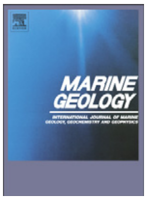
Marine Geology 346 (2013) 101–123

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo



Carbonate and terrigenous sediment budgets for two inshore turbid reefs on the central Great Barrier Reef

N.K. Browne [a,*], S.G. Smithers [b], C.T. Perry [c]

[a] Experimental Marine and Ecology Laboratory, Dept. of Biological Sciences, National University of Singapore, Singapore 117543, Singapore
[b] School of Earth and Environmental Sciences, James Cook University, Townsville, Queensland 4811, Australia
[c] Department of Geography, College of Life and Environmental Sciences, University of Exeter, Exeter EX4 EPS, UK

ARTICLE INFO

Article history:
Received 21 May 2012
Received in revised form 17 August 2013
Accepted 24 August 2013
Available online 31 August 2013

Communicated by J.T. Wells

Keywords:
carbonate budgets
coral community
bioerosion
sedimentation
turbidity
reef accretion

ABSTRACT

Inshore turbid zone reefs on the Great Barrier Reef (GBR) occur within 20 km of the mainland coast under marine environmental conditions (with respect to sedimentation rates, turbidity and water quality) that are generally considered marginal for reef growth. Despite this, data from various benthic habitat assessments report high (>30%) coral cover in these environments and reef core records show them to be characterised by relatively rapid rates of vertical accretion (2–8 mm/year), a long-term trend indicative of high net carbonate productivity and in-situ carbonate framework accumulation. However, the lack of quantitative data on terrigenous sediment input and flux rates, and on carbonate production rates has inhibited understanding of both ecological timescale rates of carbonate production and the aggregated long-term net impacts of sediments on reef growth. To address this knowledge gap a modern carbonate budget and terrigenous sediment model, that quantified allochthonous sediment inputs onto, within and off reef, was developed at two inshore reefs: Middle Reef and Paluma Shoals. Both are located within the central region of the GBR and are subjected to high terrigenous sediment load (>11,000 tonnes/year) and fluctuating turbidity (5 to >100 mg/L) regimes. Based on sediment dynamic modelling, over 81% of sediments delivered were transported off reef, with net sediment accumulation limited to sheltered reef habitats. Net carbonate production was high (>6.9 kg/m^2/year) due to high coral cover (>30%), high coral calcification rates (*Acropora* average 6.3 g/cm^2/year), and low bioerosion rates (0.3 to 5 kg/m^2/year), but varied spatially with highest net carbonate production (>10 kg/m^2/year) within deep (>−2 m at LAT) windward reef zones. High carbonate framework production has enabled Middle Reef and Paluma Shoals to vertically accrete rapidly: Middle Reef establishing at depths of ~4 m, Paluma Shoals at ~3 m depth and both reaching sea level in <1200 years. Carbonate and terrigenous sediment inputs were used to develop a reef growth model with time and depth that illustrates how rates and modes of reef growth varied temporally as the reefs approached sea level. Both Middle Reef and Paluma Shoals are still actively accreting, although vertical reef growth potential is increasingly constrained as the reef flats infill at present sea level.

1. Introduction

Turbid zone reefs on the central Great Barrier Reef (GBR) are situated inshore (within <20 km of the mainland coast) in shallow water (<15 m) where high sediment yields and wave-driven resuspension of fine sediments from the seafloor lead to large fluctuations in turbidity (0 to >100 mg/l). Suspended sediments reduce light availability for photosynthesis and energy production (Rogers, 1990; Wolanski and De'ath, 2005), and deposited sediments can increase coral mortality by smothering and burial (Loya, 1976), reduce larval settlement, and increase the prevalence of tissue infections (Bruno et al., 2003; Nugues and Callum, 2003; Fabricius, 2005). Sediments are delivered to these inshore regions through land and river runoff from urban and agricultural catchments, and are often associated with nutrients and contaminants (Fabricius and Wolanski, 2000; Fabricius et al., 2003). The inshore zone also includes the inshore sediment prism (ISP), a thick (5–10 m) wedge of terrigenous mixed sand and mud derived from long-term fluvial inputs deposited (Larcombe and Carter, 1998; Hopley et al., 2007). These environmental conditions are generally considered marginal for reef growth, which together with the lack of detailed ecological descriptions of turbid zone reefs (often impeded by limited visibility associated with high turbidity), has led to inferences that these reefs are degraded and characterised by low coral cover and species diversity (Neil et al., 2002; Woolridge et al., 2006; Jupiter et al., 2008). However, these perceptions are in stark contrast to the often high coral cover and diversity reported on many turbid zone reefs (Veron, 1995; Sweatman et al., 2007; Browne et al., 2010), and the rapid vertical accretion rates (range 2 to 13 mm/year) calculated for these environments, rates often exceeding those determined in offshore clear-water settings (Perry et al., 2009; Palmer et al., 2010; Perry and Smithers, 2010;

---

* Corresponding author at: DHI Water and Environment (S) Pte Ltd, 200 Pandan Loop, #08-03 Pantech 21, Singapore 128388, Singapore. Tel.: +65 83016079.
E-mail address: Nicola.Browne@my.jcu.edu.au (N.K. Browne).

http://dx.doi.org/10.1016/j.margeo.2013.08.011

Perry et al., 2012, in press). These studies suggest that benthic communities on inshore turbid reefs have adapted to high sedimentary regimes and are potentially more robust and resilient than previously thought. A recent review of inshore turbid zone reefs by Browne et al. (2012a) discusses these key environmental issues as well as synthesising available geological and palaeoecological data to provide a context to current community change. The review highlights the lack of data on inshore reefs compared to their clear-water counterparts and, as such, current understanding of how inshore turbid reefs have grown and developed remains limited, as are predictions of inshore reef resilience to future environmental change.

The accumulation of reef framework required for reef growth is reliant on the balance between carbonate production by calcifying organisms (corals, calcareous coralline algae (CCA), molluscs, crustaceans, bryozoans, foraminiferans, serpulid worms), carbonate framework erosion from bioerosion (borers, urchins, fish) and physical destruction (e.g. storm event; Stearn et al., 1977; Hubbard et al., 1990) and sediment input and export rates (Kleypas et al., 2001). Carbonate destruction produces carbonate sediments, which are either stored on the reef (Hubbard et al., 1990) or are transported off-reef (Hughes, 1999). The assessment of gross carbonate production, destruction and sediment production is quantified as a reef carbonate budget, and can provide valuable insights into reef growth potential (Edinger et al., 2000; Perry et al., 2012, in press). For example, the assessment of the dominant coral taxa and of rates of carbonate production will give an indication of coral community stability and temporal variations in productivity which influence reef growth (Perry et al., 2008a; Perry et al., 2013). However, few studies have quantified carbonate budgets for coral reefs in detail, exceptions include studies from the Caribbean by Stearn et al. (1977), Scoffin et al. (1980), Hubbard et al. (1990), Eakin (2001), Mallela and Perry (2007), Perry et al. (2012a, 2012b), a study in Hawaii by Harney and Fletcher (2003), work by Edinger et al. (2000) in Indonesia, and by Hart and Kench (2007) in Torres Strait.

In particular, the role of terrigenous sediments in influencing carbonate budgets, and thus reef growth in terrigenous sediment influenced settings is poorly understood, although it has been conceptually modelled (Woolfe and Larcombe, 1999). This model depicts the balance between the accumulation of terrigenous sediments on a reef, together with carbonate production and removal, to explain how reefs can persist where turbidity is high. Kleypas et al. (2001) also recognised the importance of sedimentary processes and defined four reef growth models based on key reef processes (production, import, export, bioerosion), which can be broadly applied to a number of reef types, including turbid zone reefs. Both models provide useful insights into reef growth and development in terrigenous sedimentary settings, but remain qualitative due to the lack of detailed data available on both rates of carbonate production and on sedimentary regimes. Assessments of carbonate production and destruction rates, combined with data on sediment import, storage and export, are thus necessary to permit assessments of temporally and spatially variable rates of reef growth. Such reef growth models would also provide novel approaches for assessing how changing environmental conditions, particularly sedimentary regimes, influence long-term reef growth and development.

A number of methods can be used to calculate a reef's carbonate budget, including the alkalinity–anomaly technique which is based on assessing spatial variations in water chemistry changes (Smith and Kinsey, 1976; Chisholm and Gattuso, 1991), geological estimates from net carbonate production (Ryan et al., 2001), and the modelling technique which also focuses on net carbonate production and accumulation (Kleypas, 1997). However, the census technique which is based on reef organism cover and calcification rates, provides a number of advantages over these techniques because it is based on individual process measurements (Stearn et al., 1977; Scoffin et al., 1980; Hubbard et al., 1990; Mallela and Perry, 2007). It can be applied at the sub-reef scale to determine how carbonate budgets vary between different reef habitats; it evaluates the carbonate contributions from different reef organisms; and it can provide critical information on how environmental changes influence reef organisms, and thus carbonate production at different reef scales and stages of reef growth.

In this paper we use both new and established techniques to quantify carbonate production and destruction together with sediment import, storage and export at a high spatial resolution for Middle Reef (19°11 · 70′ S, 146°48 · 70′ E) and Paluma Shoals (19°5 · 43′ S, 146°33 · 5′ E). Middle Reef and Paluma Shoals are two turbid zone reefs located approximately 30 km apart on the inner-shelf region of the central GBR, and are of comparable size (~0.35 km^2). Both reefs are subjected to different hydrodynamic and anthropogenic influences: Middle Reef is relatively sheltered from strong offshore winds and waves, but is more exposed to elevated anthropogenic influences (e.g. dredge events, boating activity), whereas Paluma Shoals is exposed to strong winds and waves but is more distant from, and therefore less impacted by, direct anthropogenic pressures. Net carbonate production is calculated for each reef, and the influence of terrigenous sediments on reef growth and development is evaluated. Estimates of carbonate production and destruction are evaluated with error analysis and compared with published budgets for other reefs. This study represents the first high resolution census based carbonate budget for an entire reef on the GBR, and the first to incorporate a quantitative analysis of terrigenous sediment dynamics onto, within and off a reef system in the development of a quantitative reef growth model.

2. Field setting

2.1. Middle Reef

Middle Reef is a linear patch reef (1.2 km × 0.3 km) aligned with the dominant north-westerly (NW) currents that flow between Magnetic Island and the mainland in Cleveland Bay, north Queensland (Fig. 1). Coral cover extends to ~3.7 m below LAT and average live hard coral cover is >39% (see Browne et al., 2010 for benthic community description). The reef lies approximately 4 km offshore from Townsville, Australia's most populous tropical city with a large industrial base, and is surrounded by a shallow sea-bed (4 m at LAT) of muddy sands and sandy muds over a muddy Pleistocene clay (Carter et al., 1993; Lou and Ridd, 1997). Wind-driven waves entering the bay resuspend sediments, which are then transported northwards by currents through the Western Channel as turbid water (Lou and Ridd, 1996). Turbidity at Middle Reef can rise to around 40–50 mg/L after several days when significant wave height exceeds 1 m (Larcombe et al., 1994). It can also rise when flood plumes from the Ross River, whose mouth is situated approximately 8 km south of Middle Reef, discharge into the bay: sediment yield to Cleveland Bay from the Ross River is estimated to deliver >330,000 tonnes of sediment annually of which approximately 15,000 tonnes are fine suspended sediments (Belperio, 1983; Bainbridge et al., 2007). Flood plumes from the Burdekin River (total discharge in 2010 was 34.83 million ML (DERM, 2011) and total suspended sediment load is on average ~4×10^6 tonnes per year; Kroon et al., 2012), situated approximately 80 km further south, may also periodically reach Cleveland Bay and Middle Reef (McAllister et al., 2000; Devlin and Brodie, 2005).

2.2. Paluma Shoals

Paluma Shoals is located in central Halifax Bay approximately 30 km north of Townsville (Fig. 1). It consists of a larger southern shoal (500 m × 820 m) and a smaller northern shoal complex (Palmer et al., 2010), both of which extend down to a depth of ~3.5 m on the windward slope. This study focuses on the southern shoal which initiated on Pleistocene clays approximately 1200–1300 yr BP (Smithers and Larcombe, 2003; Perry et al., 2008b; Palmer et al., 2010), and has a mean hard coral cover of >30% (Browne et al., 2012b). The surrounding sea bed is shallow (3.5 m at LAT) and is dominated by mixed siliclastic