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3.6 Coral Microatolls

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Synopsis: Coral microatolls are valuable paleo-sea-level indicators not only because of their vertical precision, but also because individual coral colonies grow and respond to sea level for decades to centuries: unlike shorter-lived organisms, they contain filtered records of sea level over sustained periods. In tectonic settings, microatolls record both gradual (interseismic and postseismic) and sudden (coseismic) vertical changes. This chapter describes how to use microatolls to reconstruct relative sea-level histories. We discuss the utility and limitations of microatolls; site and sample selection; field techniques; documentation strategies; slab processing, analysis, and interpretation; dating; vertical accuracy; sources of error; and indicative meaning.

3.6.1. Introduction

Microatolls are coral colonies with living outer margins, but with flat, dead upper surfaces. They are commonly found growing into the lower intertidal zone on reef flats and in shallow-water lagoonal environments. Microatoll morphology is most often developed in massive corals, however branching and foliaceous corals may also develop a similar form when their upward growth is constrained (Figure 3.6.1).

The term “microatoll” was adopted to describe large, flat-topped corals with a subcircular ring of living polyps around the margin; they were named because their shape is reminiscent of the much larger, true atolls they are sometimes found upon. Large colonies of coral with this growth form were noted on the Cocos (Keeling) Islands in the Indian Ocean by Darwin (1842). Dana (1849, p. 39) correctly deduced that they formed when sea level restricted their further upward growth, describing how “corals, when growing beneath the water, form solid hemispheres, or rounded hillocks; but on reaching the surface, the top dies, and enlargement takes place only on the sides. In this manner the hemisphere is finally changed to a broad cylinder with a flat top.” They were referred to as “miniature atolls” by Guppy (1886), and were first called “micro-atolls” by Krempf (1927, pp. 13–19). Kuenen (1933, pp. 64–65) defined a microatoll as “a colony of corals [with] a raised rim, more or less completely surrounding a lower, dead surface.”

Although some authors have ascribed the formation of microatolls to other causes such as the accumulation of sediment on their interior upper surfaces and the consequent death of the colony’s upper corallites (e.g., Wood-Jones, 1910, p. 107), it is now clear that it is exposure at lowest tides that prevents further upward growth; hence the value of microatolls as sea-level indicators (Smithers, 2011). The term is now used to describe single coral colonies that are usually, but not always, circular in planform with living vertical sides, and sub-horizontal dead upper surfaces. “Fossil” coral microatolls are those in which no living polyps survive—the colony died completely at some time in the past—but the morphology is preserved.

The upper surface of a microatoll has been described as the microatoll plane, and there are commonly a series of concentric ridges, or annuli, that can be seen across this plane. Microatolls growing in close proximity tend to exhibit very similar form, suggesting that they are responding to the same environmental cues. Hopley (1982, p. 113) reviewed their usefulness as indicators of relative sea-level tendency, recognizing four common microatoll forms, including the “*classical*” coral microatoll form with a relatively flat upper surface, a “*top hat*” morphology with an elevated center and lower rim, an “*upgrown*” microatoll form with outer rims substantially elevated above the interior microatoll plane, and “*multiple ringed*” morphologies in which the upper limit to coral growth has oscillated over time (Figure 3.6.2) (Flora and Ely, 2003). While upward growth of a microatoll is restricted by the water/air interface, downward growth is restricted by the sand/water interface (Scoffin and Stoddart, 1978).

Microatolls of *Porites* grow at rates of 5–25 mm a⁻¹ and can reach diameters of 9 m. Scoffin and Stoddart (1978) determined that, for the northern Great Barrier Reef, where microatolls grow in “open water” settings, they tend to have living rims at an elevation around mean low water springs (MLWS); this relationship has been commonly assumed to be applicable elsewhere, but neither a precise nor a universal relationship has been demonstrated. When microatolls grow in areas not freely connected to the open ocean, such as behind storm ridges, they may grow to higher elevations because the ebb tide is moated (Hopley, 1982, p. 109).

Many massive corals, including *Porites*, are annually banded. The banding results from seasonal contrasts in density and fluorescence. Although the exact causes of these contrasts in *Porites* corals are not well understood, Juillet-Leclerc and Reynaud (2010) studied the growth of the branching coral *Acropora* under different light conditions, identifying relationships between growth rates, microstructures, and photosynthetic activity. In particular, they recognized two distinct growth modes: skeleton thickening is light-enhanced, whereas extension growth is light-suppressed. Coral formed during thickening is denser than that formed during extension.

Microatolls provide information in their growth patterns about present low water level and past sea-level change. They are particularly valuable paleo-sea-level indicators not only because of their vertical precision, but also because individual coral colonies grow and respond to sea level for decades to centuries: unlike shorter-lived organisms, they contain a filtered record of sea level over a sustained period. Individual microatolls may record relative sea level over a period of decades to more than a century, and by combining records from microatolls of different ages, coral microatolls can inform multi-century to millennial-scale relative sea-level trends. In tectonically active settings, microatolls can record both gradual (interseismic and postseismic) and sudden (coseismic) vertical changes.

This chapter is designed to provide an overview of how to use coral microatolls to reconstruct a history of relative sea level for a site. We discuss the utility and limitations of microatolls; considerations for site and sample selection; field techniques; documentation strategies; slab processing, analysis, and interpretation; dating; and vertical accuracy, sources of error, and indicative meaning. We also include a note on permit considerations.

3.6.2. Relative sea level: understanding what microatolls do and do not record

Microatolls start their lives as hemispherical corals below the intertidal zone and for a period of time grow radially outward and upward, unconstrained by low tide or the effects of exposure. They begin to take their microatoll form when they grow high enough, or relative sea level falls low enough, that a coral colony’s upper surface is exposed, if only briefly, and those polyps that are desiccated die. The death of the uppermost part of a coral colony, due to exposure

at extreme low water, is called a diedown. These coral colonies continue to live below their highest level of survival, or HLS (Taylor *et al.*, 1987), and they continue to grow outward and upward from below that highest level of survival. Because of fluctuations in sea level, a site's highest level of survival can vary by several centimeters or more from one year to the next, an amplitude that exceeds the annual growth rate of the coral (commonly $\sim 10 \text{ mm a}^{-1}$, with a demonstrated range of 5–25 mm a^{-1} for *Porites*) (Scoffin *et al.*, 1989, Isdale, 1984). When a microatoll experiences a diedown, its highest level of survival is controlled by low water levels; subsequently, the height to which a coral can grow is limited instead by its growth rate. We will use the term highest level of survival to refer to the elevation down to which a coral dies following an uplift or a period of particularly low sea level; the rest of the time, we will use the term “highest level of growth” (or “HLG”) to emphasize that a coral's elevation is limited only by the rate at which it can grow back up to the theoretical highest level at which it could then survive. Some authors have referred to these collectively as the height of living coral or HLC.

If the lowest water level of the year at a site was the same from one year to the next, if the lowest water level always occurred at the same time of day and in the same season, and if the air temperature, cloud cover, wind, and waves were always the same at those times of maximum exposure, then, in the absence of any land-level changes affecting the site, we might expect a coral microatoll to experience a small diedown each and every year. In this hypothetical situation, any small changes in elevation from one year to the next could be attributed to longer-term trends in relative sea level. Yet none of those required conditions are true. Even if weather effects are ignored, the lowest astronomical tide of the year varies from one year to the next, and that year-to-year variation tends to be bigger where the tidal range is larger. In regions where the El Niño / Southern Oscillation (ENSO) or Indian Ocean Dipole (IOD) influences sea level, markedly lower or higher water levels can persist for weeks to months during strong ENSO or IOD events, and these sea level anomalies can have amplitudes of plus or minus tens of centimeters (Woodroffe and McLean, 1990, Meltzner *et al.*, 2010). Weather and waves can vary dramatically from one hour to the next, let alone from one year to the next. Storm surges can dramatically affect sea level, as can monsoonal wind blowing across broad, shallow continental shelves. Distant storms on the open ocean can drive swells that, in turn, modulate wave heights and affect wave splash. And, all else being equal, an exposed coral is more likely to die down at noon on a scorching, sunny day, than overnight or on a cool, rainy day. For any and all of these reasons, we might expect microatolls to have bigger diedowns some years than others, and perhaps no diedowns at all in other years. Microatolls are remarkably useful proxies for former sea level, but we must take care to understand what microatolls do and do not record.

In Figure 3.6.1, we illustrate microatoll development under several different relative sea level history scenarios. The first three cases show how a microatoll might develop under stable

sea level conditions, under gradually falling sea level, and under gradually rising sea level. In all three cases, we superimpose on the long-term trend a realistic interannual variability: at 11.1 and 14.1 years, we simulate temporary local oceanographic lowerings such as those that tend to happen during La Niña events at Kiritimati (Christmas) Island in the central Pacific or during positive IOD events in Sumatra. Several conclusions to draw from these simple cartoons include: (1) diedowns do not occur every year but instead respond to local minima in the relative sea level time series; (2) corals can sometimes take several years or more to grow back up to their theoretical highest level of survival following a diedown; and (3) the relative elevations of the concentric annuli can inform us about the overall trend of sea level during the coral's lifetime, but we must take care to interpret each annulus correctly. Regarding the second conclusion, we note that a coral might die down farther during a severe ENSO or IOD event than during a mild event, and hence it would take a coral longer to grow back up to its theoretical highest level of survival following a severe event than following a mild event; that said, a coral with a fast growth rate will grow back up to its theoretical highest level of survival more quickly than a coral with a slow growth rate. Regarding the third conclusion, we note that in the case of stable sea level (Case 1), the two annuli are at the same height; in the case of falling sea level (Case 2), the outer annulus is lower; and in the case of rising sea level (Case 3), the outer annulus is higher, but there is an extra ("out-of-sequence") interior annulus, equivalent in age to the outer annulus; this extra annulus grew because of the peculiarities of this coral's sea level history. Although this out-of-sequence interior annulus is shown in Figure 3.6.1 at exactly the same elevation as the outer annulus, we find that the interior growth can be higher than the outer contemporary annulus—by several centimeters or more—perhaps because water can sometimes pool on the interior upper surface of a microatoll at low tide and allow for locally higher growth. Such out-of-sequence interior annuli are common in areas of rising sea level, and they actually protect the underlying inner surface of the microatoll from erosion. That said, one must be careful not to misinterpret a coral's relative sea level history based on out-of-sequence annuli. Furthermore, we ignore the higher interior annuli when calculating a coral's highest level of growth (or survival) for a given year.

At least two studies have shown that a microatoll's diedowns, which can be separated by less than a year to more than a decade, track low water levels. Woodroffe and McLean (1990) compared a representative microatoll from the Kiribati Islands with a 3-month running mean of monthly sea level recorded on a tide gauge 140 km away and showed that the diedowns on the microatoll coincided with the lowest water levels at the tide gauge. More recently, Meltzner *et al.* (2010) compared satellite altimetry data with Sumatran microatolls and concluded that every diedown on the microatolls since the beginning of satellite altimetry in 1992 could be explained by coseismic uplift or by periods of anomalously low sea surface height. All in all, microatolls preserve a record of the water level that limits upward coral growth (not mean sea level), but

microatoll response to rapid sea-level rise is limited by coral growth rate. Still, the exact causes of microatoll diedowns, and the exact relationship between a coral's highest level of survival and the tidal cycle, are not well understood. We will explore this relationship in Section 3.6.9.

3.6.3. Selecting a site: what makes a good site?

Most field geologists come to realize, usually sooner rather than later, that the geologist is at the mercy of the geology, and that a perfect field site is difficult (often impossible) to come by. There are situations in which any site with more than a handful of microatolls is a good site. But if the geologist has some flexibility in choosing a field area or has several decent potential sites to choose from within the field area, then there are certain factors he or she should consider.

At bare minimum, a good site will contain one or more populations of coeval microatolls, not simply a few isolated dissimilar coral colonies; each unique population should contain several (≥ 4 –10) morphologically similar microatolls at the same elevation. If the researcher is interested in studying only living microatolls, there should be a sizable selection of living microatolls scattered over the site. If the researcher is interested in reconstructing past sea level with fossil microatolls, there should be a population of living microatolls plus populations from one or more distinct generations of fossil microatolls; the more unique generations at a site, the better the site.

For studies involving fossil microatolls, the researcher should attempt to identify and differentiate different generations of fossil microatolls, although this may not always be possible by field inspection alone and may require range-finder dates to confirm approximate ages of different colonies (if practical). If microatolls at a site are all responding to changing sea level over their lifetimes, then all microatolls alive at a site at a particular time should have grown with a similar morphology. Some microatolls might have reached their highest level of survival earlier than others, so some microatolls of a particular generation might have more annuli than others, but the outer annuli should all be similar if the microatolls died synchronously (Figure 3.6.3). Microatolls growing at a different time would have responded to a different sea level history, so a different generation should have a different morphology and might be at a different elevation. To illustrate this point we consider the fossil microatolls found at a site on northern Simeulue island, off the west coast of Sumatra (Meltzner *et al.*, 2010). At least eight fossil microatolls with a low interior and high outer double rim (Figure 3.6.4 a–b), all of which had outer-rim elevations within a narrow range of ~10 cm, were found scattered over ~200 m at the site; interspersed among these were at least seven fossil microatolls of another generation with a low interior, high middle annulus, and intermediate outer annulus (Figure 3.6.4 c–d), consistently ~20 cm lower than the first generation. By recognizing in the field that this site had multiple generations of fossil microatolls—in addition to a generation of recently living microatolls that died from uplift in 2004—they anticipated this would be a good site. They invested substantial time and effort into

developing and documenting this site, and it turned out to be central to uncovering the 14th–15th century predecessors of the 2004 earthquake.

Because microatolls' reference water level can be complicated to determine—an issue we will discuss in Section 3.6.9—finding living microatolls is important for reconstructing past relative sea level, even for studies focused on fossil microatolls. At sites where both fossil and living microatolls are found, constructing a relative sea-level history for the site is a process of directly comparing the fossil microatolls' elevations with their living counterparts. It is not necessary to know the exact relationship between the highest level of survival and the tidal cycle; one must simply assume that that relationship, at that site, has remained the same over the lifetimes of all the microatolls at the site, and one must know the variation in both the living and fossil populations' elevations at the site. If, however, living microatolls cannot be found, it is necessary to find nearby sites with living microatolls, and to carefully determine the relationship between the highest level of survival and the tides, i.e., the microatolls' indicative meaning.

3.6.4. Surveying and documentation strategies

Recognizing the highest living corallites on a living coral is normally easy to do, once one knows what to look for (Figure 3.6.5). Living coral should be brightly pigmented, although if it has recently bleached, it may appear white. In contrast, once corallites die, they tend to be quickly covered by algae, if they remain below approximate mean tide. If a microatoll has experienced a diedown within the past year or so, its highest level of survival should appear as a smooth, nearly horizontal level separating brightly pigmented coral below from dark algae-covered coral above. If the boundary between living and dead coral is irregular or not roughly horizontal, it suggests that parts of the coral may have died for reasons other than reaching the highest level of survival; in cases such as these, the highest living coral on the colony provides only a lower bound (minimum estimate) of the highest level of survival. As the coral grows upward and outward from below its highest level of survival, a lip will gradually form around the perimeter of the microatoll at its new highest level of growth, and if the microatoll goes several years or more without an additional diedown, the outer lip will grow into a full-fledged outer ring or outer rim. After 3–5 years since a microatoll's most recent diedown, it should have an outer rim that is brightly pigmented, but inside of the outer rim, the top of the microatoll should be dark and algae-covered. The highest living coral on the outer rim is, by definition, the highest level of growth. On a fossil microatoll, the highest level of growth may be defined either as the highest preserved coral on the outer rim, or as the highest preserved coral anywhere on the colony. For a microatoll whose center is higher than its perimeter, this can be ambiguous, so authors should specify their intended meaning of the highest level of growth.

We have already discussed the importance of surveying the highest level of growth on multiple coeval microatolls, preferably distributed over the footprint of the site, for each unique generation of microatolls at a site. Such an exercise in the field will subsequently facilitate the arguments (a) that any sampled (slabbed) colony is not an anomaly and instead represents an entire population of morphologically similar microatolls; (b) that the sampled microatoll's elevation is representative of the entire population's elevation; and (c) that no part of the site slumped or settled with respect to another part of the site. This will also allow the researcher to quantify the range of the highest level of growth or highest level of survival at the site, and to reduce vertical uncertainties.

In addition to surveying the highest level of growth on multiple microatolls, it is important to survey multiple highest level of growth points on each microatoll, to establish consistency, or to quantify variability. Smithers and Woodroffe (2000) established the practice of measuring the highest level of survival or highest level of growth at four cardinal and four intermediate compass points (N, NE, E, SE, S, SW, W, NW) around each microatoll perimeter, but they skipped measurements at compass points lacking living coral. They noted that microatolls with incomplete or locally depressed living rims are common, and can be caused by partial burial, bioerosion or physical damage.

Where feasible, it is also wise to survey multiple points on multiple concentric annuli of a microatoll, to demonstrate that a microatoll has not experienced tilting, either during its life or after its death. Additionally, in some cases, one or several microatolls at a site will die while most others survive; this may be due to a biological response on an individual coral, or due to the fact that microatolls living in deeper water (growing up to the highest level of survival but from a deeper substrate) might survive a low diedown that would kill shallower microatolls. In such cases, it is helpful to have elevation data on multiple annuli on each microatoll, to allow the researcher to correlate parts of one microatoll to another (Figure 3.6.3), without extracting a cross section from each colony.

Lastly, we point out the importance of documenting a microatoll's radial symmetry in the field, with photographs, careful sketches, notes, and a careful survey (Figure 3.6.6). If there has been moderate erosion, some diedowns may not be preserved in a particular cross section, even if a concentric annulus has formed on the surface. Nonetheless, a radially symmetric annulus generally forms in the years following an even, radially symmetric diedown, so the presence of an annulus on the microatoll's upper surface, even if subtle, suggests that a diedown had occurred and that a coral had reached its highest level of survival at that point in the coral's lifetime.

3.6.5. Sampling strategies: methods and selection of microatolls to sample

Options for sampling a microatoll include slabbing (extracting a radial or diametrical cross-sectional slab from the microatoll, using a saw) and coring (extracting a core from the microatoll, using a core drill). We begin this section with a discussion of the advantages of slabbing over coring. With only a cylindrical core, one can use only the coral's surface morphology to infer diedowns, an often reliable but nonetheless indirect method. One cannot, with simply a core, determine either the exact timing or the exact elevation of each diedown. With a slab, however, one can examine the coral's banding pattern to confirm that the coral's concentric annuli result from diedowns and that the growth is continuous throughout the microatoll (in rare cases, a coral will die entirely and be recolonized subsequently, and this process may impart on the coral a morphology that resembles a microatoll). One can also precisely count the number of annual bands between successive diedowns, and one can determine the coral's highest level of survival or highest level of growth each year or as frequently as desired.

As a rule of thumb, a researcher should slab at least one microatoll per unique generation, but a second slab (from a second microatoll) may be considered (a) to assess any vertical error in the highest level of survival; (b) in the situation where one microatoll from a particular generation may be better preserved earlier in its history and another microatoll may be better preserved later in its history; or (c) if there is uncertainty or reason to believe that the microatolls may be from different generations or may have died at different times. Additionally, dating issues should be considered at the slabbing stage: *Porites* sp. corals tend to provide the best slabs morphologically, yet Zachariasen (1998, §3.4b), Natawidjaja *et al.* (2006), Sieh *et al.* (2008), and Meltzner *et al.* (2010) found that, in comparison to *Porites* corals, *Goniastrea* corals tend to have far lower thorium concentrations (i.e., they are “cleaner”) and hence provide a more precise estimate of the coral's age by U-Th dating techniques, often to better than ± 5 years. For this reason, if a population of fossil microatolls includes both genera of corals, it may be advantageous to take a slab from a *Porites* microatoll, to provide the best relative sea level history, and an additional slab or sample from a *Goniastrea* microatoll, to provide the best estimate of the generation's age. If both corals are from the same generation, they should yield replicate U-Th ages, but the *Goniastrea* sample will commonly yield a much more precise age, because it was so much “cleaner” than the *Porites* sample. We note, however, that comparisons of highest level of survival from different species should be made with caution, as systematic differences in highest level of survival exist between different genera and species (Natawidjaja *et al.*, 2006, Scoffin *et al.*, 1997).

Lastly, we discuss considerations for choosing the best microatolls to slab. An important point is that the biggest colonies of a generation are not necessarily the best, particularly if they have few annuli or are more eroded. A large colony with few concentric annuli may have grown

for a long time, but it would have been below its highest level of survival for most of its life, and therefore its record of relative sea level is limited to the short period spanned by its annuli. Instead, a researcher should search for the microatoll from each generation with the most concentric annuli, regardless of the size of the microatoll itself. Sometimes, the inner annuli of a microatoll will be overgrown (e.g., Figure 3.6.7), and the overgrowth (“out-of-sequence” interior annuli, as discussed earlier) will protect the inner annuli and inner diedowns from subsequent erosion. These microatolls can be the best microatolls to slab because of their superb preservation, but recognizing which of these microatolls will have a good set of hidden, protected inner annuli is challenging and requires a combination of experience, skill, and luck on the part of the researcher.

3.6.6. Slabbing techniques and subsequent slab processing

Once a microatoll is selected for slabbing, the best radius should be chosen for the actual slab. Considerations for choosing a radius include: finding the radius where the most diedowns tend to be best preserved and least eroded; avoiding cracks, irregularities, or areas of substantial bioerosion; and aligning the slab with the coral’s growth direction as closely as possible. In some cases, cutting an entire diameter or more than one radial slab might be advantageous. Once the location of the slab has been chosen, it is helpful to mark the location where the cuts are to be made; a string or other straightedge can be useful for ensuring that the cuts are not crooked.

It will also be important to tie the slab’s elevation into the overall site survey, and to retain information about the slab’s original horizontality. Screws should be placed at intervals along the radius or diameter of what will become the slab. We use an “eggbeater”-type hand drill to drill small holes into the top of the coral where the screws will be located; we then insert plastic anchors and screw in the screws. We recommend at least 4 or 5 screws per slab. At minimum, two screws are needed to reconstruct horizontal, but a third screw is important for verification and redundancy; a fourth (and fifth) screw is recommended because sometimes a piece of the slab breaks off, or a screw can fall out, and in the end it is important to have at least three useable screws. For slabs longer than ~1.75 m, 6 or more screws should be considered. The screws should be surveyed carefully before the slab is cut. In addition to the screws in the slab, we recommend placing an additional “reference” screw elsewhere in the microatoll, which will be left behind after work at the site is completed; this can serve as a useful survey benchmark in case the site ever needs to be reoccupied and resurveyed.

For slabbing microatolls, several types of saws are available. In the Cocos (Keeling) Islands, where microatolls tend to be pancake-shaped (thin and wide), C.D.W. and colleagues initially mounted a diamond rock saw blade on a modified brush cutter (string trimmer), but later used a modified circular saw to cut slabs. In Christmas (Kiritimati) Island, they used a petrol

powered concrete cutting saw. Chappell and others have used a cross-cut saw. In Sumatra, where microatolls tend to be taller because of interseismic subsidence, A.J.M. and colleagues have used a hydraulic chainsaw. ICS® (<http://icsbestway.com/>) manufactures diamond-coated hydraulic chainsaws, designed for cutting concrete underwater, with guide bars up to 63 cm long; this allows for cutting microatoll slabs nearly 63 cm deep, both above and below water level (Figure 3.6.8a). Zachariasen (1998, §2.2c) described in detail the method for extracting a slab with such a chainsaw. However, living or recently dead coral can be cut without too much difficulty using only a hand saw.

After sawing and extracting an approximately 8–10 cm thick slab along a chosen radius or diameter of the microatoll, samples must be extracted for dating, and the slab must be cut into slices thin enough to be x-rayed. Several important steps are involved in processing the slab (e.g., Figure 3.6.8). First, a line of original horizontality should be constructed and drawn (with permanent marker) on one face of the slab. This can be done by using the surveyed elevation of each screw in the slab and projecting down from each screw to an arbitrary zero elevation; a line through the set of projected points should indicate what was horizontal when the coral (and slab) was observed *in situ*. The elevation of this horizontal line relative to one of the screws (or to the site survey) should be noted. Second, a set of small holes should be drilled along the horizontal line, through the entire slab; these small holes will collectively define a plane of original horizontality and will allow the horizontal to be identified on an x-ray of any slice of the slab. Third, samples should be extracted for radiometric dating, using a small (~1 cm diameter) core drill, and the samples should be labeled on the face of the slab. If the samples for dating do not extend through the entire thickness of the slab, it is important to use a drill to extend the hole from each sample entirely through the slab; again, this is so that the samples can be located on an x-ray of any slice of the slab. Fourth, if the slab has broken into multiple pieces, these pieces should all be glued back together; special epoxies exist, created by mixing an epoxy resin and a hardener, that are well suited for this purpose. If there are small, irregular pieces of coral protruding from the microatoll's upper surface, they should be “anchored” to the rest of the coral with generous amounts of epoxy or concrete, so that they don't break off when the slab is cut into thin slices. Fifth, photos should be taken of the face of the slab, with the horizontal line and holes marked and dating samples labeled. Sixth, wooden boxes may be built to hold each slab upright. Seventh, the slabs should be positioned upright in the boxes, and concrete could be poured around the base of each slab to lower the center of gravity and prevent the slab from falling over. Care should be taken to ensure that the slab is positioned as close to vertical as possible; carpenter's levels are handy for this. Eighth, once the concrete is dry (usually after 2 days, depending upon atmospheric conditions), the slabs can be transported to a location to be sliced into thin 5–8 mm thick “bread slices”. In Indonesia, A.J.M. and colleagues transport the upright slabs by pickup

truck to a nearby marble tile factory. At the factory, a marble saw cuts each slab into 2 or 3 parallel slices. There is a tradeoff in the slices' thickness: because x-rays show an average density through the slice rather than preferentially sampling one depth or surface, bands are more likely to show up clearly in thinner slices (Barnes *et al.*, 1989); however, a thinner slice is fragile and prone to fragmenting. We find a thickness of 6–7 mm to be a good balance for the coral slices. Finally, the preferred slice from each slab should be x-rayed. Increasingly, digital x-rays of sufficient resolution (~250 pixels per inch or better) are available; otherwise, traditional x-ray film negatives should be obtained and scanned at sufficient resolution. We recommend that the first step (drawing a horizontal line) be completed before the slab is transported far, to minimize slab breakup or the loss of any screws; however, steps 4 and onward are best completed in a “laboratory setting” (a workshop or other sheltered location) once field work is complete.

3.6.7. Dating strategies

For living coral slabs and for dead coral slabs whose date of death is known precisely, annual density bands can be counted backwards from the outer edge to determine the true age of any part of the coral. The validity and accuracy of band counting is supported by Smithers and Woodroffe (2001), who demonstrated synchronous undulations, spanning most of the twentieth century, over the upper surface of two microatolls collected live from the eastern and southern reef flats of the Cocos (Keeling) Islands. Additionally, they verified an annual periodicity for the fluorescent bands observed in these samples by comparison with density bands, seasonal trends in stable carbon isotopes, alizarin staining, and reference to a skeletal stress band that formed during a severe coral stress event in March 1983. On northern Simeulue Island, Indonesia, Meltzner *et al.* (2010) demonstrated synchronous diedowns from 1961 to 2004, based on band counting, on all slabbed microatolls collected following coseismic uplift in 2004; in particular, the band counting indicates that the largest non-tectonic diedowns in that period all align with known positive IOD events in 1961, 1982, and 1997 (Rao *et al.*, 2002), when sea surface heights in the eastern tropical Indian Ocean would likely have been lowest. These correlations, which persist over four decades, support the accuracy of band counting.

For fossil corals whose age is not independently known, small samples can be drilled out of the slab—during the slab preparation stage, described earlier—for dating. Commonly applied dating methods include radiocarbon (^{14}C) dating and uranium-thorium (U-Th) techniques, although each method has its own pitfalls. For ^{14}C analysis, the marine reservoir effect (ΔR) is often poorly known and must be assumed or determined independently. For U-Th analysis, the system must be assumed to have been closed to both uranium and thorium, and the initial $^{230}\text{Th}/^{232}\text{Th}$ ratio is assumed or determined by isochron (Shen *et al.*, 2008). In addition, McGregor *et al.* (2011) demonstrated the utility of uranium-series age dating using laser ablation

multi-collector inductively coupled plasma mass spectrometry (LA MC-ICPMS) to rapidly and inexpensively find low-precision ages on a large suite of fossil corals.

Whether ^{14}C or U-Th dating techniques are used, increasingly precise estimates of a microatoll's age can be obtained by considering weighted averages of dates from multiple samples from a single slab. For U-Th analyses, consider a sample from a band $n \pm \varepsilon$ years prior to the outer preserved edge of the slab (determined by counting annual bands; with clear banding, ε is effectively zero) that gives a corrected U-Th age of $t_{\text{sample}} \pm 2\sigma_{\text{sample}}$ years before “present” ($2\sigma_{\text{sample}}$ is the analytical 2σ error, and for the sake of simplicity, ε is also treated as a 2σ error); then the age of the outer preserved edge of the slab is given by:

$$t_{\text{edge}} = t_{\text{sample}} - n$$

and the error of that age estimate is the sum of the two errors added in quadrature:

$$2\sigma_{\text{edge}} = (2\sigma_{\text{sample}}^2 + \varepsilon^2)^{1/2}$$

If multiple samples from various bands on a single slab, each $n_i \pm \varepsilon_i$ years prior to the outer preserved edge of the slab, give respective ages of $t_i \pm 2\sigma_i$ years before “present”, then the age of the outer preserved edge of the slab is given by:

$$\frac{\sum_i [(t_i - n_i) / (2\sigma_i^2 + \varepsilon_i^2)]}{\sum_i [1 / (2\sigma_i^2 + \varepsilon_i^2)]}$$

and, unless overdispersion has occurred, the error of that age estimate is:

$$\sqrt{\frac{1}{\sum_i [1 / (2\sigma_i^2 + \varepsilon_i^2)]}}$$

The analogous procedure for radiocarbon dating—taking a weighted average of ^{14}C dates from multiple samples from various bands on a slab—is more complicated, but it can be handled explicitly in OxCal (available at <http://c14.arch.ox.ac.uk/embed.php?File=oxcal.html>) using the D_Sequence() function (Bronk Ramsey, 2008).

If a compelling argument can be made that two microatolls at a site lived coevally, their dates can be combined in a manner similar to that just described. Meltzner *et al.* (2010), (2012) considered several cases in which multiple microatolls from a site yielded similar but insufficiently precise radiometric ages. By carefully counting and comparing the intervals between successive diedowns on each microatoll and noting the highest level of survival following each diedown, they identified slabs with matching diedown histories, i.e., places where the slabs recorded similar elevation changes and identical intervals between the respective diedowns. Using this “diedown matching” technique—which is in some ways akin to matching the thickness of successive magnetic stripes on the seafloor or of successive magnetostratigraphic

units in sedimentary sequences, and in other ways akin to matching annual growth ring histories in trees—they were able to identify precisely the portions of the microatolls that corresponded with one another, even if different growth rates or other irregularities initially masked the temporal overlap. The ability to correlate individual annual bands on the various slabs allowed all the dates to be combined into a single, far more precise weighted mean than would otherwise have been possible.

Chapters 5.1 and 5.4, respectively, discuss the methodologies of ^{14}C and U-Th dating in greater detail. These chapters explore potential sources of error associated with each technique and potential issues regarding sample integrity, including alteration and open-system diagenesis. We refer readers to these chapters for further valuable information.

3.6.8. Vertical accuracy and sources of error

In any year, the height to which a microatoll's living coral rim grows (the highest level of growth) may lag beneath the level at which it may potentially survive (the highest level of survival) if the rate of relative sea-level rise exceeds the coral growth rate. Where the limiting water level rises at a rate greater than the coral growth rate, including in cases of coseismic or rapid postseismic tectonic subsidence, the upper level of coral growth will decouple from the water level and the living coral rim may be growing up to a still rising, a stable, or even a falling water level. Under these circumstances a microatoll's upper surface morphology may inaccurately reflect the rate and even direction of relative sea-level fluctuations over timescales of months to years. For these reasons, we remind the reader that although a microatoll's diedowns track low water levels and a microatoll's overall morphology provides valuable information on multi-decadal trends in relative sea level, care must be taken to understand the limitations of a microatolls' record. Spencer *et al.* (1997), for example, determined that it would take two decades for the living coral rim around a microatoll on Tongareva, Cook Islands, to regrow to near its limiting water level following a marked (>20 cm) fall in rim height associated with the 1982–1983 ENSO event. Nevertheless, the sea-level variations of tens of centimeters that accompany severe ENSO episodes in the central Pacific or IOD events in the eastern Indian Ocean tend to be recorded as minor annuli of a few centimeters on the tops of microatolls on several Pacific island reef flats (Woodroffe and McLean, 1990, Spencer *et al.*, 1997) or as annuli with up to 10–20 cm relief on the reef flats off northern Sumatra (Meltzner *et al.*, 2010).

Microatolls' utility as paleo-sea-level indicators notwithstanding, there can be geographical variation across a reef in the elevation that limits coral upward growth (Table 3.6.1). Chappell *et al.* (1983) found the tops of microatolls within any single field on the inner Great Barrier Reef, where the tidal range is ~3 m, to usually lie within a vertical range of 10 cm. Likewise, in the Mentawai Islands off the west coast of Sumatra, Indonesia, where the tidal range

is ~1.1 m and reefs tend to be narrow, Zachariasen *et al.* (2000) reported the typical variation of highest level of survival on a single *Porites* colony to be less than ± 3 cm, and the variation in the average highest level of survival between microatolls at a single site to be about 5–15 cm. On the Cocos (Keeling) Islands, with a tidal range of ~1.2 m, Smithers and Woodroffe (2000) similarly observed that the highest level of survival around most individual microatolls fluctuates within a 2–3 cm range when outliers obviously not constrained by water level are omitted from the analysis. In addition, they reported that the tops of open water microatolls are typically elevated between MLWS and MLWN (mean low water neaps) around the atoll as a whole. Yet accurate surveying of 282 living *Porites* microatolls at a total of 19 sites—although showing consistency on the heights of adjacent microatolls in the same field—demonstrated an overall variation of up to 40 cm. Irrespective of whether the microatolls were in an open reef flat, interisland passage, or lagoonal habitat, they found that the highest level of growth (or highest level of survival) on the various surveyed microatolls spanned more than 10 cm at 9 of the 19 sites, and more than 20 cm at 3 sites. Although some of that variability may be related to subtle hydrodynamic conditions such as wave setup, wave splash, and local tidal conditions, Smithers and Woodroffe (2000) proposed that considerable variability may arise from subtle moating (or ponding), recognizing that “microatolls at many sites clearly survive at elevations substantially above contemporaries lower in the tidal range ... usually in small shallow ponds held in subtle depressions in the reef surface as the tide ebbs.” Smithers and Woodroffe (2000) further noted that “although individual pools are shallow and may raise water levels only slightly, the cumulative impact of numerous shallow ponds at progressively higher elevations can produce the large depth ranges occupied by microatolls at many sites.”

Moating or ponding can play an important role in the upper limit to coral growth, even in cases where the presence of elevated pools is not obvious. Although one pool may raise the water level at extreme low tide by only a centimeter or two over the level in an adjacent pool immediately seaward, and although this may be observable only at extreme low tide, the cumulative effect of multiple subtle ponds at progressively higher elevations can be to raise the highest level of survival in the highest pools by >10 cm on the wider and more physiographically complex reefs (Smithers and Woodroffe, 2000). Ironically, in high wave-energy environments, those highest pools tend to be the most protected and the most conducive to large microatoll growth, so the best microatolls at a site may all have a raised highest level of survival due to the effects of moating. Hence, it is imperative that in any microatoll study the researcher considers the reef morphology, both at present and how it might have appeared in the past. The highest level of survival history on a microatoll affected by moating tends to reflect changes in the elevation of the moat sill, rather than regional changes in relative sea level (Smithers, 2011). If the researcher can recover and analyze contemporaneous microatolls that grew hundreds of

meters or even kilometers apart, and if these microatolls yield consistent histories with diedowns in the same years at approximately the same elevations, then it is unlikely that either microatoll was affected by moating.

Sediment compaction, settling, or slumping of the substrate can also affect the elevation of microatolls. This can be a problem particularly in tectonically active settings, where sites may be frequently affected by shaking, although muddy substrates can be problematic anywhere. At one site off the west coast of Sumatra, Sieh *et al.* (2008) documented a population of microatolls that was uplifted and died around AD 1380; the highest level of survival of these microatolls spanned 40 cm. Although this range is identical to that documented in the Cocos (Keeling) Islands by Smithers and Woodroffe (2000), the narrowness of the reef off Sumatra, the lack of moating apparent in contours of substrate elevation, and the site's proximity to sources of strong shaking, collectively suggest that shaking-induced settling or slumping is a more reasonable explanation at the Sumatra site for the range in the highest level of survival. The microatolls were systematically higher landward and lower seaward, suggesting that progressively more settling had occurred closer to the reef edge. The settling probably occurred during an earthquake about AD 1380, because the highest level of survival variation for younger microatolls is far less. At another site farther north along the outer-arc chain of islands, Meltzner *et al.* (2010) identified a cluster of microatolls near the reef edge that was 30 cm lower than the rest of the contemporaneous population of microatolls. Again, the problem was localized, and unrecognized subtle moating on this low-relief reef cannot easily explain such an abrupt and large variation in the highest level of survival elevations, leaving localized slumping as the most likely explanation.

Whatever the causes for the variability in the highest level of survival, it is useful to document not only the elevation of the highest level of survival on a single (slabbed) microatoll from a particular generation, but also the variability of that highest level of survival. Had only a single microatoll or a single cluster of adjacent microatolls been surveyed at a site with large highest level of survival variation, it would be difficult to determine how well the surveyed highest level of survival represented relative sea level. Surveying coeval highest level of survival on multiple colonies spread over a site gives a sense of the reliability and accuracy of those elevations. Although there is no perfect way to do this for fossil microatolls, we suggest surveying the highest level of survival on a suite of morphologically similar microatolls. If all such microatolls are at nearly identical elevations, an argument can be made that the slab's highest level of survival accurately represents the highest level of survival for that generation; as Chappell *et al.* (1983) described of their work on the northern Great Barrier Reef, "only those groups of dead microatolls that were extensive and consistent in height were sampled for dating." If, however, there is large variability in the surveyed elevations, the researcher should decide whether to investigate further or to use the range of elevations to estimate the vertical error.

Alternatively, if a population is not extensive, the researcher should consider assigning vertical errors that match or exceed the largest documented vertical spread of any population at the site.

It is also important to recognize whether a microatoll, when found by a researcher, is in its original growth position. Large microatolls may be secured to the substrate beneath them by only a small pedestal, from which they can be detached, or in some cases microatolls may rest on a sandy substrate their entire lives. Occasionally corals will be transported during large storms or tsunamis. If a transported coral is deposited right-side-up, it could be interpreted as *in situ* when it is not (McLean *et al.*, 1978). This is another reason to demonstrate that the sampled microatoll is part of a population of morphologically similar microatolls all at the same elevation: it is unlikely that multiple microatolls would all be transported and deposited at the same level.

McLean *et al.* (1978) highlighted a number of assumptions that are inherent in sea level studies using microatolls: (1) fossil features equivalent in form and composition, but at higher or lower levels than their contemporary counterparts, developed with a sea level that was higher or lower than present, the magnitude of sea level change being the difference between the two levels; (2) features inferred to be related to present sea level are indeed so related; (3) ranges in elevation between equivalent contemporary features for all reefs surveyed are similar to the ranges of relict features; and (4) there have been no significant changes over time in the tidal range or wave climate at a particular site.

In general, it is best to relate the elevations of fossil microatolls to elevations of living counterparts nearby, rather than attempting to relate fossil microatoll elevations to low water level or even to living microatoll elevations tens of kilometers away. A key problem of relating the highest level of survival to low water level is that the relationship is poorly defined and could vary considerably from one environment or region to another; we will discuss this problem in Section 3.6.9.

On Christmas (Kiritimati) Island in the Line Islands, Woodroffe *et al.* (2012) inadvertently discovered the effect of a strong geoidal gradient that has implications for surveying over long distances in any sea level study. Using real-time kinematic (RTK) GPS, they surveyed the elevations of an extensive suite of more than 100 fossil microatolls spanning ~40 km across the island and found disparities from one end of the island to the other that reveal a significant gradient of the geoid. Although the elevations of all fossil microatolls on the island are within a remarkably narrow range of 0.1 m of adjacent living microatolls, the living microatolls themselves, and contemporaneous sets of fossil microatolls, showed a variation of ~1 m in the RTK GPS survey, a range comparable to the variation around the island in the height of the geoid itself (Woodroffe *et al.*, 2012). This should serve as a note of caution to any researcher surveying and directly comparing the elevations of sea level markers over distances of more than a few kilometers: variations in the height of the geoid matter!

3.6.9. Indicative meaning

The upper limit to coral growth (a coral's highest level of survival) is generally thought to be constrained near to the elevation of a critical low water level by prolonged subaerial exposure, possibly due to the influence of desiccation, temperature stress, UV exposure, or some combination. However, the exact nature of these controls is poorly understood: a coral's highest level of survival may be influenced by the duration of exposure, intensity of solar radiation, air and water temperature, frequency of wave splash, capillary action on the coral itself, or other factors. It is not yet clear how best to define a reference water level for coral microatolls' highest level of survival. The reference water level certainly varies by genus (and perhaps by species) and is setting-dependent; ultimately, it may well prove to be a parameter that is site-specific. Even considering only *Porites* microatolls in open water settings, and ignoring moated colonies, does not resolve the problem.

Different studies at different sites have led to different estimates of reference water level. On the northern Great Barrier Reef, where the tidal range is ~3 m, Scoffin and Stoddart (1978) found open water microatolls' highest level of survival to occur around MLWS. In the Cocos (Keeling) Islands, where the tidal range is ~1.2 m, Smithers and Woodroffe (2000) reported that the tops of open water *Porites* microatolls are typically elevated midway between MLWS and MLWN. Off the west coast of Sumatra, where the overall tidal range varies from 0.8 to 1.0 m, Meltzner *et al.* (2010) took a different approach, arguing that the highest level of survival for *Porites* more closely tracks the annual extreme low water (for years in which there are diedowns), lying 19 ± 8 cm above the lowest water level recorded at a site in a given year. Considering all the factors that may influence a coral's highest level of survival, however, it would be surprising if the relationship determined for the west coast of Sumatra applied generally.

We expect the relationship between the highest level of survival and extreme low water, MLWS, MLWN, or any other part of the tidal cycle to depend in part upon the shape of the tidal curve at a site, the site's typical wave environment, and perhaps even the morphology of the reef. A reference water level determined in a microtidal region characterized by narrow reefs with high wave energy and semidiurnal tides is not expected to apply in a mesotidal environment, a region with low wave energy or diurnal tides (if the duration of exposure is important), or on broad reefs. Similarly, the indicative range is expected to be larger on wider and more physiographically complex reefs. If knowledge of the indicative meaning of coral microatoll's highest level of survival is desired, a researcher must collect sufficient data to determine the relationship for his or her field area, and cannot simply rely on values determined elsewhere.

3.6.10. Reconstructing relative sea level time series

After microatoll slices have been x-rayed, the x-rays should be mosaicked together in a raster graphics editor such as Adobe® Photoshop®. At this stage, any deformation of the slice caused by cracks can be corrected for by fitting individual fragments together, and the contrast of the x-rays can be improved so that banding is clearer, as long as care is taken to ensure that any adjustments merely emphasize the banding and growth patterns visible in the original x-rays and that no artifacts (such as false bands) are introduced. Subsequently, the mosaicked x-ray image can be imported into a vector graphics editor such as Adobe® Illustrator®, wherein annual bands can be traced. As a note of caution, one should check that the scale on the final image represents the actual scale of the coral slice, and that the horizontal line, indicated by a line of holes in the slab x-rays—if the procedures recommended earlier were followed—is indeed horizontal.

Relative sea level histories can be reconstructed by accurately measuring the highest level of growth or highest level of survival at regular intervals on each annotated slab x-ray mosaic. Smithers and Woodroffe (2001) measured the highest living coral at two points per annual growth band (for semiannual resolution); Meltzner *et al.* (2010) measured only one point per year in most years, but for every diedown they measured both the highest level of growth immediately before each diedown and the highest level of survival immediately thereafter. When plotting these time series, Meltzner *et al.* (2010) were careful to distinguish four different types of data obtained from the coral slice: highest level of survival elevations immediately after a diedown; highest level of growth elevations immediately before a diedown; uneroded highest level of growth elevations where no diedown occurred (a minimum bound on the highest level of survival for that year); and eroded highest level of growth or highest level of survival elevations, where the upper part of the growth band has been removed by erosion (a minimum bound on both the highest level of growth and highest level of survival for that year). Extensive discussions of methods to determine rates of relative sea level change, the significance of those rates, and appropriate errors on those rates are presented by Meltzner *et al.* (2010), (2012). The time series records from individual microatolls at a site can be combined into a single plot for the site, and all time series can be plotted relative to the highest level of growth at present or at any arbitrarily chosen point in time.

3.6.11. Differentiating tectonic from non-tectonic diedowns

Criteria for distinguishing oceanographically induced diedowns (those caused by sea level fluctuations) from tectonically induced diedowns (those caused by changes in land level) have been discussed by Taylor *et al.* (1987), Zachariasen (1998, §1.5c), and Meltzner *et al.* (2010). These authors recommend considering the microatoll morphology, contemporaneous microatoll records from other sites regionally, and any historical information available

independently. First, the amplitude of the diedown matters: diedowns larger than 10 cm are more likely to be tectonic (Taylor *et al.*, 1987), although ENSO- or IOD-related diedowns of ~15 cm have been documented (Meltzner *et al.*, 2010). Second, the geographic distribution of the diedown and the spatial variability of the amplitude are important: the amplitude of tectonic uplifts tends to vary markedly over short distances, whereas diedowns caused by temporarily lower sea level (as can occur during ENSO or IOD events) should be similar over distances of tens to hundreds of kilometers and should occur simultaneously at sites in tectonically active areas and in adjacent stable regions. Third, the duration of the sea level change is telling: tectonically induced relative sea level changes are more likely to persist through time, as a step function, whereas oceanographic fluctuations should be short-lived, as a delta function (Zachariasen, 1998, §1.5c). Meltzner *et al.* (2010) suggested that, following a large nontectonic diedown, the coral should have unrestricted upward growth without additional diedowns until that upward growth approaches the coral's previous highest level of growth. In contrast, a tectonic uplift should not be followed by unusual unrestricted upward growth, and subsequent diedowns should all be lower than diedowns preceding the uplift (Figure 3.6.1, Case 4). Lastly, coincidence in time and location between known earthquakes and changes in relative sea level favors a tectonic cause.

3.6.12. Environmental and administrative issues

We conclude with a note about environmental and administrative considerations. It is advisable to ensure that the necessary permits have been researched and obtained well before field sampling. If living corals are to be sampled from shallow water then a permit will likely be needed, particularly in marine protected areas, and it will be necessary to check zoning plans to ensure that research can be undertaken and the necessary slabs or cores of coral can be collected. There is little consistency as to which organizations will need to be approached—it may be environmental agencies, natural resources divisions, or land and wildlife agencies, and in many countries clearance may be required from fisheries authorities, either to collect or to export coral samples. It will also be important to consider whether the slabs of coral collected can be freighted between countries under the provisions of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Coral is listed under CITES, and regulations are becoming increasingly stringent. Live corals, dead corals and “live rock” require CITES permits for export from and import into most countries, often with specifications to genus, or even species level. Fossil coral, and coral that is dead but may have been alive when collected and in which corallites remain distinct, remain contentious with some countries requiring a CITES permit to import, regardless of whether an export permit is required by the laws of the country of origin. Coral samples collected from on land may be subject to quarantine restrictions,

if only to ensure there are no traces of soil, plants, or insects. It is prudent to have applied for the necessary quarantine clearance or permits before undertaking fieldwork.

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Suggestions for cross-references to other articles within the Handbook

- 3.5. Coral Reefs
- 3.9. Reference Water Level and Tidal Datum
- 5.1. Radiocarbon and Calibration
- 5.4. Uranium-Thorium
- 6.1. Glacial Isostatic Adjustment
- 6.2. Tides
- 6.3. Compaction

References

- Barnes, D.J., Lough, J.M. & Tobin, B.J., 1989. Density measurements and the interpretation of X-radiographic images of slices of skeleton from the colonial hard coral *Porites*, *J. Exp. Mar. Biol. Ecol.*, 131, 45-60, doi:10.1016/0022-0981(89)90010-5.
- Bronk Ramsey, C., 2008. Deposition models for chronological records, *Quat. Sci. Rev.*, 27, 42-60, doi:10.1016/j.quascirev.2007.01.019.
- 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 J. Aust. Geol. Geophys.*, 8, 223-235.
- Dana, J.D., 1849. *United States Exploring Expedition, During the Years 1838, 1839, 1840, 1841, 1842, Under the Command of Charles Wilkes, U. S. N., Vol. X: Geology*, C. Sherman, Philadelphia. Available at <http://archive.org/details/unitedstatesexpl10unitrich> or <http://www.biodiversitylibrary.org/item/62759#page/9/mode/1up>.
- Darwin, C., 1842. *The Structure and Distribution of Coral Reefs: Being the First Part of the Geology of the Voyage of the Beagle, under the Command of Capt. Fitzroy, R.N. during the Years 1832 to 1836*, Smith Elder and Co., London. Available at <http://darwin-online.org.uk/content/frameset?itemID=F271&pageseq=1&viewtype=text> or http://darwin-online.org.uk/converted/pdf/1842_Coral_F271.pdf.
- Flora, C.J. & Ely, P.S., 2003. Surface growth rings of *Porites lutea* microatolls accurately track their annual growth, *Northwest Sci.*, 77, 237-245. Available at http://www.vetmed.wsu.edu/org_nws/NWSci%20journal%20articles/2003%20files/Issue%203/v77%20p237%20Flora%20and%20Ely.PDF.
- Guppy, H.B., 1886. Notes on the characters and mode of formation of the coral reefs of the Solomon Islands, being the results of observations made in 1882-84, during the surveying cruise of H.M.S. "Lark", *Proc. R. Soc. Edinb.*, 13, 857-904. Available at <http://books.google.com/books?id=3tgfAQAAIAAJ&pg=PA857>.
- Hopley, D., 1982. *The Geomorphology of the Great Barrier Reef: Quaternary Development of Coral Reefs*, 470 pp., John Wiley & Sons Inc., New York.
- Isdale, P., 1984. Fluorescent bands in massive corals record centuries of coastal rainfall, *Nature*, 310, 578-579, doi:10.1038/310578a0.
- Juillet-Leclerc, A. & Reynaud, S., 2010. Light effects on the isotopic fractionation of skeletal oxygen and carbon in the cultured zooxanthellate coral, *Acropora*: implications for coral-growth rates, *Biogeosciences*, 7, 893-906, doi:10.5194/bg-7-893-2010.
- Krempf, A., 1927. *Travaux du Service Océanographique des Pêches de l'Indochine ..., 2e Mémoire: La Forme des Récifs Coralliens et le Régime des Vents Alternants*, Gouvernement général de l'Indochine, Saigon.
- Kuenen, P.H., 1933. *Wetenschappelijke uitkomsten der Snellius-expeditie onder leiding van P.M. van Riel (The Snellius-Expedition in the Eastern Part of the Netherlands East-Indies 1929-1930, under Leadership of P.M. Van Riel)*, vol. 5 (Geological Results), part 2: *Geology of Coral Reefs*, E. J. Brill, Leiden.

- McGregor, H.V., Hellstrom, J., Fink, D., Hua, Q. & Woodroffe, C.D., 2011. Rapid U-series dating of young fossil corals by laser ablation MC-ICPMS, *Quat. Geochronol.*, 6, 195-206, doi:10.1016/j.quageo.2010.10.002.
- McLean, R.F., Stoddart, D.R., Hopley, D. & Polach, H., 1978. Sea level change in the Holocene on the northern Great Barrier Reef, *Philos. Trans. R. Soc. London Ser. A*, 291, 167-186, doi:10.1098/rsta.1978.0097.
- Meltzner, A.J., 2010. Earthquake recurrence, clustering, and persistent segmentation near the southern end of the 2004 Sunda megathrust rupture, Ph.D. thesis, California Institute of Technology, Pasadena, CA.
Available at <http://resolver.caltech.edu/CaltechTHESIS:06012010-082222484>.
- Meltzner, A.J., Sieh, K., Chiang, H.-W., Shen, C.-C., Suwargadi, B.W., Natawidjaja, D.H., Philibosian, B. & Briggs, R.W., 2012. Persistent termini of 2004- and 2005-like ruptures of the Sunda megathrust, *J. Geophys. Res.*, 117, B04405, doi:10.1029/2011JB008888.
- Meltzner, A.J., Sieh, K., Chiang, H.-W., Shen, C.-C., Suwargadi, B.W., Natawidjaja, D.H., Philibosian, B.E., Briggs, R.W. & Galetzka, J., 2010. Coral evidence for earthquake recurrence and an A.D. 1390–1455 cluster at the south end of the 2004 Aceh–Andaman rupture, *J. Geophys. Res.*, 115, B10402, doi:10.1029/2010JB007499.
- Natawidjaja, D.H., Sieh, K., Chlieh, M., Galetzka, J., Suwargadi, B.W., Cheng, H., Edwards, R.L., Avouac, J.-P. & Ward, S.N., 2006. Source parameters of the great Sumatran megathrust earthquakes of 1797 and 1833 inferred from coral microatolls, *J. Geophys. Res.*, 111, B06403, doi:10.1029/2005JB004025.
- Rao, S.A., Behera, S.K., Masumoto, Y. & Yamagata, T., 2002. Interannual subsurface variability in the tropical Indian Ocean with a special emphasis on the Indian Ocean Dipole, *Deep-Sea Res. II*, 49, 1549-1572, doi:10.1016/S0967-0645(01)00158-8.
- Scoffin, T.P. & Stoddart, D.R., 1978. The nature and significance of microatolls, *Philos. Trans. R. Soc. London Ser. B*, 284, 99-122, doi:10.1098/rstb.1978.0055.
- Scoffin, T.P., Tudhope, A.W. & Brown, B.E., 1989. Fluorescent and skeletal density banding in *Porites lutea* from Papua New Guinea and Indonesia, *Coral Reefs*, 7, 169-178, doi:10.1007/BF00301595.
- Scoffin, T.P., Brown, B.E., Dunne, R.P. & LeTissier, M.D.A., 1997. The controls on growth form of intertidal massive corals, Phuket, south Thailand, *Palaos*, 12, 237-248, doi:10.2307/3515425.
- Shen, C.-C., Li, K.-S., Sieh, K., Natawidjaja, D., Cheng, H., Wang, X., Edwards, R.L., Lam, D.D., Hsieh, Y.-T., Fan, T.-Y., Meltzner, A.J., Taylor, F.W., Quinn, T.M., Chiang, H.-W. & Kilbourne, K.H., 2008. Variation of initial $^{230}\text{Th}/^{232}\text{Th}$ and limits of high precision U-Th dating of shallow-water corals, *Geochim. Cosmochim. Acta*, 72, 4201-4223, doi:10.1016/j.gca.2008.06.011.
- Sieh, K., Natawidjaja, D.H., Meltzner, A.J., Shen, C.-C., Cheng, H., Li, K.-S., Suwargadi, B.W., Galetzka, J., Philibosian, B. & Edwards, R.L., 2008. Earthquake supercycles inferred from sea-level changes recorded in the corals of West Sumatra, *Science*, 322, 1674-1678, doi:10.1126/science.1163589.

- Smithers, S., 2011. Microatoll, in *Encyclopedia of Modern Coral Reefs: Structure, Form and Process*, pp. 691-696, ed. Hopley, D., Encyclopedia of Earth Sciences Series, Springer, Dordrecht, The Netherlands, doi:10.1007/978-90-481-2639-2.
- Smithers, S.G. & Woodroffe, C.D., 2000. Microatolls as sea-level indicators on a mid-ocean atoll, *Mar. Geol.*, 168, 61-78, doi:10.1016/S0025-3227(00)00043-8.
- Smithers, S.G. & Woodroffe, C.D., 2001. Coral microatolls and 20th century sea level in the eastern Indian Ocean, *Earth Planet. Sci. Lett.*, 191, 173-184, doi:10.1016/S0012-821X(01)00417-4.
- Spencer, T., Tudhope, A.W., French, J.R., Scoffin, T.P. & Utanga, A., 1997. Reconstructing sealevel change from coral microatolls, Tongareva (Penrhyn) Atoll, northern Cook Islands, in *Proceedings of the 8th International Coral Reef Symposium, vol. 1*, pp. 489-494, eds. Lessios, H. A. & Macintyre, I. G., Smithsonian Tropical Research Institute, Panama. Available at <http://www.reefbase.org/download/download.aspx?type=1&doid=7727>.
- Taylor, F.W., Frohlich, C., Lecolle, J. & Strecker, M., 1987. Analysis of partially emerged corals and reef terraces in the central Vanuatu Arc: comparison of contemporary coseismic and nonseismic with Quaternary vertical movements, *J. Geophys. Res.*, 92, 4905-4933, doi:10.1029/JB092iB06p04905.
- Wood-Jones, F., 1910. *Coral and Atolls: Their History, Description, Theories of their Origin both before and since that of Darwin, the Influence of Winds, Tides and Ocean Currents on their Formation and Transformations, their Present Condition, Products, Fauna and Flora*, Lovell Reeve & Co., Ltd., London. Available at <http://ocp.hul.harvard.edu/dl/expeditions/005186246> or <http://catalog.hathitrust.org/Record/003482694>.
- Woodroffe, C. & McLean, R., 1990. Microatolls and recent sea level change on coral atolls, *Nature*, 344, 531-534, doi:10.1038/344531a0.
- Woodroffe, C.D., McGregor, H.V., Lambeck, K., Smithers, S.G. & Fink, D., 2012. Mid-Pacific microatolls record sea-level stability over the past 5000 yr, *Geology*, 40, 951-954, doi:10.1130/G33344.1.
- Zachariasen, J., 1998. Paleoseismology and paleogeodesy of the Sumatran subduction zone: a study of vertical deformation using coral microatolls, Ph.D. thesis, California Institute of Technology, Pasadena, CA. Available at <http://resolver.caltech.edu/CaltechETD:etd-04112005-132058>.
- Zachariasen, J., Sieh, K., Taylor, F.W. & Hantoro, W.S., 2000. Modern vertical deformation above the Sumatran subduction zone: paleogeodetic insights from coral microatolls, *Bull. Seismol. Soc. Am.*, 90, 897-913, doi:10.1785/0119980016.

Figure Captions

Figure 3.6.1. (*Top*) Microatoll development under different relative sea level history scenarios: under stable sea level conditions (Case 1), under gradually falling sea level (Case 2), and under gradually rising sea level (Case 3). In all three cases, we superimpose on the long-term trend a realistic interannual variability: at 11.1 and 14.1 yr, we simulate temporary local sea level lowerings such as those that tend to occur during La Niña events in the central Pacific, during El Niño events in the western Pacific, or during positive IOD events in the eastern Indian Ocean. Note that concentric annuli form in open water (unmoated) environments simply from year-to-year fluctuations in the low water level and HLS. Also note the “out-of-sequence” interior annuli that form where relative sea level is rising rapidly enough; this overgrowth protects the underlying inner surface of the microatoll from erosion. (*Bottom*) Microatoll development affected by sudden (tectonic) changes in land level. Case 4 illustrates the microatoll from Case 3, followed by coseismic uplift at 17.1 yr; Case 5 illustrates the microatoll from Case 1, followed by coseismic subsidence at 17.1 yr. In each case, the long-term trend is superimposed on a typical ENSO or IOD cycle, with an additional short-lived period of lower local sea level at 20.1 yr. In Case 4, the uplift must have been sudden at 17.1 yr, but if we found the microatoll in Case 5, we could not distinguish between sudden coseismic subsidence at 17.1 yr and rapid interseismic subsidence (at an average rate exceeding the coral’s growth rate) beginning at 17.1 yr.

Figure 3.6.2. Four common microatoll forms. Adapted from Hopley (1982, figure 4.6, p. 113). Reproduced with permission of John Wiley & Sons.

Figure 3.6.3. Potential variability in contemporaneous microatolls. Microatolls (a), (b), and (c) all experienced the relative sea level history depicted in Cases 3 and 4 of Figure 3.6.1., having formed under gradually rising sea level with a modest uplift event at year 17.1. Microatoll (b) is the specimen from Case 4 in Figure 3.6.1. Microatoll (a) started growing at the same time in a depression but at the same basal elevation as Microatoll (b), but irregular topography resulted in less accommodation space. The substrate to the left of the coral is sufficiently high that the microatoll’s left side did not survive the diedown at year 17.1. The substrate to the right of the coral is slightly lower, which allowed the right side to survive the year-17.1 diedown, but not the lower diedown at year 20.1. Microatoll (c) grew from the same basal elevation as Microatoll (b) but started growing only in year 4; hence, its highest level of growth was lower at year 11.1 and it did not die down then. After year 14.1, Microatoll (c) recorded a similar history as Microatoll (b). White horizontal lines denote elevations of annuli that could be surveyed in the field.

Figure 3.6.4. Photos of microatolls, all within ~200 m of one another, from LKP-B site of Meltzner *et al.* (2010), northern Simeulue, Sumatra, Indonesia. (a, b) Examples from a population of fossil microatolls characterized by a low interior and high outer double rim, all of which had outer-rim elevations within a narrow range of ~10 cm. (c, d) Examples from a second

population interspersed among the first; these are characterized by a low interior, high middle annulus, and intermediate outer annulus, and they are consistently ~20 cm lower than the first population. The authors initially anticipated these two populations represented different generations of microatolls; dating confirmed that the first population (a, b) died around AD 1394, and the second population (c, d) died ~56 years later. Photos from Meltzner (2010).

Figure 3.6.5. Recognizing the highest living corallites (HLS or HLG) on a microatoll is normally easy to do, if one knows what to look for. Close-up (a) and wider view (b) of HLS ~3 cm above the water line on a coral at the PPY-A site of Meltzner *et al.* (2012), northeastern Simeulue, Sumatra, Indonesia. This coral experienced a diedown of ~40 cm due to uplift in the December 2004 and March 2005 earthquakes, but the coral survived around its base and continued to grow outward and upward from below its HLS. Three years later, in an earthquake in February 2008, the microatoll experienced another diedown of ~2 cm. Above the 20-cm mark on the ruler, the coral is dead and covered by 4 years' accumulation of algae. At the 20-cm mark, ~5 cm above the water line, a lip circumscribes the microatoll, marking the coral's HLG from early 2005 to early 2008. The uppermost ~2 cm of this lip, from ~20 cm to ~18 cm, is thinly coated by algae; these are the polyps that died in 2008. Below ~18 cm, the coral is alive and polyps are not coated by algae. An incipient outer lip is forming, ~2 cm below the previous lip, though this is not obvious in the photos. Photos taken February 2009. When considering the scale, note the optical illusion that only the upper ~5 cm, and the reflection of those ~5 cm, are visible, due to the bright reflection of the metallic ruler. (c) Stark contrast between dull, algae-covered, dead polyps above the HLS, and bright, living polyps below, on recently uplifted microatolls along the coast of northern Tetepare Island, Western Province, Solomon Islands, June 2012. (d) Field of living microatolls in a moated pool, Mapur Island, Riau Islands, Indonesia, April 2012. Again, note the contrast between the bright living corallites on the rim and perimeter of the colony, and the dull, fine sediment-covered inner upper surface.

Figure 3.6.6. Example field notes showing *in situ* documentation of key observations, including: a general description of the microatoll to be slabbbed and its surroundings; the GPS location; photographs; a radial profile along the slab, showing surveyed features, locations of surveyed screws, and corresponding survey points. This reflects the minimum information necessary for every slabbbed microatoll; more information is often needed in complicated or irregular situations.

Figure 3.6.7. PPY-1 microatoll and slab. (a, b, c) Views of the microatoll in the field. Removal of the slab allowed us to view below the inner surface of the microatoll, but prior to the slab's removal, only the overgrowth—the flat inner surface of the microatoll—was visible. (d) Photo of the slab after removal and initial processing. The slab was subsequently x-rayed, and the x-rays were mosaicked (e) and annotated (f). Although some erosion of the low interior annuli occurred and is evident on the x-rays, the erosion was minor. Once the low interior annuli were overgrown, they were protected from additional erosion.

Figure 3.6.8. Steps involved in obtaining and processing the slab. (a) Cutting a slab with an ICS® diamond-coated hydraulic chainsaw and 63-cm guide bar and chain. This is not the microatoll from which the slab in (b) and (c) came. (b) The pieces of a slab—one radius of a microatoll—have been fitted together, and a line of original horizontality has been drawn on the slab by measuring down an appropriate distance from each surveyed screw; the locations of the screws are indicated by upward pointing arrows. The elevation of the horizontal line relative to the outer screw (the left-most screw in this photo) is indicated, and because the outer screw was surveyed, the elevation of the line can be determined relative to the entire site survey. (c) A set of small holes has been drilled along the horizontal line, collectively defining a plane of original horizontality; samples (labeled A1, A2, B1, B2, etc.) have been extracted for radiometric dating; and the various pieces of the slab have been glued together. A “hole” in the face of the slab near the upper right has been filled with epoxy, so that the upper right piece of the slab does not break off during slicing. (d) Slabs being set upright in concrete in wooden boxes. (e) A marble saw is used to cut each slab into 2 or 3 parallel slices.

$t = \text{year } 8$

$t = \text{year } 11$

$t = \text{year } 11.1$

$t = \text{year } 14$

$t = \text{year } 14.1$

$t = \text{year } 17$

Case 1

Case 2

Case 3

$t = \text{year } 17$

$t = \text{year } 17.1$

$t = \text{year } 20$

$t = \text{year } 20.1$

$t = \text{year } 23$

Case 4

LEGEND

— annual banding

- - - sea level

— living perimeter

- - - short-lived period of lower sea level

Case 5

Classical

Top hat

Upgrown

Multiple ringed

center line

Side view

Cross section

(a)

(b)

(c)

16 June 2011

07:30

Site TKUB

Living Porites Microatoll TKUB-M1

GPS Waypoint:

TKUB-M1

Photos:

1186-1192

1244-1272

1341-1351

1445-1483

Approx. 2.2×2.8 m low-relief microatoll with 5 concentric rings. The outer living rim is raised ~ 2 cm above the immediately adjacent dead coral, but it is 1-2 cm lower than the 2nd ring, which is the highest.

We are observing and surveying this coral near low spring tide. Although it is near the seaward edge of the reef, and although it does not appear to be in a raised pool at the moment, it is possible that this microatoll would be in a raised pool if the tide were 5-10 cm lower. We will investigate this possibility by surveying many living microatolls at this site and by slabbing 1-2 additional living microatolls.

Radial Profile (along slab): Survey PointDescription

103	outer screw in slab	} see sketch above
104	2nd screw in slab	
105	3rd screw in slab	
106	4th screw in slab	
107	inner screw in slab	
108	'reference screw' left behind in outer rim for site reoccupation	
109-132	outer living rim (living HLG) -- there has been ~ 2 cm upward growth and 3-4 cm radial growth since last diedown	
133-145	2nd concentric ring	} see sketch above
146-155	3rd concentric ring	
156-160	4th concentric ring	
161-166	5th concentric ring (subtle)	
167	approx. geometrical center of microatoll	
168	indentation near center of microatoll *	

(a)

(c)

(b)

(d)

Table 3.6.1.

Documented highest level of growth (HLG) variability on living open-ocean *Porites* microatolls

Location	Tidal range	HLG variation per microatoll	HLG variation per site	Reference
inner Great Barrier Reef, Australia	~3.0 m		tops of microatolls within a field usually lie within a vertical range of 10 cm	Chappell et al. [1983]
Mentawai Islands, Sumatra, Indonesia	~1.1 m	less than ± 3 cm	about 5–15 cm	Zachariasen et al. [2000]
Cocos (Keeling) Islands, Australia	~1.2 m	2–3 cm when outliers obviously not constrained by water level are omitted from analysis	more than 10 cm at 9 of 19 sites; more than 20 cm at 3 of 19 sites; 282 living microatolls at a total of 19 sites demonstrated overall variation of 40 cm	Smithers and Woodroffe [2000]