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Mine waste disposal leads to lower coral cover, reduced species richness and a predominance of simple coral growth forms on a fringing coral reef in Papua New Guinea

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ABSTRACT

A large gold mine has been operating at the Lihir Island Group, Papua New Guinea since 1997. The mine disposes of waste rock in nearshore waters, impacting nearby coral communities. During 2010, 2012 we conducted photographic surveys at 73 sites within 40 km of the mine to document impacts of mining operations on the hard coral communities. Coral communities close to the mine (~2 km to the north and south of the mine) were depaurperate, but surprisingly, coral cover and community composition beyond this range appeared to be relatively similar, suggesting that the mine impacts were limited spatially. In particular, we found mining operations have resulted in a significant decrease in coral cover (4.4% 1.48 km from the disposal site c.f. 66.9% 10.36 km from the disposal site), decreased species richness and a predominance of less complex growth forms within ~2 km to the north and south of the mine waste disposal site. In contrast to the two 'snapshot' surveys of corals performed in 2010 and 2012, long term data (1999–2012) based on visual estimates of coral cover suggested that impacts on coral communities may have been more extensive than this. With global pressures on the world's coral reefs increasing, it is vital that local, direct anthropogenic pressures are reduced, in order to help offset the impacts of climate change, disease and predation.

1. Introduction

Coral reefs worldwide are threatened by multiple stressors including climate change, eutrophication, pollution, ocean acidification, pathogens, crown-of-thorns starfish and increased turbidity and sedimentation (Ban et al., 2014). Of these, the impacts of increased sediments and nutrients are amongst the most serious with 25% of the world's coral reefs estimated to be under threat from increasing exposure to both sediments and nutrients (Burke et al., 2011). High levels of sedimentation and turbidity may be derived from natural or anthropogenic sources (Erftemeijer et al., 2012). Natural sources of sedimentation include stream discharge (Loya, 1976; Golbuu et al., 2008, 2011), terrestrial runoff after heavy rain (Jokiel et al., 1993; Fabricius et al., 2007) and resuspension of sediments after storms (Dutra et al., 2006). Anthropogenic sources of increased sedimentation include dredging (Rogers, 1983, 1990; Brown et al., 1990; Erftemeijer et al., 2012), mine waste disposal (Risk and Edinger, 2011; Edinger, 2012) and the exacerbation of natural processes through land clearing, over grazing and coastal development (McClanahan and Obura, 1997; Storlazzi et al., 2011).

Sedimentation and turbidity impacts corals either directly through smothering or indirectly through reducing the amount of light reaching the coral polyps. Sediment that has settled on the substrate may smother and/or bury corals (Hubbard, 1986; Fabricius and Wolanski, 2000; Philipp and Fabricius, 2003) reducing coral growth rates (Aller and Dodge, 1974), increasing expenditure of energy through sediment removal (Riegl and Branch, 1995), hampering coral larval settlement (Babcock and Davies, 1991) and survival (Sato, 1985) and modifying coral growth forms (Risk and Edinger, 2011; Fabricius et al., 2012). Suspended sediments increase turbidity limiting the amount of light available to phototrophic organisms (Loya, 1976; Anthony and Connolly, 2004). This can reduce calcification (Gattuso et al., 1999) and coral fertilization rates (Humphrey et al., 2008) and increase the vulnerability of corals to pathogens through reduced vitality (Pollock et al., 2014).

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Papua New Guinea (PNG) is the largest Pacific Island nation (462,840 km^2) (Govan et al., 2009) and is comprised of >600 islands located in the western Pacific Ocean to the north of Australia (Bulia and Sullivan, 1990). Coral reefs (mostly fringing and patch reefs) are found around much of the PNG coastline (Huber, 1994) covering an estimated area of 13,840 km^2 (Chin et al., 2011). PNG reefs are globally significant in terms of their extent and the fact that they are located in the Indo-West Pacific biogeographic centre of coral diversity (Veron, 1986, 1993, 2000).

While PNG's reefs are thought to be in relatively good condition, they have been poorly studied (Huber, 1994). The few studies that have been conducted in the area indicate they support a diverse range of reef organisms. For example, 860 species of fish and 400 species of coral have been identified from a single bay (Kimbe Bay on the north coast of New Britain (Chin et al., 2008)). Monitoring surveys conducted by The Nature Conservancy and the Wildlife Conservation Society indicate the reefs are generally in good condition with coral cover ranging from 40 to 50%. However, coral cover has been reduced in some areas as a result of crown of thorns starfish outbreaks (Chin et al., 2008) and in more localized areas live coral has been impacted by mine waste, sedimentation, nutrient runoff from agriculture and over-fishing (Miller and Sweatman, 2004).

The Lihir Island Group is 650 km from the PNG mainland and 50 km from the nearest large island (New Ireland) and surrounded by deep (~1800 m) oceanic water. Although it experiences a high rainfall (mean annual rainfall of ~3000 mm) that results in temporarily elevated Total Suspended Solids (TSS) in the surface layer, TSS levels are usually low (<5 mg L^{-1}, Thomas et al. (2003)). However, since the late 1990s a gold mine has been operating on the eastern coast of the island, disposing of waste rock into coastal waters, close to a fringing coral reef and TSS levels at depths ranging from 6 to 10 m are >25 mg L^{-1} for 90% of the time with regular short-term peaks above 500 and 1000 mg L^{-1} (Thomas et al., 2003).

Most documented impacts of sediment on coral communities have occurred in shallow nearshore environments as a result of riverine runoff or plumes generated by dredging (Dodge and Vaisnys, 1977; Prouty et al., 2010; Golbuu et al., 2011; Erftemeijer et al., 2012; Butler et al., 2013; Fabricius et al., 2014). Studies of the impacts of sediment and increased turbidity on coral reef communities adjacent to deep, oligotrophic oceanic water, such as those at the Lihir Island Group are rare (although for exceptions see (Roy and Smith, 1971; Gabrie et al., 1985; Rotmann and Thomas, 2012). Given that corals growing in these environments are unlikely to be naturally exposed to elevated sediment levels for extended periods, the disposal of soil and waste rock adjacent to the Lihir Island coral communities provides an opportunity to investigate how an oceanic coral community responds to anthropogenic sediment inputs.

2. Materials and methods

2.1. Study site

The Lihir Island Group (3° S, 152° 30′ E) is part of the Bismark Archipelago, located in Papua New Guinea, 920 km northeast of the nation's capital, Port Moresby (Fig. 1). The largest island, Niolam (~10 × 20 km) is comprised of 5 Miocene-Pleistocene volcanoes. The crater of one of the volcanoes (Luise) contains the largest epithermal gold deposit ever discovered (Müller et al., 2002). Most of the island is fringed by a narrow reef flat and seaward of the reef edge, the seabed slopes steeply into deep water (>1500 m) within 15–20 km to the east of Luise harbour.

The Lihir gold mine (currently owned by Newcrest Mining Limited) has been operating on Niolam Island since 1997. Waste from the gold refining process is referred to as tailings and is disposed via two pipelines that discharge below the euphotic zone (90 m) at a depth of 115 m into Luise harbour. The tailings material consists of a fine slurry of solids (silt 93%, clay 5% fine, sand 2%), water, dissolved metals (Zn, Cu, As, Cd, Hg, Pb, Ni, Cr and Ag) and small amounts of process chemicals (Lihir Gold Limited, 2005). The tailings slurry is denser than the surrounding seawater and so is designed to sink and not be entrained into the surface waters (NSR, 1989). Approximately 60 km^2 of the surrounding seabed is impacted by mine-derived material (Lihir Gold Limited, 2005). To date, there has been no clear evidence of upwelling of the submarine tailings into surface waters.

Overburden (soil and rock overlying the ore body) that is too low in ore for refining is dumped into Luise harbour by split hopper barges that operate 24 h a day, 365 days each year. Thirty-five Mt y^{-1} of overburden is disposed into depths of ~100 m, between 1 and 3 km from the shore. During trial dumping operations it was estimated that as much as 5% of the dumped waste did not reach the seabed, but remained in suspension (NSR, 1989). The fine material accompanying the overburden creates turbidity plumes that, depending upon the sea and weather conditions, may extend to reach the nearby fringing coral reefs (author pers. obs.).

Additional sources of sediment to Luise Harbour as a result of mining operations include erosion of a shoreline low grade ore stockpile, wind-borne dust from the mine, roads and processing areas and rainfall-associated erosion of exposed soils being transported in a number of coastal streams draining disturbed areas. Agricultural herbicides such as tebuthiuron, atrazine and diuron are known to inhibit photosynthesis of the coral's symbiotic dinoflagellates (Jones et al., 2003). However, whilst these may be present in the runoff from other regions where large-scale agriculture is practiced, herbicides are not used in the Lihir Island Group as the local people are subsistence farmers (Dambacher et al., 2007).

Most of the east coast of Niolam Island is fringed by a narrow coral reef which shelves to a terrace at ~10 m and then slopes steeply into deep water (>500 m depth). Coral communities are most abundant in waters shallower than 20 m depth, with the seabed below this depth often being very steep rubble/sand slopes inhabited mainly by sponges and soft-corals. The exception to this is Luise harbour which was formed by the partial slope failure of the original stratovolcano (Müller et al., 2002). The northern end of the harbour originally comprised a black sand beach (Turtle Beach; since reclaimed by mining operations and covered in tonnes of waste rock). From the shoreline the sandy seabed slopes gently to ~40 m and coral reef is generally absent. There were some coral reefs inside Luise harbour prior to the mine construction, but these were destroyed when wharves were constructed (Thomas, 2003). Reefs were also reported in deeper water (~60 m) within the harbour, but these would now be buried under several metres of dumped rock and sediment (Done, 1996a; Thomas, 2003). The nearest live coral reefs to the mine site in Luise harbour are at Kapit Reef to the north and Puput Point to the south (Fig. 2).

The prevailing climate is monsoonal, with a high average rainfall of about 3000 mm y^{-1}. Rainfall is relatively high during most of the year, but heavier during the period from December to March. The major influencing ocean current is the South Equatorial Current (SEC) that flows westward and bifurcates at the Papua New Guinea mainland, becoming the East Australian Current to the south. The tidal range is relatively small: 0.3 m during the neaps and 1.5 m during spring tides. The prevailing swell is highest during the austral summer when it is mainly from the northeast; swell height reduces in winter and is mostly from the east-southeast (NOAA, 2015). Winds are generally strongest during winter when they