene (Hayne and Chappell, 2001; Nott and Hayne, 2001). Sand particles dominated by quartz and feldspar are typically weathering products of the local granite bedrock, whilst the finer mud-sized particles are sourced from local surface soils as well as from land-derived sources from rivers such as the Burdekin and Ross Rivers (Lewis, 2005).

The benthic foraminifera assemblages also provide some important insights into palaeoenvironmental changes on the Nelly Bay fringing reef. Low diverse large benthic foraminifera assemblages with high abundance of *Elphidium* are characteristic of the deepest parts of the photic zone (Renema and Troelstra, 2001). Importantly, all foraminifera assemblages observed in core 13 (X1–X6; Fig. 2) typically occur at upper reef slopes in turbid environments at depths between 3 and 8 m. Important for this interpretation are the presence of *Elphidium* spp. in the absence of clear water reef taxa such as even the most tolerant genera *Heterostegina* and *Calcarina*. *Elphidium* has chloroplast retention instead of obligate endosymbiosis, and is more tolerant to low light and/or high nutrient conditions. It dominates assemblages in the lowest part of the photic zone, especially in seasonal environments (Renema and Troelstra, 2001). The increase in obligate symbiont-harbouring species of benthic foraminifera between 155 cm (X4) and 126 cm (X3) depths in core 13 indicate a slight decrease in water depth and/or turbidity (Table 3). The presence of typical reef base foraminifera, such as *Operculina*, in core 2 represents a reef base environment. The typical depth at which this assemblage was observed in the Palm Island Group and nearshore Princess Charlotte Bay was between 8 and 12 m (W. Renema, unpublished data). An assemblage change in core 2 reflects a slight increase in water depth or an increase in turbidity.

### *5.5. The mid to late Holocene period (6.0–1.5 ka)*

Between 6.0 and 1.5 ka ago, the Nelly Bay reef flat experienced intermittent rapid vertical and lateral seaward progradation, during which most of the ~5 m thick reef sequence accumulated based on both bore hole (McIntyre and Associates, 1989; Golder Associates, 2000) and seismic data. This is comparable to other fringing reefs of the GBR which typically range between 5 and 10 m in thickness (Smithers et al., 2006). Although the estimated vertical accretion rates for the Nelly Bay fringing reef vary widely (~1–5 mm/yr) due to the limited C-14 ages, vertical accretion rates may have been initially ~5 mm/yr that then slowed to 2 mm/yr based on most age dates. Our mean vertical accumulation rate to the tops of the cores is ~0.5 mm/yr but this would be an underestimate given the growth hiatuses observed in the cores. These rates are lower than the average vertical accretion rate calculated for Fantome Island (6.7 mm/yr; Johnson and Risk, 1987) or the overall mean vertical accretion rate for fringing reefs of the GBR (~7.5 mm/yr; Smithers et al., 2006).

The estimated lateral accretion rate (~100–120 mm/yr) for Nelly Bay equates to ~100 m/1000 yr, which compares well with the lateral accretion rates calculated for the Fantome Island fringing reef (i.e. Johnson and Risk, 1987) that range from ~60 to 170 mm/yr and for Orpheus Island (i.e. Hopley et al., 1983) that range from ~30 to 160 mm/yr. Given that the maximum lateral extent of the Nelly Bay reef flat is ~500 m and that approximately 300 m had accumulated in the first 3000 yr of reef growth (as indicated by the distance between cores 13 and 2), then the remaining ~200 m of reef flat must have accumulated over the last 3500 yr at a rate of 57 mm/yr or 55 m per thousand years. Therefore, while lateral accretion rates have nearly halved in the last 3500 yr, the Nelly Bay fringing reef is still accreting laterally at appreciable rates.

Around Magnetic Island, the reefs developed on a gently sloping Pleistocene alluvial plain where space for lateral progradation was not restricted. This contrasts with many fringing reefs of the GBR which have 'turned off' over the last three thousand years (Smithers et al., 2006). Today, branching and massive corals, essential for continued fringing reef accretion (Smithers et al., 2006), including massive long-living *Porites* corals (>2 m), are commonplace in the waters off the Nelly Bay reef flat (Mapstone et al., 1992).

Early and mid-Holocene coral reef productivity in Nelly Bay was very high as indicated by rapid accretion and development and is similar to other reefs within the region including Rattlesnake Island and reefs of the Palm Island Group (Hopley et al., 1983; Johnson and Risk, 1987). In Nelly Bay, fast sediment accretion and a stable mid-Holocene sea level may have led to rapid reef-flat build-ups around the large *Porites* corals and caused their subsequent demise (Lewis, 2005). Microatolls found at the reef flat surface in Geoffrey Bay on Magnetic Island as well as around many other continental islands of the GBR (Chappell et al., 1983; Hopley et al., 1983) also suggest relatively fast seaward reef progradation. The age structures of microatolls on these reef flats typically become progressively younger seawards and these are used to calculate seaward progradation rates (Smithers et al., 2006).

Information collected during jet-probe investigations on the neighbouring Geoffrey Bay reef flat have led to the suggestion that this fringing reef developed offshore from the present shoreline on Pleistocene sediments and, once the reef became established, formed a low-energy lagoon behind the fore reef (Hopley et al., 1983; Hopley, 1986; Hopley and Partain, 1987). The lagoon was then infilled by a combination of terrigenous sediments from the land and biogenic carbonate material from the reef front while isolated stands of massive coral heads grew within the lagoon. The fore reef would have predominately grown seawards from its initial foundations. Such a lagoonal-type development of the present reef flat would have most likely been favoured by low-energy conditions with occasional high energy storm events. The occurrence of *Porites* and Mussid fragments (Porites Group 1) in the basal facies of core 8, the very high mud contents (virtually 100% at the bottom of this core) and relatively young age (~2100 yr BP) of shell fragments in the core indicate deposition in a very low energy leeward environment that must have been behind a seaward reef complex that acted as a baffle. The changes in the composition of coral rubble assemblages in the sediment cores highlight relatively long periods of slow accumulation and reworking, evident from the extensive coralline algal crusts observed in Acropora Groups 2 and 3, were followed by rapid deposition of better preserved delicate fragments such as those of Acropora Group 1.

Interestingly, solid reef frameworks such as those known from the outer reefs of the GBR (e.g. Webster and Davies, 2003), have rarely been described from inshore fringing reefs, which typically have matrices of terrigenous sediments, despite the fact that many of them have modern reef-associated structures dominated by carbonate sediments. While percussion coring would bias against areas of solid coral, the geotechnical investigations and harbour dredging also highlighted a distinct lack of solid reef framework with the exception of the large coral bommies. So either the reef framework structures collapse and break to coral rubble due possibly to storm events and combined with the inshore sediment runoff, accumulate as muddy sand with coral rubble with the occasional in-situ coral bommies, or the offshore structure was more comparable to broadly stretched and coast parallel reefal mounds. In their comprehensive review, Kennedy and Woodroffe (2002; and references therein) suggested that the internal structures of many fringing reefs around the world were composed of unconsolidated detritus lacking in situ frameworks with particular emphasis on the role of high energy storm events which break up these reefal frameworks. Coral rubble fragments from sediment cores taken from the fringing reefs around Grand Cayman were described by Blanchon et al. (1997) to be abraded and capped with coralline algae crusts which are similar to those observed in our study. These unconsolidated fragments were thought to be the product of storm deposits (Blanchon et al., 1997). Moreover, sea-level change during the mid-late Holocene may have eroded and reworked the reefal structures.

### 5.6. 1.5 ka to present

While there are notable differences in eastern Australian sea level reconstructions in terms of the magnitude and nature of the mid-Holocene sea-level highstand, the most recent studies show that sea-level fell to its present position from +0.5 to 1.0 m after 1200–1500 yr BP (Lewis et al., 2008; Woodroffe, 2009). This sea-level fall coincided with considerable changes in the Nelly Bay reef environment, which left the shallow reef flat area in Nelly Bay exposed to erosion and denudation. While most of the smaller and fragile corals on this shallow reef flat would have been fragmented and reworked due to the increased exposure levels from the sea-level fall, the large fossil elevated microatolls remained well preserved on the reef flat due to their resistance to erosional processes including waves, sand abrasion, etc. 'Destructive' reef erosional processes related to the recent sea-level fall have also been observed on the reef flat from Low Isles Reef (Frank, 2008). The radiocarbon dates from core 8 suggest that the modern beach deposit is younger than 1840 ± 130 yr BP based on the age of a shell fragment in the facies directly below the beach sand facies (Fig. 3). Interestingly, several modern nearshore, shallow and muddy incipient fringing reefs along the Queensland coastline initiated around 1200 yr BP (Smithers and Larcombe, 2003; Perry and Smithers, 2006; Perry et al., 2008, 2009), which also suggests marked hydrodynamic and environmental changes. In cores 13 and 2 of Nelly Bay, such changes are observed in the benthic foraminifera assemblage towards the core tops, where the species diversity decreases significantly and suggests deposition below the photic zone in shallower and more turbid conditions (Table 3).

Sediment cores from other fringing reefs of the GBR such as Fantome Island (Johnson and Risk, 1987) and Dunk Island (Perry et al., 2011) also reveal distinct, but relatively continuous (in terms of chronology) coarsening upwards sequences with a coarse sandy-matrix supported facies containing coral rubble/framework in the upper section of the cores. While the descriptions of these upper reefal facies closely resemble those observed in our study, a notable difference is that the ages for the siliciclastic sand with coral rubble facies at Nelly Bay are all younger than 2000 cal yr BP compared to the dates from the comparable facies on Fantome Island (up to 6320 ± 260 cal yr BP: Johnson and Risk, 1987) and Dunk Island (up to 6689 cal yr BP: Perry et al., 2011). Such significant age differences also occur in core 13 and core 2 between the basal muddy sand with coral rubble facies (6340 cal yr BP and 3510 cal yr BP, respectively) and the upper siliciclastic sand with coral rubble facies (600 cal yr BP and modern to 1070 cal yr BP, respectively) (Table 5). We interpret this large time gap or hiatus in the cores as an erosional unconformity perhaps associated with the late Holocene sea-level

**Table 5**
Summary data for the main sedimentary facies within Nelly Bay.

| Sedimentary facies | $CaCO_3$% range | Sand% range | Silt% range | Clay% range | Coral assemblages | Benthic foram |
|---|---|---|---|---|---|---|
| Siliciclastic sand | 13–23% | 78–99% | 1–11% | 0–11% | N/A | N/A |
| Clast supported coral rubble | N/A | N/A | N/A | N/A | Acropora Grp. 3 | N/A |
| Siliciclastic sand with coral rubble | 22–89% | 84–98% | 2–11% | 0–7% | Acropora Grps. 1, 1.5, 2 and 3, Montipora Grp. 1, Pavona Grp. 1 | *Elphidium*, *Peneroplis* and *Amphistegina* |
| Muddy sand with coral rubble | 50–100% | 33–85% | 12–46% | 2.6–21% | Acropora Grps. 1, 1.5, 2 and 3, Porites Grp. 1, Montipora Grp. 1 | *Elphidium*, *Peneroplis*, *Amphistegina* and *Operculina* |
| Mud with coral rubble | 71–92% | 0.14–2.5% | 47–50% | 47–53% | Porites Grp. 1 | N/A |
| Pleistocene sediment | <1% | 64% | 32% | 4% | N/A | N/A |

fall. A hiatus of this kind is not in accordance with the age structure of the available models for fringing reef development which suggest relatively continuous deposition over time (Kennedy and Woodroffe, 2002; Smithers et al., 2006), although it has been noted that significant growth hiatuses occur on many fringing reefs of the GBR (see Perry and Smithers, 2011). We note that the only other known location where a large time gap occurs between the lower muddier reefal facies and the coarser overlying veneer is the fringing reef at Low Isles (see Frank, 2008).

While the postulated development of the fringing reef in Geoffrey Bay (Hopley et al., 1983) may also be applicable to Nelly Bay, our results mainly favour the more classic seaward prograding model (e.g. Hopley and Partain, 1987; Kennedy and Woodroffe, 2002; Smithers et al., 2006). The age structure (i.e. dates become progressively younger seawards) of the sediment cores taken across the Nelly Bay reef flat provides strong evidence that the fringing reef developed first in shallow waters along the coast and prograded very quickly seawards as illustrated in our stratigraphic model (Fig. 4). The coral microatoll record from Geoffrey Bay also shows a seaward sequence towards younger ages (Chappell et al., 1983).

## 6. Conclusions

The Nelly Bay fringing reef system was examined to investigate its foundations, initiation, internal structure and development and its record of environmental changes. Nelly Bay is an important site in the study of fringing reefs in the GBR because it is among the few reefs still laterally accreting and the reef experiences relatively high turbidity compared to other studied fringing reefs of the GBR. Our key findings include:

1) The Nelly Bay fringing reef initiated on gently sloping unconsolidated or weakly cemented Pleistocene/early Holocene sediments before 6300 yr BP. This is comparable to the initiation of the fringing reef on Fantome Island but several hundred years later than other fringing reefs in the region. This suggests that during the early stage of the Nelly Bay reef, it may have grown as a 'catch up' reef;
2) The reefal platform is up to ~5 m thick, which is comparable, although at the lower end, to other fringing reefs of the GBR. Estimated average vertical accretion rates for the Nelly Bay fringing reef are also at the lower end at ~0.5 to 2 mm/yr but were much higher (~5 mm/yr) during reef initiation. Lateral accretion rates vary from 98 to 120 mm/yr and are comparable to other fringing reefs in the region;
3) The chronological framework of the sediment cores provided by the coral and shell fragments suggests that coral fragments provide a more reliable age control than the shells which displayed marked age reversals;
4) The age structure of the lower muddy sand with coral rubble facies is compatible with the classic seaward prograding model where the reef initiates close to the present day shoreline, grows to lowest astronomical tidal level and then progressively accretes laterally seaward forming a sizable reef flat. However, the considerably younger age (<1100 yr BP) of upper siliciclastic sand with coral rubble facies which drapes across the reef flat suggests an erosional unconformity possibly linked to the late Holocene sea-level fall and does not fit the classical seaward prograding model;
5) The gently sloping relief of the Nelly Bay reef foundation substrate still presents sufficient space for reef accretion to continue at present.
6) The multi-proxy analyses employed in our study highlight the complex growth and development of inshore fringing coral reefs of the Great Barrier Reef and provide a better understanding of reef evolution. The coral rubble assemblages reveal marked changes in disturbance regimes on reefs with relatively long periods of reworking coupled with pulsed storm events while the benthic foraminifera assemblages provide insights into environmental conditions on fringing reefs including changes in relative water depth and turbidity.

Our analyses of sediment cores from the Nelly Bay reef that incorporates radiocarbon dates, textural and compositional descriptions, particle size, mineralogy, total carbon as well as changes in coral rubble and benthic foraminifera assemblages provide a comprehensive context for understanding the evolution and environmental changes of fringing coral reefs. Our integrated approach provides insights into natural compositional variability of fringing reefs and demonstrates that in the past the coastal fringing reefs in the GBR region were exposed to considerable turbid conditions and yet managed to grow rapidly and form extensive reef flats. This suggests that turbidity levels may not seriously limit reefal growth; however, we note that this does not include potential adverse effects from anthropogenic effluents including pesticides and fertiliser residues.

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## References


Bellwood, D.R., Hughes, T.P., Folke, C., Nystrom, M., 2004. Confronting the coral reef crises. Nature 429, 827–833.

Belperio, A.P., 1979. Negative evidence for a mid-Holocene high sea level along the coastal plain of the Great Barrier Reef province. Marine Geology 32, M1–M9.

Berkelmans, R., De'ath, G., Kininmonth, S., Skirving, W.J., 2004. A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predications. Coral Reefs 23, 74–83.

Blanchon, P., Jones, B., Kalbfleisch, W., 1997. Anatomy of a fringing reef around Grand Cayman: storm rubble, not coral framework. Journal of Sedimentary Research 67, 1–16.

Brodie, J., Fabricius, K., De'ath, G., Okaji, K., 2005. Are increased nutrient inputs responsible for more outbreaks of crown-of-thorns starfish? An appraisal of the evidence. Marine Pollution Bulletin 51, 266–278.

Carter, R.M., Johnson, D.P., 1989. Offshore seismic investigation, Nelly Bay Magnetic Island. Unpublished report, 7th August, 1989, James Cook University.

Carter, R.M., Johnson, D.P., Hooper, K.G., 1993. Episodic post-glacial sea-level rise and the sedimentary evolution of a tropical continental embayment (Cleveland Bay, Great Barrier Reef shelf, Australia). Australian Journal of Earth Sciences 40, 229–255.

Chappell, J., Chivas, A., Wallensky, E., Polach, H.A., Aharon, P., 1983. Holocene palaeo-environmental changes, central to north Great Barrier Reef inner zone. BMR Journal of Australian Geology and Geophysics 8, 223–235.

Collins, J., 1987. Fringing reefs of Magnetic Island. In: Baldwin, C.L. (Ed.), Fringing Reef Workshop: Science, Industry and Management: Proceedings of a Workshop Held at Arcadia Resort, Magnetic Island, Australia, October 23–25th 1986. Great Barrier Reef Marine Park Authority, Townsville, pp. 44–49.

DeVantier, L., De'ath, G., Turak, E., Done, T., Fabricius, K., 2006. Species richness and community structure of reef-building corals on the nearshore Great Barrier Reef. Coral Reefs 25, 329–340.

Easton, W.H., Olson, E.A., 1976. Radiocarbon profile of Hanauma Reef, Oahu, Hawaii. Geological Society of America Bulletin 87, 711–719.

Fabricius, K., De'ath, G., 2001. Biodiversity on the Great Barrier Reef: large-scale patterns and turbidity related local loss of soft coral taxa. In: Wolanski, E. (Ed.), Oceanographic Processes on Coral Reefs. CRC Press, Boca Raton, pp. 127–143.

Fabricius, K., De'ath, G., McCook, L., Turak, E., Williams, D., 2005. Changes in algal, coral and fish assemblages along water quality gradients on the inshore Great Barrier Reef. Marine Pollution Bulletin 51, 384–398.

Fabricius, K.E., Okaji, K., De'ath, G., 2010. Three lines of evidence to link outbreaks of the crown-of-thorns seastar *Acanthaster planci* to the release of larval food limitation. Coral Reefs 29, 593–605.

Fink, D., Hotchkis, Hua, Q., Jacobsen, G., Smith, A.M., Zoppi, U., Child, D., Mifsud, C., van der Gaast, H., Williams, A., Williams, M., 2004. The ANTARES AMS facility at ANSTO. Nuclear Instruments and Methods in Physics Research Section B 223–224, 109–115.

Frank, T.D., 2008. Late Holocene island reef development on the inner zone of the northern Great Barrier Reef: insights from Low Isles Reef. Australian Journal of Earth Sciences 55, 669–683.

Golder Associates Pty Ltd., 2000. Geotechnical investigation proposed revetments Nelly Bay harbour development Magnetic Island, Queensland. Unpublished report March 2000.

Hayne, M., Chappell, J., 2001. Cyclone frequency during the last 5000 years at Curacoa Island, north Queensland, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 168, 207–219.

Hopley, D., 1986. Magnetic Keys Development, Nelly Bay–Magnetic Island – Impact Assessment Study Volume 2 – Technical Reports. Job No. 5233, May 1986. McIntyre and Associates Pty. Ltd.

Hopley, D., Partain, B., 1987. The structure and development of fringing reefs off the Great Barrier Reef province. In: Baldwin, C.L. (Ed.), Fringing Reef Workshop: Science, Industry and Management: Proceedings of a Workshop held at Arcadia Resort, Magnetic Island, Australia, October 23–25th 1986. Great Barrier Reef Marine Park Authority, Townsville, pp. 13–33.

Hopley, D., Slocombe, A.M., Grant, C., 1983. Nearshore fringing reefs in north Queensland. Coral Reefs 1, 151–160.

Hopley, D., Smithers, S.G., Parnell, K.E., 2007. The Geomorphology of the Great Barrier Reef: Development, Diversity and Change. Cambridge University Press, Cambridge.

Hughen, K.A., Baillie, M.G.L., Bard, E., Bayliss, A., et al., 2004. Marine04 marine radiocarbon age calibration, 26–0 ka BP. Radiocarbon 46, 1059–1086.

Hughes, T.P., Bellwood, D.R., Baird, A.H., Brodie, J., Bruno, J.F., Pandolfi, J.M., 2011. Shifting base-lines, declining coral cover, and the erosion of reef resilience. Comment on Sweatman et al. Coral Reefs 30, 653–660.

Johnson, D.P., Risk, M.J., 1987. Fringing reef growth on terrigenous mud foundation, Fantome Island, central Great Barrier Reef, Australia. Sedimentology 34, 275–287.

Kennedy, D.M., Woodroffe, C.D., 2002. Fringing reef growth and morphology: a review. Earth-Science Reviews 57, 255–277.

King, B., McAllister, F., Wolanski, E., Done, T., Spagnol, S., 2001. River plume dynamics in the Central Great Barrier Reef. In: Wolanski, E. (Ed.), Oceanographic Processes of Coral Reefs: Physical and biological links in the Great Barrier Reef. CRC Press, Boca Raton, pp. 145–160.

Kleypas, J.A., 1996. Coral reef development under naturally turbid conditions: fringing reefs near Broad Sound, Australia. Coral Reefs 15, 153–167.

Kosnik, M.A., Hua, Q., Kaufman, D.S., Wüst, R.A., 2009. Taphonomic bias and time-averaging in tropical molluscan death assemblages: differential shell half-lives in Great Barrier Reef sediment. Paleobiology 35, 565–586.

Lambrechts, J., Humphrey, C., McKinna, L., Gourge, O., Fabricius, K.E., Mehta, A.J., Lewis, S., Wolanski, E., 2010. Importance of wave-induced bed liquefaction in the fine sediment budget of Cleveland Bay, Great Barrier Reef. Estuarine, Coastal and Shelf Science 89, 154–162.

Larcombe, P., Ridd, P.V., Prytz, A., Wilson, B., 1995. Factors controlling suspended sediment on inner-shelf coral reefs, Townsville, Australia. Coral Reefs 14, 163–171.

Larcombe, P., Costen, A., Woolfe, K.J., 2001. The hydrodynamic and sedimentary setting of nearshore coral reefs, central Great Barrier Reef shelf, Australia: Paluma Shoals, a case study. Sedimentology 48, 811–835.

Lewis, S.E., 2005. Environmental trends in the GBR lagoon and Burdekin River catchment during the mid-Holocene and since European settlement using Porites coral records, Magnetic Island, QLD. Unpublished PhD thesis, School of Earth Sciences, James Cook University, Townsville.

Lewis, S.E., Shields, G.A., Kamber, B.S., Lough, J.M., 2007. A multi-trace element coral record of land-use changes in the Burdekin River catchment, NE Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 246, 471–487.

Lewis, S.E., Wüst, R.A.J., Webster, J.M., Shields, G.A., 2008. Mid-late Holocene sea level variability in eastern Australia. Terra Nova 20, 74–81.

Lewis, S.E., Brodie, J.E., Bainbridge, Z.T., Rohde, K.W., Davis, A.M., Masters, B.L., Maughan, M., Devlin, M.J., Mueller, J.F., Schaffelke, B., 2009. Herbicides: a new threat to the Great Barrier Reef. Environmental Pollution 157, 2470–2484.

Mapstone, B.D., Choat, J.H., Cumming, R.L., Oxley, W.G., 1992. The fringing reefs of Magnetic Island: benthic biota and sedimentation — a baseline study. Research Publication No. 13, Great Barrier Reef Marine Park Authority, Townsville, Queensland.

McCulloch, M.T., Fallon, S., Wyndham, T., Hendy, E., Lough, J., Barnes, D., 2003. Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement. Nature 421, 727–730.

McGregor, H.V., Gagan, M.K., McCulloch, M.T., Hodge, E., Mortimer, G., 2008. Mid-Holocene variability in the marine $^{14}$C reservoir age for northern coastal Papua New Guinea. Quaternary Geochronology 3, 213–225.

McIntyre and Associates Pty Ltd., 1989. Magnetic Quay Development Nelly Bay — Geotechnical Investigation Report Job No. 5565.

McIntyre and Associates Pty. Ltd., 1986. Magnetic Keys Development, Nelly Bay – Magnetic Island – Impact Assessment Study, May 1986.

Montaggioni, L.F., Braithwaite, C.J.R., 2009. Quaternary Coral Reef Systems, Volume 5: History, Development, Processes and Controlling Factors (Developments in Marine Geology). Elsevier, Oxford, UK.

Nott, J., Hayne, M., 2001. High frequency of 'super-cyclones' along the Great Barrier Reef over the past 5,000 years. Nature 413, 508–511.

Orpin, A.R., Brunskill, G.J., Zagorskis, I., Woolfe, K.J., 2004. Patterns of mixed siliciclastic-carbonate sedimentation adjacent to a large dry-tropics river on the central Great Barrier Reef shelf, Australia. Australian Journal of Earth Sciences 51, 665–683.

Pandolfi, J.M., Bradbury, R.H., Sala, E., Hughes, T.P., et al., 2003. Global trajectories of the long-term decline of coral reef ecosystems. Science 301, 955–958.

Perry, C.T., Smithers, S.G., 2006. Taphonomic signatures of turbid-zone reef development: examples from Paluma Shoals and Lugger Shoal, inshore central Great Barrier Reef, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 242, 1–20.

Perry, C.T., Smithers, S.G., 2010. Evidence for the episodic "turn on" and "turn off" of turbid-zone coral reefs during the late Holocene sea-level highstand. Geology 38, 119–122.

Perry, C.T., Smithers, S.G., 2011. Cycles of coral reef 'turn-on', rapid growth and 'turn-off' over the past 8500 years: a context for understanding modern ecological states and trajectories. Global Change Biology 17, 76–86.

Perry, C.T., Smithers, S.G., Palmer, S.E., Larcombe, P., Johnson, K.G., 2008. 1200 year paleoecological record of coral community development from the terrigenous inner shelf of the Great Barrier Reef. Geology 36, 691–694.

Perry, C.T., Smithers, S.G., Johnson, K.G., 2009. Long-term coral community records from Lugger Shoal on the terrigenous inner shelf of the central Great Barrier Reef, Australia. Coral Reefs 28, 941–948.

Perry, C.T., Smithers, S.G., Roche, R.C., Wassenburg, J., 2011. Recurrent patterns of coral community and sedimentary facies development through successive phases of Holocene inner-shelf reef growth and decline. Marine Geology 289, 60–71.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., et al., 2009. INTCAL09 and Marine09 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 51, 1111–1150.

Renema, W., Troelstra, S.R., 2001. Larger foraminifera distribution on a mesotrophic carbonate shelf in SW Sulawesi (Indonesia). Palaeogeography, Palaeoclimatology, Palaeoecology 175, 125–147.

Roche, R.C., Perry, C.T., Johnson, K.G., Sultana, K., Smithers, S.G., Thompson, A.A., 2011. Mid-Holocene coral community data as baselines for understanding contemporary reef ecological states. Palaeogeography, Palaeoclimatology, Palaeoecology 299, 159–167.

Sinclair Knight Merz, 1998. Nelly Bay Supplement: Nelly Bay Harbour — Supplementary Environmental Impact Study (Appendix D — Seismic Survey), October 1998.

Smith, A., 1978. Case study: Magnetic Island and its fringing reefs. In: Hopley, D. (Ed.), Geographical Studies of the Townsville Area. : Department of Geography Monograph Series No. 2. James Cook University, Townsville, pp. 59–65.

Smithers, S., Larcombe, P., 2003. Late Holocene initiation and growth of a nearshore turbid-zone coral reef: Paluma Shoals, central Great Barrier Reef, Australia. Coral Reefs 22, 499–505.

Smithers, S.G., Hopley, D., Parnell, K.E., 2006. Fringing and nearshore coral reefs of the Great Barrier Reef: Episodic Holocene development and future prospects. Journal of Coastal Research 22, 175–187.

Stuiver, M., Reimer, P.J., Reimer, R.W., 2005. CALIB 5.0. www.calib.org.

Sweatman, H., Delean, S., Syms, C., 2011. Assessing loss of coral cover on Australia's Great Barrier Reef over two decades, with implications for longer term-trends. Coral Reefs 30, 521–531.

Taylor, J.C., 1991. Computer programs for standardless quantitative analysis of minerals using the full powder diffraction profile. Powder Diffraction 6, 2–9.

Walker, T., 1981. Seasonal salinity variations in Cleveland Bay, northern Queensland. Australian Journal of Marine & Freshwater Research 32, 143–149.

Webb, A.D., Dickens, G.R., Oliver, N.H.S., 2003. From banded iron-formation to iron ore: geochemical and mineralogical constraints from across the Hamersley Province, Western Australia. Chemical Geology 197, 215–251.

Webster, J.M., Davies, P.J., 2003. Coral variation in two deep drill cores: significance for the Pleistocene development of the Great Barrier Reef. Sedimentary Geology 159, 61–80.

Wiesler, M.I., Hua, Q., Zhao, J.X., 2009. Late Holocene $^{14}C$ marine reservoir corrections for Hawai'i derived from U-series dated archaeological coral. Radiocarbon 51, 955–968.

Woodroffe, S.A., 2009. Testing models of mid to late Holocene sea-level change, north Queensland, Australia. Quaternary Science Reviews 28, 2474–2488.

Yu, K.F., Zhao, J.X., 2010. U-series dates of Great Barrier Reef corals suggest at least +0.7 m sea level 7000 years ago. The Holocene 20, 161–168.

Yu, K.F., Zhao, J.X., Hodge, E., Hua, Q., Barbetti, M., Fink, D., 2007. Paired U-series and radiocarbon dating of Holocene corals from the South China Sea: evidence for large temporal variability in $^{14}C$ marine reservoir ages. Quaternary International 167–168, 468.