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Strong tidal currents and labile organic matter stimulate benthic decomposition and carbonate fluxes on the southern Great Barrier Reef shelf

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ABSTRACT

The southern Great Barrier Reef (GBR) shelf is characterized by a sharp across-shelf gradient from terrigenous to marine-derived organic matter, and by the presence on the outer shelf of the Pompey Reef Complex (PRC). The PRC runs parallel to the shelf edge and consists of many narrow, turbid channels where strong tidal currents and eddies foster high suspended loads and phytoplankton production that sustain lush gardens of suspension-feeding, benthic communities. Rates and pathways of benthic carbon decomposition and carbonate kinetics in relation to these characteristics were measured across the shelf. Flux rates of DIC, O_2, Mn, and dissolved inorganic nutrients across the sediment–water interface were rapid, increasing from inshore and peaking at the channels within the PRC. Rates of DIC (mean: 39.5 mmol m^{-2} d^{-1}; range: 14.5–103.2) and NH_4^+ production (mean =5.4 mmol m^{-2} d^{-1}; range=1.6–23.7) from incubated sediments were rapid compared with other shelves. Sulfate reduction (mean:1.2 mmol S m^{-2} d^{-1}; range: 0.1–6.1) and iron reduction (mean: 2.7 mmol Fe m^{-2} d^{-1}; range: 0.6–4.6) were minor diagenetic pathways, measured only in inshore and mid-shelf deposits. Manganese reduction (mean: 12.5 mmol Mn m^{-2} d^{-1}; range: 0.5–55.9) was the second most important pathway, as sites seaward of the inner shelf were dominated by aerobic respiration (63–99% of total C oxidation). There was no detectable production of either CH_4 or N_2O. Rates of O_2 consumption were rapid (mean: 44.6 mmol m^{-2} d^{-1}; range: 10.2–121.9) with the percentage of O_2 involved in chemical oxidation declining from 90% to 92% inshore to $<10\%$ at the shelf edge. From inshore to the mid-shelf reefs, $\approx 20\%$ of remineralized DIC was involved in carbonate dissolution whereas $\approx 10\%$ was involved in authigenic mineral formation on the outer shelf and at the shelf edge. N_2 production was rapid and much greater than nitrogen fixation but neither showed across-shelf patterns. High tidal energy within the PRC leads to increased exposure of high-quality organic matter to microbes and oxygen, fostering rapid rates of aerobic respiration, manganese reduction, and carbonate dissolution. Our data supports the notion that tropical shelves act as efficient 'incinerators' of organic matter.

1. Introduction

The world's continental shelves are key ecosystems for the deposition, cycling, and storage of essential elements, especially carbon, nitrogen, and phosphorus, found in organic and inorganic matter, including the shells, tests, and skeletons of biota. Organic matter depositing onto continental margins is derived from a number of sources, including terrestrial material exported via estuaries and marine material produced in situ and imported from the open sea. Recent estimates suggest that about 90% of total organic carbon, 65% of total carbonate, and about 80% of terrigenous matter reaches the coastal zone and accumulates in shelf sediments (Gao, 2010). The spatial and temporal distribution of these materials is poorly constrained to the extent that generalizations are difficult; at best, it can be stated that physical forces play a key role in regulating the distribution of organic matter on shelves (Brink, 2004) and that typology of shelf ecosystems is ordinarily delimited by latitude (Alongi, 2005). What is clear is that the biogeochemistry of many shelf ecosystems, particularly those in the tropics, remains poorly understood.

Tropical shelf margins receive at least an order of magnitude more water, sediment, and organic matter compared with shelves of higher latitude, acting as 'organic carbon incinerators' (Aller and Blair, 2006) respiring nearly all organic matter, with minor storage in sediments (Brunskill, 2010); a large fraction of recycled inorganic carbon is likely removed as $CaCO_3$ on tropical margins (Milliman, 1993). In the tropics, storage of carbonate carbon is important in coral reefs and on carbonate-dominated shelves,

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such as the GBR (Kench, 2011). Many tropical shelves, however, may be carbon neutral or net sources of CO_2 to the atmosphere due to the predominance of microbial life in warm temperatures, although it is likely that there is seasonal switching between being a net CO_2 source or sink, as discovered recently in the Gulf of Papua (McKinnon et al., 2007).

On the northern and central sections of the Great Barrier Reef shelf, highly variable fluxes of carbon, nitrogen, and other nutrients reflect the physical and biological complexity of the shelf proper (Furnas et al., submitted for publication); differences in net carbon flux are apparent both along- and across-shelf (Alongi et al., 2007). The most consistent shelf feature is high rates of microbial respiration in both waters and sediments to the extent that little organic material is preserved; pelagic nutrients are intensely recycled within the microbial loop and passed up to the mesozooplankton (Alongi and McKinnon, 2005). A carbon mass balance (Brunskill et al., 2002) for the central section of the GBR shelf indicates that production and respiration are roughly balanced with relatively little carbon burial in coastal bays and mangrove estuaries; most carbon removal is inorganic carbonate accumulation on the mid- and outer-shelf.

A sharp across-shelf gradient of inshore terrigenous mud and quartz sand to mixed terrigenous-carbonate deposits mid-shelf to impure and pure carbonate habitats on the outer margin, is the dominant sedimentological characteristic of the GBR shelf (Hopley et al., 2007). The persistence of water trapping due to friction and coastal boundary layers ensure that most terrigenous material persists as a narrow band along the inner shelf (Wolanski, 1994). The middle shelf is sediment-starved, having only a thin veneer of Holocene skeletal carbonate sediment; this is a transitional region with mixed sources of sediment and organic matter (Larcombe and Carter, 2004), with cyclones transporting post-storm mud drapes into the skeleton carbonate deposits. These sediments are fully remixed by persistent bioturbation. Cyclone-driven flow produces shelf-parallel, bed-sediment transport that is delimited as dunes and ribbons on the middle shelf (Belperio and Searle, 1988; Larcombe and Carter, 2004).

The southern section of the GBR shelf is similarly characterized by an across-shelf gradient of sedimentary facies and habitats, yet has several unique characteristics. First, it contains the largest number of coral reefs, and the largest individual reefs, being the largest (and widest) section of the shelf by area. Second, dissolved and particulate nutrient levels are relatively high, partly owing to the fact that most terrestrial material enters the southern section (Furnas, 2003). Third, tides reach 10 m inshore and exceed 4 m within the reefs. Fourth, the southern section contains the unique Pompey Reef Complex, composed of a large number of individual reefs (many between 50 and 100 km^2) extending over a distance of 140 km. This complex parallels the shelf edge and is 10–15 km wide. The entire reef tract is not on the shelf edge, which lies another 20 km seaward.

The outer shelf margin is dominated by a series of fault-controlled steps (Hopley et al., 2007) where sediments scoured from the Pompey Reef Complex have accumulated (Maxwell, 1970). Finally, narrow channels cut through the Pompey Reef Complex, reaching depths of 60–75 m (Hopley, 2006); tidal currents of up to 4 m s^{-1} have been measured, scouring the channels and sustaining gardens of numerous and highly diverse, suspension-feeding benthic communities that thrive on the hard-bottom carbonate platforms at both ends of each channel (Pitcher et al., 2009). Interspersed among these communities is a thin veneer of unconsolidated gravel, coarse carbonate sand and coral rubble that is colonized by cryptic fauna and encrusting bryozoans (Maxwell, 1968). Pitcher et al. (2007) have identified many species of bryozoans, sponges, gorgonians, crinoids, fishes, crustaceans, bivalves, starfish, urchins, and corals among these communities, and have identified areas of relic coralline outcrops with a rich sessile fauna that includes living corals. These invertebrate gardens benefit from high loads of suspended food particles and high rates of phytoplankton production stimulated by the strong tidal currents and eddies (Crosbie and Furnas, 2001; Furnas, 2005).

In this paper, we describe measurements taken across the southern GBR shelf to test the hypotheses that (A) absolute rates of benthic microbial decomposition will increase, and (B) the relative contribution of anoxic metabolism to total benthic carbon decomposition will decrease, in relation to increases in tidal current velocities and organic matter quality from the inshore to the Pompey Reef Complex. We also assess the impact of changes in these microbial processes on carbonate dissolution and precipitation in sediments across the shelf.

2. Methods

2.1. Study sites

Sampling was conducted at 15 stations in April and September 2009 and in February 2010 across the southern GBR shelf (Fig. 1; Table 1). Inshore stations IS9 and IS10 were located north of Shoal Point in Sand Bay and near Cape Parmerston in Ince Bay, respectively. Stas. MS7 and MS8 were located at mid-shelf, south of Parker Reef, and southwest of Pompey Reef, respectively. Stas. BR1, GR1, and PR1 were located within mid-shelf reef lagoons (Fig. 1; Table 1). Sta. BR1 was located within the lagoon formed by Box, Stevens, Credlin, Cannan, and Nixon Reefs; Sta. GR1 was located with the lagoon enclosed by Chavel, Goble, Cole, Briggs, and McIntyre Reefs. Sta. PR1 was situated on the northern leeward side of Pompey Reef. Three stations (Stas. PRC4, PRC5, and PRC6) were established within the outer lagoon of the greater Pompey Reef Complex, in close proximity to channels formed between the outer shelf reefs of the complex. Two stations (Stas. OS1B and OS2) were located on the open ocean side of these channels. Sta. OS1 was originally sampled on the first cruise, but due to lack of sufficient unconsolidated sediment, subsequent sampling was conducted at Sta. OS1B (Table 1; Fig. 1). Sediment samples were taken at Sta. OS1 only for grain size and stable isotopes. Two stations (Stas. SB13 and SB14) were located at the shelf break at depths of 150 and 160 m, respectively (Table 1; Fig. 1).

Sediment cores to a maximum penetration depth of 25 cm were taken using a modified 0.027 m^2 Bouma boxcorer at Stas. IS9, IS10, MS7, MS8, GR1, BR1, PR1, SB13, and SB14. The remaining stations were sampled with a 0.2 m^2 Smith-McIntyre grab with rubber-sealed lids.

2.2. Sediment granulometry and solid-phase elements

Samples for sediment granulometry and solid-phase elements were taken in April 2009. Median grain size, sorting coefficient, percent silt, sand, and clay of surface (0–5 cm) sediments were determined using the standardized procedure of Folk (1974) on an automated particle size counter. Further sub-samples were frozen, wet and dry weighted to determine water content, and ground to a fine powder for determination of total carbon and total nitrogen on a Perkin-Elmer 2400 CHNS/O Series II Analyzer and for total organic carbon on a Shimadzu TOC Analyzer with solid sampler. Total P, S, Mn, and Fe were determined after strong acid digestion on a Varian Liberty inductively coupled atomic emission spectrometer following the procedure of Loring and Rantala (1992). Total inorganic carbon was assumed as $CaCO_3$, and was determined by difference between the total carbon and total organic carbon concentrations.