Coral Tissue Thickness as a Bioindicator of Mine-Related Turbidity Stress on Coral Reefs at Lihir Island, Papua New Guinea

BY SEA ROTMANN AND SÉVERINE THOMAS

Luise Harbor with dumping barge in the foreground. *Photo courtesy of Lihir Management Company*

ABSTRACT. Work described here assessed the feasibility of using variations in tissue thickness in massive Porites corals as a bioindicator for mine-related sediment stress. We examined parameters influencing coral tissue thickness, including water depth, location, season, and time period within the lunar month. Coral tissue thickness was observed to grow linearly over the lunar cycle until it dropped abruptly by about 20% after the day of the full moon. Although some relationship was observed between tissue thickness reduction and turbidity, no systematic relationship was found between turbidity zones and light levels. The aim was to develop sampling protocols that minimized the effect of natural variability and maximized the potential use of tissue thickness by mine management as a cheap, reliable, real-time indicator of coral stress response to increased turbidity on Lihir Island, Papua New Guinea. This method could prove particularly useful at remote locations or where a fast assessment of coral stress response (< 1 month) needs to be made.

INTRODUCTION

Coral reefs are among the most diverse and productive ecosystems on Earth. Though they are well adapted to surviving natural environmental changes, and acute natural disturbances are critical to maintaining diversity in coral reefs (Richmond, 1993), much concern has been raised in the past two decades about the rapid degradation of coral reefs. Radiation stress (temperature and UV light, together with extreme weather events related to climate change) is the primary stress factor for coral reefs, with cumulative anthropogenic stressors (sedimentation and eutrophication) acting as significant stress-reinforcing factors (e.g., Carpenter et al., 2008; Maina et al., 2011). Anthropogenic stressors do not always fall neatly into only one of these major stress categories (climate change, sedimentation, and eutrophication), yet they can transform natural disturbances into persistent and chronic problems (e.g., terrestrial runoff mixed with pollutants). Thus, it is important to identify natural environmental variability in coral reef systems before it is possible to identify changes due to unnatural stressors, such as the mining-related sediment loading on Lihir Island (Papua New Guinea, PNG) discussed here.

SEDIMENT-RELATED STRESS ON CORAL REEFS

Increased turbidity, consequent reduced light levels, and sediment accumulation, are among the most common anthropogenic stressors on coral reefs (see literature reviews in Rotmann, 2004, and Fabricius, 2005). These sediment-related impacts may affect coral colonies physically through smothering, in the case of high sediment accumulation (e.g., Fabricius, 2005), or physiologically, through a reduction in carbohydrate production and modified oxygen production due to reduced light or photosynthetically available radiation (PAR; e.g., Piniak and Storlazzi, 2008). The issue becomes more complex when assessing mining-derived, rather than naturally occurring, sediment in the water column as it involves additional contaminants and often greater rates of (chronic) sedimentation.

We found turbidity to be the prominent sediment-related impact on shallow-water communities on Lihir Island. Turbidity reduces exposure of photosynthetic reef organisms to PAR by absorbing and scattering light (Thomas et al., 2003). Increased turbidity may result in decreased coral species diversity and abundance, changes in coral morphology and metabolism, reduced tissue biomass and lipids, and a shift in coral zonation toward shallower depths (for a review, see Fabricius, 2005). It was also found to lead to both increased and decreased coral bleaching incidents (see, e.g., Rogers, 1979, and Ayoub, 2009, respectively).

Corals adapt to increased turbidity by photo-adaptive mechanisms similar to those used to adapt to increased depth, including undergoing changes at the cellular level and changing their symbionts, behaviors, and morphologies (Meesters et al., 2002). Some studies found no coral tissue damage or mortality as a result of elevated turbidity (see Fabricius, 2005), and increased turbidity can be beneficial by supplying organic material as a food source (Anthony, 2000; Weber et al., 2006) or by mitigating the deleterious effects of bleaching by reducing the amount of solar radiation reaching the zooxanthellae (Baker et al., 2008;

Sea Rotmann *(drsea@orcon.net.nz) is an environmental consultant in Wellington, New Zealand.* **Séverine Thomas** *is a research program manager at the Université de Brest, Institut Universitaire Européen de la Mer, Plouzané, France.*

Ayoub, 2009). However, it is expected that species composition will change in highly turbid conditions, as some species are significantly more adept at surviving in highly turbid waters than others (see Fabricius, 2005).

Values of suspended sediment concentration (SSC) around coral reefs vary greatly with natural conditions (turbidity may be directly related to SSC via calibration with field samples, and both terms are used interchangeably from here onward): SSC at reefs in pristine conditions have been measured to be less than 1 to more than 30 mg L^{-1} (see Thomas, 2003, for a literature review). This variation explains why, despite the abundant literature on the subject, it remains impossible to define environmental threshold levels that separate natural conditions from anthropogenic influence (Kirsch, 1999; Orpin et al., 2004; Wolanski et al., 2008; Browne et al., 2010). In the context of this study, it implies that local impact zones had to be defined based on a baseline study and measurements during mining operations in order to assess the effect of mining activity on fringing coral reefs.

CORAL TISSUE THICKNESS AS A BIOINDICATOR FOR SEDIMENT STRESS

Various measurements have been used to assess sediment stress response in corals. However, these techniques do not always give clear results and often involve expensive and sophisticated equipment, making them of limited use in remote locations or developing countries where 90% of the world's reefs are located.

A promising method for remote locations is to use tissue thickness of *Porites* corals as a bioindicator for coral "health" (Barnes and Lough, 1992; Cooper et al., 2009). Bioindicators are organisms that change visibly or measurably in response to changes in ecosystem health at the level of individuals, populations, and assemblages, and the best bioindicators respond in known and predictable ways. A good bioindicator species is representative of other species in the ecosystem, is abundant as well as easy to identify and to sample, and shows a graduated response to increasing stress. Coral tissue thickness of *Porites* refers to the depth of skeleton occupied by tissue. It fulfils all the criteria listed above for a good bioindicator and was ranked as a high-priority indicator for use in both long- and short-term reef monitoring programs by Cooper et al. (2009).

Indeed, tissue thickness is found to be an important stress-response indicator in corals that bleach (Loya et al., 2001), corals in areas of high sedimentation (Barnes and Lough, 1999), shaded corals (True, 2004), corals living closest to terrestrial and fluvial runoff (Jupiter et al., 2010), corals in competition with turf algae (Quan-Young and Espinoza-Avalos, 2006), corals in waters that have lower nutrient content (Lough and Barnes, 2000; Cooper, 2008), and estrone-treated corals (Tarrant et al., 2004). Tissue thickness of *Porites* was also shown to vary naturally with water depth (True, 1995) and over the surface of a colony, being highest on the summits (Barnes and Lough, 1992). Finally, there was no difference in tissue thickness between different species of massive *Porites* (Barnes and Lough, 1992). In this study, we aimed to assess, in detail, the usefulness of the tissue thickness of *Porites* corals as a bioindicator for mining-related sediment stress on corals.

General Process of Tissue Growth

Porites corals have perforated skeletons in which vertical skeletal elements have many holes, and thus all skeletal cavities above the last dissepiment are interconnected. A dissepiment is a thin, horizontal skeletal bridge formed between vertical skeletal elements that isolates the coral tissue from the skeleton vacated by the tissue during growth (see Plate 1 in Barnes and Lough, 1992). Thus, the uplift of the lower surface of the tissue (polyp base) and emplacement of new dissepiments must occur at the same time over the entire colony. Barnes and Lough (1993) developed a conceptual model—the "Townsville model of coral growth"—showing that three growth processes are involved in annual density band formation in massive *Porites*:

1. Extension of skeletal elements at the outer surface of a colony
2. Thickening of skeletal elements throughout the depth of the tissue layer
3. Periodic and abrupt uplift of the lower margin of the tissue layer, reducing tissue thickness by about 20%, and simultaneous building of new dissepiments at the base of the tissue.

Influence of the Lunar Cycle on Tissue Thickness

Lunar cycles are a potential environmental cue for synchronous uplift of the tissue layer, as they are known to trigger spawning and larval release (Harrison et al., 1984). Gorbunov and Falkowski (2002) suggested that photoreceptors would enable corals to sense blue moonlight. Despite this recognition of a probable link between lunar cycles and dissepiment emplacement and fine band formation (e.g., Winter and Sammarco,

2010), systematic experimental analysis to determine the exact timing and way in which this process occurs has not been carried out to date. This study quantifies the influence of the lunar cycle on tissue thickness and how this knowledge can be applied when using tissue thickness measurements as a bioindicator of coral stress.

STUDY SITE: LIHIR ISLAND, PAPUA NEW GUINEA

Site Description

The Lihir Island Group is located approximately 50 km northeast of New Ireland in Papua New Guinea (3°05'S 152°38'E, Figure 1). Lihir Island is ~ 20 km long and 10 km wide and was formed around five Miocene-Pleistocene extinct volcanoes. It is mostly mountainous, and has dome-shaped peaks up to 600 m high and razorback ridges separated by deep valleys. The coastal plain is narrow and infrequently bordered by sandy beaches. Most of the coast is fringed by a shallow coral reef plateau, except Luise Harbor, which is the naturally collapsed and submerged part of a caldera and is covered mostly by volcanic black sand without coral reefs. The mining activity is taking place within the land-based part of the caldera.

Mining Operations and Sediment Issues

In 1997, the Lihir Management Company (LMC), now taken over by Newcrest Mining Limited, began operating an open-pit gold mine in Luise Harbour, on the east coast of Lihir Island, to exploit one of the world's largest gold deposits to date. The plant site is located at PutPut Point (see the photo on the first page of this article and Figure 2) where a deep-sea tailings discharge point is located 115 m below sea level. As this depth is below the thermocline, material discharged from this outlet was not expected to be re-entrained to the surface (NSR, 1989). After 14 years of operations, the initial forecast seems to have held true, with no clear evidence of upwelling of mill tailings from the submarine tailings disposal (STD) system. A detailed study on the impacts of STD on deep-sea benthos showed higher levels of arsenic and beryllium close to the tailings outfall at 60 m depth (SAMS, 2010). However, it was thought likely to be derived from surface run-off from acid rock drainage.

Mine construction and operations also increased sediment-loaded runoff to the nearby sea due to vegetation clearing; road, airport, and operational infrastructure construction; and the accumulation of low-grade ore stock piles near the coast exposed to a wet climate. It was

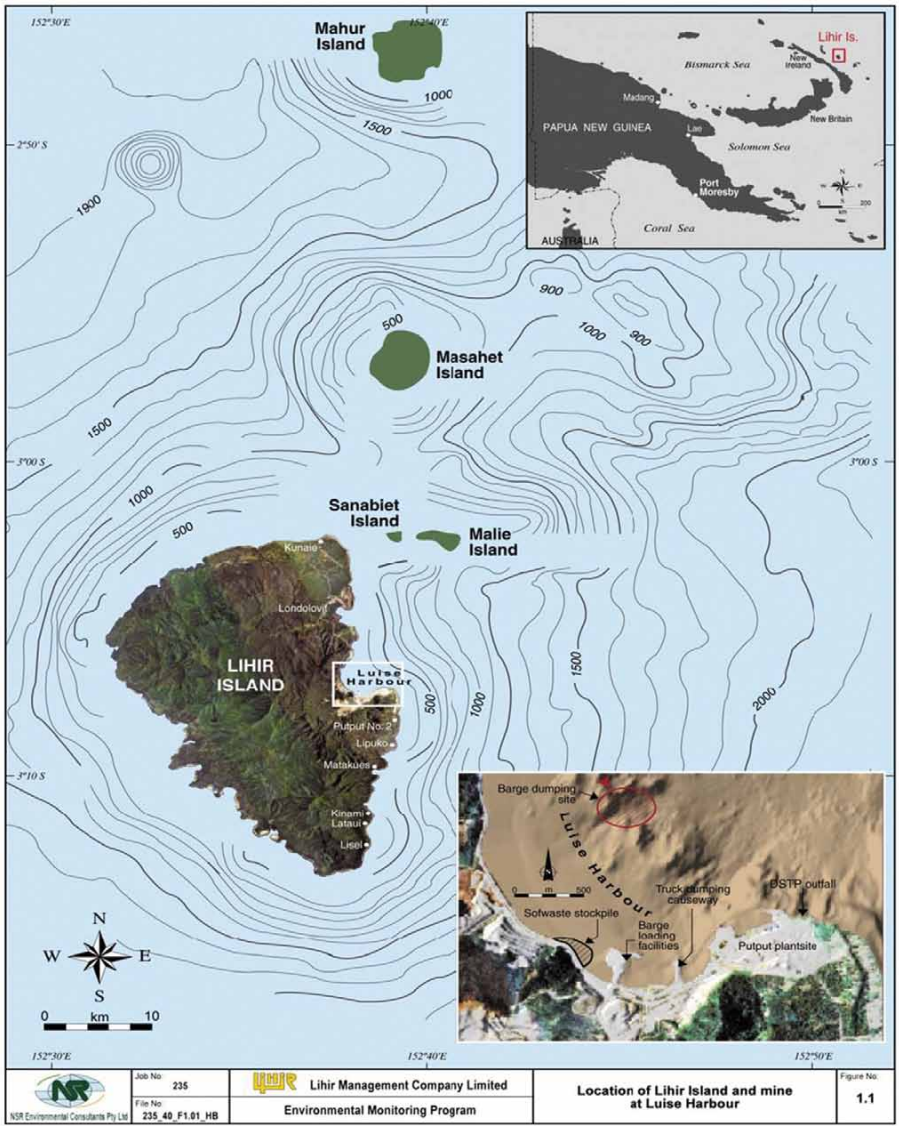

Figure 1. Location of Lihir Island and gold mine in Luise Harbor. *Courtesy NSR Environmental Consultants Pty Ltd*

estimated that approximately 60 Mt of low-grade ore would be stockpiled near the shore until after extraction operations are completed. With frequent rainfall, the stockpiles create regular acid runoffs containing various metal ions (McKinnon, 2002).

In parallel, the hard and soft rock waste that is too low grade for treatment or storage is disposed of through ocean dumping. Considering the lack of appropriate land-based storage area due to a steep terrestrial relief and an unstable environment, this method was assessed as the most environmentally and financially feasible for waste disposal due to the island's steep submarine slopes and deep surrounding ocean (1,600 m; NSR, 1989). By the time the mine is closed (projected to be in 2029 but may be as late as 2042; Dambacher et al., 2007), a minimum of 600 Mt (340 Mt hard rock and 260 Mt soft rock, 98% of which is comprised of argillic soil and colored oxide clays) will have been disposed of by using split-hopper barges operating 24 hours a day, 365 days a year.

At the time of this survey (2001–2003), split hopper barges with loads of approximately 1,000 m^3 each (1,300–2,000 tons) were sailing from 1 and 3 km out into Luise Harbor from the loading dock (Figure 1) to dump waste rocks in water depths over 100 m at a rate of 9–24 Mt yr^{-1} for the first 12 years of mining, falling to 0.5 Mt yr^{-1} by year 16 of operation (NSR, 1992). In 2011, 6.2 Mt of waste rock were disposed of in Luise Harbor (Newcrest Mining Ltd, *pers. comm.*, January, 25, 2012). The dump site was planned to be greater than 100 m depth so that, at the completion of mining exploitation, material from the waste pile potentially resuspended by ocean currents or turbulence would not be entrained into the mixed layer. Barge dumping operations create surface plumes in Luise Harbor (see the photo on the first page of this article) that, depending on weather and current conditions, may reach the fringing reefs in places along Lihir Island (Thomas et al., 2003). The combined potential effect of sediment over corals caused by barge dumping and increased terrestrial runoff was the focus of this study.

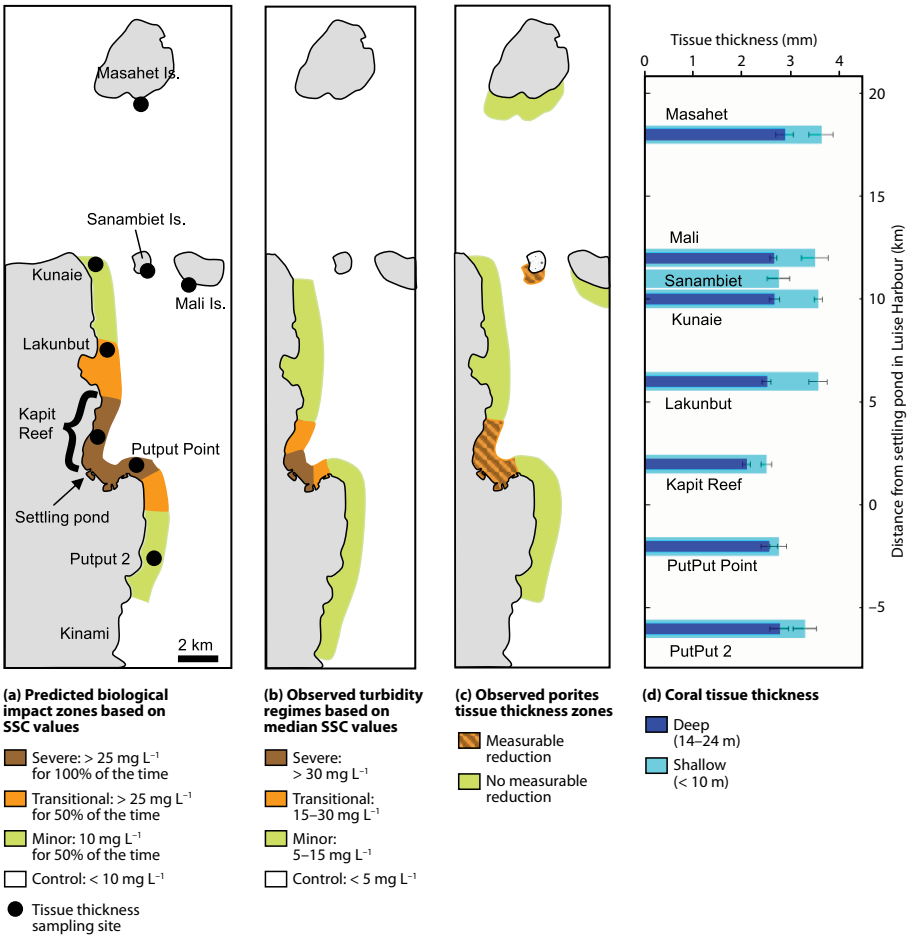

Figure 2. (a) Tissue thickness sampling sites and predicted impact zones based on NSR Environmental Consultants Pty Ltd baseline study. (b) Observed impact zones based on suspended sediment concentration (SSC) regimes. (c) Observed impact zones based on tissue thickness measurements. (d) Observed *Porites* coral tissue thickness along Lihir east coast.

METHODOLOGY

Baseline Survey of Predicted Impact Zones (Pre-operations)

The likely effects of mining operations on the Lihir Island coral reefs were predicted in a baseline environmental impact study by NSR Environmental Consultants Pty Ltd (NSR, 1989); this firm was also later commissioned by LMC to monitor the fringing coral reefs' health with photos and video transects (beginning in 1994) in conjunction with the CSIRO (Commonwealth Scientific and Industrial Research Organisation) involvement. The baseline survey proposed four zones of biological impact for long-term exposure of the fringing

reef to the combined effects of sediment deposition, suspended sediments, turbidity, and diminished water quality (NSR, 1989). These zones were termed *severe* (> 100 mg L^{-1} total suspended solid [TSS] concentrations), *transitional* (> 25 mg L^{-1}), *minor* (> 10 mg L^{-1}, which is twice that of oceanic conditions), and *control* (< 10 mg L^{-1}) and were defined based on 50% exceedence probability values of these TSS thresholds (Figure 2a; for the purpose of this paper, TSS is considered to be comparable to SSC).

The LMC Environment Department undertook a regularly revised three-yearly Environmental Management and Monitoring Program (EMMP) and included studies on "nearshore sedimentation rates and turbidity" and "fringing coral reefs."

Observed Turbidity Impact Zones (June 2000–December 2001)

Turbidity records collected continuously over 1.5 years during mining operations (June 2000–December 2001) with fully submersible James Cook University (JCU) optical backscatter sensors (OBSs; Ridd, 1992) provided a map of impact zones based on turbidity thresholds similar to those used in the prediction survey by NSR (Figure 6a in Thomas et al., 2003). Data were calibrated in SSC (mg L^{-1}) using field samples. The main zoning features were (a) that an extreme turbidity gradient persisted between the inner harbor (turbidity levels of 100–1,000 mg L^{-1}) and the adjacent reefs (turbidity levels in the order of 10 mg L^{-1}), and (b) that observed zones remained within pre-operations impact predictions. Detailed analysis of turbidity regimes versus particular events such as strong wind and high rainfall events can be found in Thomas et al. (2003).

Four sediment accumulation sensors were also deployed for up to three months where coral reefs were found closest to the activity zone, and this assessment did not detect significant sediment accumulation over fringing coral reefs (Thomas and Ridd, 2005).

Neither of these studies took the biochemical features of mine-derived sediment into account. SAMS (2010) studied mining-related impacts on the deep-sea (> 850 m) fauna at Lihir Island and found significant differences in abundance of macro- and meiofauna between control and impacted sites.

Light Survey

In parallel to turbidity and sediment accumulation, light levels were measured from June to September 2001 at 6 m depth at the southern and northern end of Kapit Reef (i.e., where corals appear to live under the most severe conditions with regard to SSC levels and where a large gradient in the turbidity regime was observed). Light levels were measured with in-built light sensors added to standard JCU OBS (Ridd and Larcombe, 1994). A receiving diode was used to measure the ambient level through a Teflon diffuser in the photosynthetically active region only (i.e., 400 to 700 nm), as controlled by an optical filter. Light sensors were calibrated using a Li-Cor underwater quantum sensor.

Tissue Thickness Measurements

Four types of surveys were conducted from 2001 until 2003 on tissue thickness changes (sites as shown in Figure 2a):

1. Natural changes over a lunar cycle: Masahet Island, away from the mining site, was chosen as the nonaffected site to assess natural changes in tissue thickness over the lunar month leading to the full moon on March 8, 2001 (note, none of the lunar experiments took place during coral spawning events—reported as October to November on Lihir Island).
2. Natural versus anthropogenically induced turbidity effect: Sanambiet Island, also away from the mining site, was chosen as a naturally turbid site to determine if tissue thickness responded similarly to naturally high levels of turbidity as to anthropogenically elevated levels.
3. Turbidity gradient effect: eight sites along the expected impact gradient were chosen (a) near NSR coral reef and sediment trap monitoring stations and within biological impact zones as predicted by NSR (1989: severe, transitional, minor, and control), (b) where sufficient numbers of suitable massive *Porites* colonies were found, and (c) in proximity to turbidity monitoring stations as described in Thomas et al. (2003).
4. Coral survival and adaptation to low light regimes: corals at the most affected site (Kapit Reef) were measured before and after the full moon in February 2001 and again in May 2003 to study the long-term effect of low tissue thickness in a chronically affected zone.

Tissue thickness was sampled on 10 colonies per site in two depths (shallow < 10 m and deep 14–24 m), where possible. Small one-inch-diameter cores were taken using a hand corer, and concrete plugs were inserted to avoid fouling and to minimize damage to the corals. The cores were then sun-dried, chiselled in half, and tissue thickness was

measured to the nearest 0.1 mm using a digital caliper. Detailed sampling protocol is described in Rotmann (2004). Tagged individual corals were revisited every year for three years.

RESULTS AND DISCUSSION

Natural Changes in Tissue Thickness Over a Lunar Cycle

There was a statistically significant, average decrease of 16% ± 2.8% (0.65 mm) in tissue thickness in shallow-water corals and a significant, average decrease of 18% ± 2.5% (0.71 mm) in deepwater corals on the day following the full moon of March 8, 2001 (Figure 3a). Thus, this study ascertained the time at which the abrupt, ~ 20% reduction in tissue thickness occurred to be the day after the full moon.

The rates of change in coral tissue thickness over the lunar month were also documented; they show an almost linear increase between two consecutive full moons (Figure 3a). Additionally, the tissue thickness of deepwater corals was significantly lower (by about 1 mm) than that of shallow-water corals at any one time.

On Lihir Island, tissue uplift on the day following the full moon was also observed in corals sampled at different times of the year (February vs. May), in different years (2001 vs. 2002), at different study sites in various impact zones, and in shallow and deep water (Figure 3b).

In the Great Barrier Reef (GBR), coral tissue thickness was found to vary temporally with seasons (True, 2004), to decrease from inshore to offshore and along a north-south GBR spatial gradient (Barnes and Lough, 1992), and to decrease inversely with water depth (True, 1995). Massive corals like *Porites* contain "annual" density bands, like tree rings that can be displayed by X-radiography of skeletal slices taken along a colony's growth axis. It has long been thought that fine-density bands found in massive corals were under lunar control, because 12–13 fine bands are found within an annual density band (Buddemeier and Kinzie, 1976; Barnes and Lough, 1993). This study proved that one major aspect of coral skeletal growth, namely tissue uplift and dissepiment formation (see Barnes and Lough, 1993) takes place every month, abruptly, on the day following the full moon.

On Lihir Island, deepwater corals had significantly thinner tissue than shallow-water corals at all sites. An average daily increase in tissue thickness over the lunar month of February 2001 was calculated to be 0.029 mm (0.81 mm per month) for shallow corals, and 0.026 mm (0.73 mm per month) for deepwater corals. These daily values were compared with actual increases in coral tissue thickness over the February lunar month in 2003, and it was found that the predicted (from 2001 data) and actual values of average tissue thickness (measured in 2003) were the same (Rotmann, 2004). Being able to allow for monthly coral tissue thickness variability means that comparable measurements of tissue thickness can be made any time during the lunar month, making it a realistic bioindicator candidate for management purposes.

Natural Versus Anthropogenically Induced Turbidity Effect Measured by Tissue Thickness

Corals from the severe impact zone as defined by the baseline study (i.e., Kapit Reef and PutPut Point on Figure 2a), corresponding to the transitional zone as defined by the turbidity observations (Figure 2b), had significantly thinner tissues than corals in all other zones

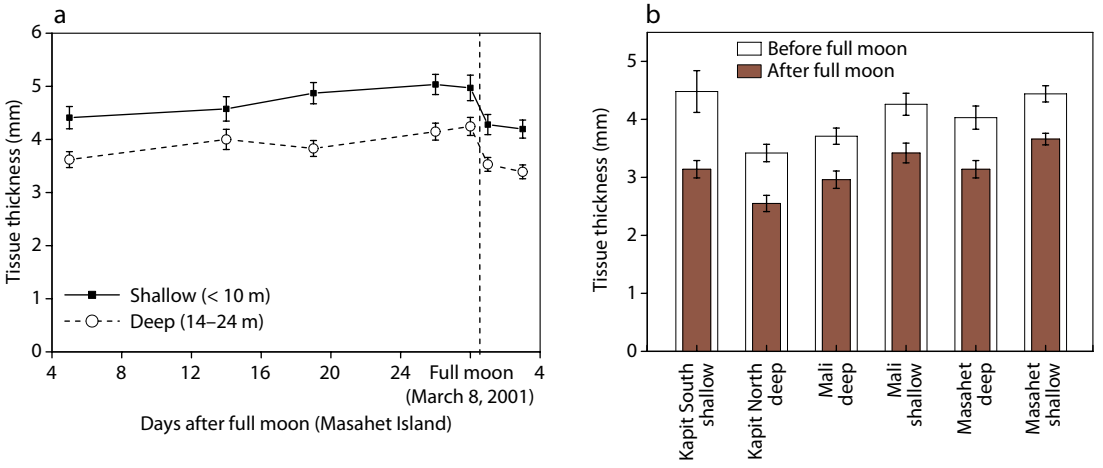

Figure 3. (a) Change in tissue thickness during the lunar month (February–March 2001) at deep and shallow nonimpacted sites at Masahet Island (average of nine colonies per depth). (b) Change in tissue thickness for six sites along the impact gradient (averaged over 10 colonies per site) before and after the full moon of May 26, 2002.

(Figure 2d). To illustrate this relationship, Figure 4 shows that for shallow-water corals as measured in 2001, the tissue thickness is significantly reduced in the transitional zone and not reduced everywhere else (Figure 2c).

Deepwater corals had significantly thinner tissue than shallow-water corals at all sites (on average 0.8 mm, or about 20 to 25% thinner), due to a doubling in depth (from < 10 m to the 14–24 m range; Figure 2d). Sanambiet Island corals (naturally impacted by turbidity; Rotmann, 2004) had significantly thinner tissues (on average 2.74 mm ± 0.2 mm) than those at all other sites (average 3.5 mm ± 0.22 mm), except at the predicted severe impact sites (average 2.61 mm ± 0.1 mm; i.e., the observed transitional zone on Figure 2b and Figure 4). These observations suggest a reduction in tissue thickness of about 20–25 % due to naturally increased turbidity.

Barnes and Lough (1999) examined the impact on tissue thickness of massive *Porites* of an up to 100-fold increase in sedimentation resulting from the construction and operation of a gold mine on Misima Island, PNG, and found that tissue thickness decreased significantly with increasing proximity to the mine site, and that corals in the most affected areas were smothered, then buried, after which they died. Sediment accumulation or burial did not occur on reefs affected by mining sediments on Lihir Island because of strong currents and water movement (Thomas and Ridd, 2005). Corals sampled on Lihir Island were mostly affected by turbidity, which is expected to be a less-extreme stressor than sediment accumulation on living surfaces (Woolfe and Larcombe, 1999).

This study, the first attempt at using tissue thickness to assess coral response to turbidity levels (see Cooper, 2008, for more recent analysis), shows 20–25% tissue thickness reduction at the most turbid sites compared to all other study sites. It also demonstrates that, using this method, it is not possible to differentiate between anthropogenic and natural turbidity impacts as no significant difference in tissue thickness was observed between the high-turbidity sites near the mine (Kapit Reef and PutPut Point) and the naturally turbid site (Sanambiet Island). This observation could mean that *Porites* corals on Lihir Island do not suffer more from mine-derived sediment in the water column than *Porites* in local, naturally turbid reefs do. However, other studies have shown significant impacts from mine-derived sediment in, for example, deep-sea fauna (e.g., SAMS, 2010) and on coral reefs and fish (e.g., Jupiter et al., 2010). More sensitive coral species than *Porites* are likely to have suffered more measurable consequences, as *Porites* are known to withstand greater levels of sediment-related stress than other species (e.g., McClanahan and Obura, 1997).

Turbidity Gradient Effect Shown by Tissue Thickness Measurements

Figure 2 compares turbidity measurements, coral tissue thickness, and predicted biological impact zones. The data indicate that coral tissue thickness significantly decreases close to the mine site compared to all other sites (Figure 2c), and in the same place where turbidity was measured to be the greatest. More specifically, based on tissue-thickness measurements, the biologically relevant turbidity impact on massive *Porites* corals on Lihir Island extended from north of Kapit Reef to PutPut Point to the south over a distance of approximately 4 km (Figure 2c). This zone was about half the length of the zone with severe sediment impacts on corals predicted by the baseline survey (NSR, 1989, and Figure 2a).

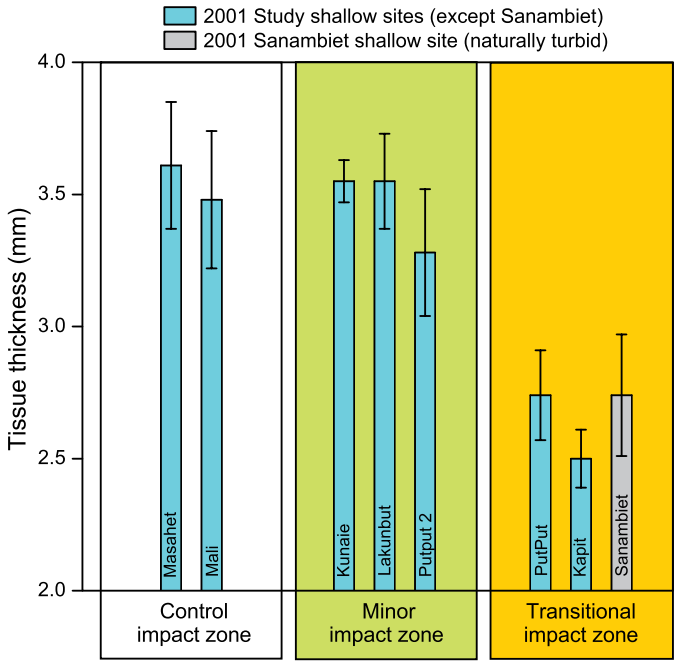

Figure 4. Qualitative correlation between tissue thickness (2001 survey) and impact zones (as defined by turbidity survey).

Regarding mining operations conditions, a median SSC > 30 mg L^{-1} defined the observed severe impact zone (as opposed to the predicted severe impact zone). There was no coral reef within this zone, and the sites closest to the mine where coral lived—Kapit Reef and PutPut Point—were within the observed transitional impact zone, determined by a median SSC of 15–30 mg L^{-1}. For the two lower SSC level zones (minor and control), tissue thickness did not show any variation between the two zones. This study therefore shows that tissue thickness measurements can be used to delineate boundaries between severe and transitional zones as observed by Thomas et al. (2003) with a measurable tissue thickness reduction (of 20–25% of 3.5 mm), and in the minor and control impact zone with no measurable reduction of tissue thickness.

Light Survey

Variations of natural surface solar radiation levels were large, with a daily maximum ranging from ~ 4,000 to ~ 200 µmol s^{-1} m^{-2} between the sunniest and the cloudiest days, respectively. These massive reductions in surface radiation did not last more than one day over the three-month deployment. Considerable variations of daily maxima were also found in the underwater light level records at 6 m depth, with a range of ~ 500–10 µmol s^{-1} m^{-2} at the southern end of Kapit Reef and ~ 750– 30 µmol s^{-1} m^{-2} at the northern end of Kapit Reef.

Figure 5 shows the percentage of daily underwater surface light that reached the reef at 6 m depth at each location. Based on the expected PAR, subsurface irradiance as a function of turbidity, depth, and time (Anthony and Fabricius, 2000), 96% of surface irradiance should reach 6 m depth in water with an SSC of 3 mg L^{-1}, and 12% in water with an SSC of 10 mg L^{-1}. In this survey, on average, 14% of the daily surface radiation reached the reef at 6 m depth at the northern end of Kapit Reef versus 5% at the southern end, about 2 km away (Figure 5). These data indicate that during this survey, light levels were reduced at both locations compared to normal conditions (defined by an SSC < 3 mg L^{-1}).

If the normal light level was taken with an SSC of 10 mg L^{-1}, which was the observed level at the southern end when there was no particular event such as strong winds or heavy rainfall, light reduction occurred for about 68% of the time at that location and about 46% at the northern end. Based on this reference, light reduction periods lasted for up to 13 days at the southern end of Kapit Reef and up to a week at the northern end.

A comparison between bottom turbidity and light records indicates that some very localized effects occurred between the southern and the northern end Kapit Reef, with no systematic relationship between the two locations, and no systematic relationship between SSC levels and light levels. This indicates that SSC monitoring is not sufficient to infer potential impacts on coral health, and that light monitoring should also be included in environmental management programs.

Coral Survival and Adaptation to Low-Light Regimes

True (1995) reported that tissue thickness in *Porites* on the GBR does not fall below 2–2.5 mm. He also suggested that tissue uplift resulting in an abrupt reduction in tissue thickness would not be possible once it decreased close to its minimum level to enable polyp survival. There is evidence that linear extension (i.e., growth) is somehow linked with tissue reserves (storing lipids like a camel's hump) and that corals with significant energy deficits may sustain skeletal growth rates in the short term by catabolizing tissue reserves (Anthony, 1999). If this is the case, then minimal values of tissue thickness and cessation of dissepiment formation might be linked with reductions or cessation of coral growth rate under stressful conditions. We examined this possible link on the most affected corals on Lihir Island.

In 2001, corals at the most severely impacted site (Kapit Reef) were found to have an average thickness of 2.1 mm (see Figure 6). An additional monthly decrease of about 20–25% would have reduced tissue levels as low as 1.6 mm,

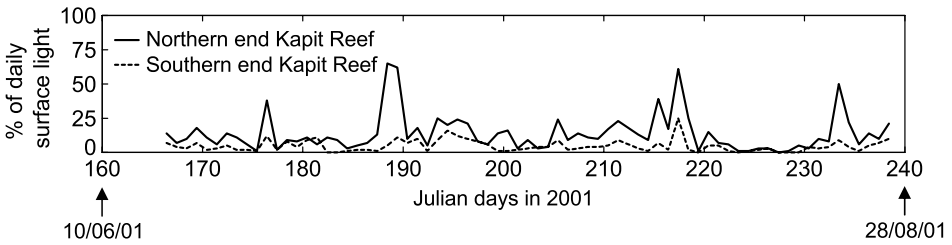

Figure 5. Percentage of daily underwater surface light that reached the reef at 6 m depth at Kapit North and South.

too low to sustain polyp survival, as it would have resulted in partial mortality due to tissue resorption. At this study site, no monthly tissue uplift could be measured in corals with tissue thickness below 2.2 mm, but the sampled corals also showed no visual tissue lesions or patchy die-off. Thus, corals at the site that was the most affected by mine-related turbidity seemed to have adapted to the lower light levels by decreasing their energy expenditure for growth in order to preserve minimum tissue reserves. In 2003, corals from the same site showed a tissue thickness of ~ 3 mm (i.e., a 1 mm or 50% increase since 2001), and tissue uplift was observed following the full moon (Figure 6).

These observations could also explain why the main coral species present in the severely impacted sites on Lihir Island is *Porites* (personal observation of author Rotmann), as similar adaptive mechanisms are not known for corals with imperforate skeletons that do not exhibit monthly tissue uplift. It is unclear from this study how long *Porites* corals can stop and start linear extension before they die, but several other studies have found that corals have great capacities for adapting to localized stress events and have good potential for recovery after the stressor is removed (e.g., Maina et al., 2011).

Ongoing monitoring of massive *Porites* tissue thickness levels at highly turbid sites could provide a real-time indicator of coral stress levels, and shed light on the adaptive abilities of these corals (Cooper et al., 2009). In the absence of smothering and burial, the single most significant impact of sediment over coral reefs is caused by light reduction.

CONCLUSIONS

Table 1 summarizes the impact of parameters on *Porites* tissue thickness studied here. This study is the first to show evidence for lunar control on monthly coral skeletal growth and for cessation and subsequent resumption of growth processes in massive *Porites* in relation to turbidity stress. *Porites*' ability to repeatedly mobilize energy reserves during monthly tissue uplift episodes may be an important mechanism to survive environmental impacts, such as those observed on Lihir Island. Monitoring average tissue thickness may indicate the relative performance of a coral colony in any given month, making it a powerful monitoring tool for the assessment of relative impacts of stressors on corals, especially in remote locations. Tissue thickness is a simple, cheap, and nondestructive method for assessing sediment stress in real time. However, the adaptive nature of massive *Porites* corals suggests that this bioindicator may only work when the turbidity contrasts are strong. Studies assessing environmental impacts on corals must ensure that accurate measurements of natural and anthropogenic levels of physical parameters such as light, sedimentation, and turbidity are taken in order to draw solid conclusions on coral stress response to such factors.

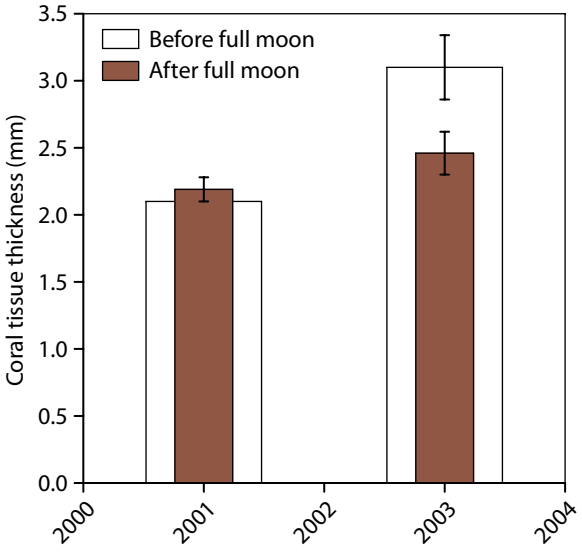

Figure 6. Comparison of tissue thickness (averaged over the same eight colonies) one day before and one day after the full moon at an impacted site on Kapit Reef two years apart (March 8, 2001, and February 18, 2003).

Table 1. Impact of parameters studied using *Porites* tissue thickness with respect to normal conditions.

Parameters	Change in tissue thickness (%) compared to normal conditions
Full moon cycle	~ 20% decrease the day after full moon
Depth	20% decrease when depth doubles
Natural turbidity impact	20 to 25%
Anthropogenic turbidity impact	20 to 25%

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