**NANYANG
TECHNOLOGICAL
UNIVERSITY**

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**CORAL MICROATOLL BASED SEA LEVEL
RECORDS FROM THE SUNDA SHELF.**

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INTERDISCIPLINARY GRADUATE SCHOOL

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Abstract

Coral microatolls are coral colonies which grow within the tidal zone and which are periodically limited in their upward growth by exposure during low water levels such as lowest astronomical tides, sea-level anomalies caused by weather or oceanographic phenomena. Vertical constraints on growth cause coral microatolls to develop a dead upper surface with growth continuing predominantly horizontally, thus forming characteristic disc shaped colonies.

Coral microatolls are an important sea-level proxy. They have been used to reconstruct Holocene relative sea-level (RSL) change, land-level changes related to the earthquake deformation cycle and oceanographic processes such as the El Niño/Southern Oscillation. Yet not all aspects of the coral microatoll methodology have been fully resolved. There are few studies that define the relationship between coral microatolls and sea level. In particular, ponding, a process whereby a microatoll is separated from the low tides behind a rampart of stone, shingle or sand, remains a source of uncertainties within microatoll reconstructions.

In my thesis, I have studied RSL of 25 coral microatolls from 8 sites in Indonesia and Malaysia, from the Sunda Shelf to address four research questions. First, I investigated the accuracy of coral microatoll RSL reconstructions and reliability. I demonstrate that open ocean microatolls track sea level and may be used to reconstruct sea-level trends.

Ponded microatolls are only partially influenced by the tidal cycle and cannot be used to recover sea level trends.

Second, I applied the coral microatoll methodology to reconstruct RSL from Mapur and Belitung using living, open ocean coral microatolls. Relative sea-level trend reconstructed from coral microatolls in Mapur (1986 to 2005) shows agreement with mean sea-level trend (1972 to 2016) reconstructed from the available tide gauge data in Singapore and Malaysia. A ninety year long (1915-2005) open-water microatoll record from Mapur shows RSL change of 0.01 ± 0.89 mm/yr. In Belitung two open-water microatolls show a range from 1.6 ± 2.11 to 4.7 ± 2.16 mm/yr over the period from 1967 to 2005.

Third, I reconstructed Holocene RSL from western Sarawak, Malaysia using surveyed and U-Th dated fossil microatolls. RSL data from western Sarawak was compared the data to a glacio-isostatic adjustment (GIA) model for the region that was calibrated to a dataset just from Thailand and Malay Peninsula. My data shows that RSL rose to 1.45 ± 0.8 m above present by 7439 BP and remained stable until 7006 BP. After a hiatus RSL is reconstructed from younger coral microatolls at $2.3 +1.15/-0.8$ m above present between 6128 and 6042 BP. My comparison shows a disagreement between the RSL reconstructions from coral microatolls and the GIA model. I infer up to 1.4 meter vertical motion post 7000 yr. BP on the Serabang fault, previously considered inactive. The motion is suggested by the offset between microatolls on the Talang Islands and the Satang Islands either side of it.

Finally, I reconstruct 115 years of a mid-Holocene RSL from Mapur, Indonesia by combining seven coral microatoll sequences from two sites on the Island. They demonstrate RSL reached ~ 0.4 m above present by 7282 cal yr BP and rose at least a further ~ 0.5 m over the following 115 years. Here I also define Sea-level index sequences, a data format more suitable to continuous RSL records such as those reconstructed from coral microatolls.

This thesis contributes to our understanding of coral microatoll methodology, and demonstrates the utility of coral microatolls for long composite sequences of relative sea level. The thesis also contributes RSL records from the Sunda Shelf, in the recent pre- instrument past, and in the mid Holocene.

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Chapter 1 Introduction

Motivation

The population of coastal mega cities, is set to continue rising and future sea level rise threatens the livelihoods of at least 650 million people who live in the coastal zones (Neumann et al., 2015). Growing coastal populations already reveal increased vulnerability and the average global annual losses from flooding in 2005 were estimated at 6 billion USD, with losses from coastal flooding expected to rise at least tenfold by 2050 (Hallegatte et al., 2013). In addition to people and cities, a considerable amount of food production is concentrated on the coastal plains and deltas of major rivers, particularly in Asia. It is also predicted that the impact of storms will also increase, because they will attack the coastline from a higher relative level (FitzGerald et al., 2008). To prepare for coastal flooding, resulting from rising sea level and storms, detailed forecasts of future sea level rise, at global and regional scales are needed.

Sea-level changes are difficult to constrain because they result from the interplay of global signals such as eustatic interaction between glaciers, polar icecaps and the oceans, volume and density changes resulting from thermal expansion of warming oceans or salinity changes (Ishii et al., 2006; Cazenave and Llovel, 2010). Regionally another layer of complexity is added from tectonics, isostatic changes like ocean syphoning resulting from the collapse of glacial fore bulges or continental levering of newly flooded continental shelves and oceanographic phenomena such as the Indian Ocean Dipole or the El Niño/Southern Oscillation (Cazenave and Llovel, 2010). Human

activity too adds further complexity, restriction of river sediment transport to the coastlines, overreliance on ground water resources and heavy construction on soft deltaic deposits can all lead to subsidence (Ericson et al., 2006).

Such complexity is hard to constrain and is commonly based on the limited data from the period represented by the instrumental, and historical records. Before the advent of satellite altimetry for sea level measurements data was primarily collected through tide gauges (Church and White, 2006). Such measurements were primarily concentrated in the high latitudes. In the tropics only six tide gauge records exist at the start of the 1900s and those that do are from tectonically active areas (Church and White, 2006). On the Sunda Shelf the oldest tide gauge records (e.g. Sultan and Raffles tide gauges in Singapore) are available only from beginning of the 1970ties. For the most part the world wide instrument record is barely more than 100 years long and is characterized by an uneven spread of data. Historical records are characterized by a similar bias, and in many cases, detailed information about historical events is sparse, and insufficient for present day reconstructions.

Current sea level rise, is caused in large part by human induced climatic changes (Kopp et al., 2016), but rising sea level is not unique and the geological record is characterized by periodic eustatic shifts in the global ice budget between oceans and polar and high elevation bodies of ice (Broecker et al., 1968). Several such mass shifts between land bound ice and the oceans have occurred in the last 500 000 years, the evidence of most is found in the uplifted ancient coral reef terraces (e.g.: Veeh and Chappell, 1970).

Where recorded the most recent sea-level highstand occurred during the mid-Holocene some ~7000-4000 years before present (Mitrovica and Milne, 2002; Peltier, 2002). Where highstands are found sea levels usually reached present day sea levels by 7000 BP and continued to climb until they peaked sometime over the following 2000 years, surpassing present sea levels, and dropping again to present day levels over the following 5000 years (Mitrovica and Peltier, 1991; Grossman et al., 1998). The Holocene sea-level highstand is evidenced by numerous sea-level markers; including geomorphological archives, such as raised sequences of beach ridges, tidal notches or erosional platforms, and biological sea-level indicators, such as oysters, diatoms or foraminifera. Many of these sea-level indicators cannot, however, provide data of sufficient resolution to reconstruct fine detail of sea-level changes over the Holocene (Shennan et al., 2015).

Fossil microatolls can be used to assist in reconstructing the elevation of the mid Holocene sea-level highstand and, so long as the changes remain within coral growth limits, its rise, fall and fluctuations, in decimeter detail. Such precision allows us to better constrain the variability of past sea level rise and test it against models based on our current understanding of sea level variability (Meltzner et al., 2017). Only if we are able to reconstruct and understand the fluctuations of past sea level rise can we have confidence in our predictions of future sea level rise.

Holocene sea level histories vary considerably spatially and need to be reconstructed for many different regions worldwide (Peltier, 2002; Mitrovica and Milne, 2002). Coral microatolls are one of the best proxies for reconstructions of sea level in tropical

regions. The Sunda Shelf is one such region, comprising much of Southeast Asia from northern Thailand through eastern Sumatra, western Java, Western half of Borneo and as far east as Palawan in the Philippines (Fig. 1-1). For simplicity in this thesis I will use the term “Sunda Shelf” to mean the tectonically stable Sundaland Block, since relative tectonic stability is one of the prerequisites for sea-level studies and they are not normally conducted in tectonically active regions which make up the rest of the Sunda Shelf. The region has a large and fast growing coastal population often concentrated in large low lying cities (e.g. Bangkok, Jakarta, Singapore) with agriculture concentrated in coastal plains and low lying river deltas such as the Mekong or Chao Phraya deltas. The Sunda Shelf is additionally understudied with less than 150 sea-level index points from several different sea-level proxies (coral, oysters, basal peats, pollen, diatoms, foraminifera) covering an area of more than 3 million square kilometers. Holocene sea level data on the Sunda Shelf is also mainly concentrated in Thailand and the Malay Peninsula (Horton et al., 2005) with only sporadic data for the rest of the region, meaning that the spatial variability of RSL change in the region is poorly known.

This thesis, focuses on two interconnected subjects:

- The first of these is the methodology of coral microatoll sea level studies. Sea level methodology has come a long way from its first application at the beginning of the 20th century, when it could only offer observations of the height of former sea levels in relative terms. Developments within and without the method have led to many improvements; today the method can reconstruct long sequences of relative sea level constrained in elevation by one or two decimeters and in time down to several years (Meltzner et al., 2017).

However, there are still several important uncertainties in the methodology, surrounding issues such as whether or not a sample has been subject to ponding, and to what extent, variability of the highest level of survival of coral microatolls, which is the proxy for sea level, and issues concerning underestimating the uncertainties of U-Th and radiocarbon dating on coral samples.

- The second problem this thesis hopes to explore is the spatial homogeneity of relative sea level records on the Sunda Shelf during the mid Holocene. This is achieved by providing data from two new locations that is in higher resolution and precision than much of the current evidence available. This contribution will assist in narrowing down temporal and spatial RSL variability in the region.

Locations

The Sunda Shelf has some of the longest and most complex coastlines of any region in the world. The Sunda Shelf is affected by the Indian Ocean in the west and the Pacific in the east, with a broad shallow South China Sea to the northeast. Apart from a complex coastline thousands of islands of varied size dot the water bodies that make up the Sunda Shelf. This thesis will present data from sites which come from three locations, Mapur Island, Indonesia, located some 100 km to the south east of Singapore, Belitung Island, Indonesia, located a further 500 km to the south, and the Talang/Satang Islands in western Sarawak, Malaysia on the Northwestern corner of Borneo. The Mapur site was chosen to allow easy comparison between the living coral microatoll records and tide gauge records in nearby Singapore. Singapore is also the site where nearly a half (62) of the existing sea-level index points were reconstructed

from and therefore offers the best case for a complete sea-level curve from a particular location on the Sunda Shelf. The Singapore proxy sea level dataset provides a good context for comparison with the fossil microatoll record from Mapur in terms of examining the accuracy and precision possible to achieve from other proxies. In contrast, the western Sarawak sites were chosen because of their distance from previously studied sites. They represent a new location for sea-level studies on the Sunda Shelf and provide a test for the variability of the Holocene highstand and its history across different parts of the Sunda Shelf.

Figure 1-1 The locations of the sites investigated in this thesis: Mapur Island, Indonesia (chapters 3 and 5), Belitung Island, Indonesia (chapter 3) and Western Sarawak, Malaysia (Chapter 4). Map modified from Meltzner et al., 2017

Materials

Coral reefs require locations with appropriate substrate, usually rocky coastlines, and water quality and sufficiently warm temperature (Veron, 1993). While temperatures are not an issue on the Sunda Shelf, the availability of hard substrates and good water quality are not so easy to come by. Because the South China Sea is shallow and has large inputs of sediment from numerous large rivers sediment loads in coastal waters may restrict coral growth close to mainland shores. Despite this many coral reefs exist within the region, particularly on islands away from the mainland. Microatolls form in the intertidal zones of many coral reefs mostly on the landward side of the reef. Not all microatolls are good for a sea-level study. Open water microatolls are those which are not protected from low water levels by any barriers. As opposed to ponded coral microatolls, which, as the name suggests, grow in ponds or lagoons formed by sand, rock or shingle barriers. Only open water microatolls are useful for sea-level studies, but they tend to occur only in a narrow band, usually seawards of the reef crest. As such, they are few and far between and at times both difficult and potentially dangerous to locate, survey and sample. Fossil microatolls which grew when sea level was higher than present tend to be raised above present reef levels and may be easier to locate and work with but in their case the additional issues of erosion, burial, and in some cases overgrowth by younger corals all contribute to the rarity of well-preserved fossil microatoll sites (Meltzner and Woodroffe, 2015).

Thesis format

In addition to this chapter this thesis contains 5 other chapters, each chapter is a stand-alone paper either in preparation or submitted to a journal, so some repetition is necessary.

Chapter: 2 - Review of coral microatoll sea level studies and the Holocene sea-level history of Sundaland

This chapter, presents a review of the development of the microatoll sea-level studies methodology and outlines some of its applications as well as a synthesis of the Holocene sea level records from the Sunda Shelf.

Chapter: 3- Measuring Relative Sea Level with Coral Microatolls

This chapter, investigates how well coral microatolls track sea level in the area in which they are growing. Although several authors have previously investigated the issue by comparing tide gauges to the microatoll sea-level reconstructions in some cases the reconstruction was too short or the sequence was disrupted. Additionally, since 1992 satellite altimetry provides an additional data set to compare with coral microatoll observations. This chapter compares six living coral microatolls from Belitung and Mapur in Indonesia with tide gauge records and predictive models based on satellite altimetry observations. Apart from investigating how well microatolls living in open water locations record sea level this chapter addresses records from ponded microatolls and compare the two in order to recommend how to avoid ponding issues in future coral microatoll studies.

Chapter 4- Relative sea level proxy records from fossil coral microatolls in Western Borneo, South China Sea: Sea-level stability around 7 ka and possible Holocene faulting

This chapter looks at a ~450-year relative sea level sequence in western Sarawak, Borneo, a previously uninvestigated part of the Sundaland. To reconstruct the relative sea level, we utilize surveys and samples of 10 fossil microatolls combined with a survey of 27 living microatolls in an improved take on the 'coring' approach. Apart from investigating sea level we discover possible, previously unknown, Holocene faulting.

Chapter 5- Sea-level index sequences from coral microatolls reveal details of higher-than-present relative sea level in the Riau Islands, Indonesia, by 7.2 ka

In this chapter, a sea level record from nine fossil microatolls from Mapur, Indonesia, are used to reconstruct a 115-year record of relative sea level. This time using the 'slabbing' methodology in order to reconstruct the best possible detail of the relative sea-level changes and contrast this with previously reconstructed data for the location and time period. In addressing the sea-level history we also define a new format for data reconstructed from coral microatolls because previous formats cannot fully represent the wealth of information supplied by microatolls.

Chapter 6- Summary

In this chapter, we summarize the contributions of the thesis and offer some suggestions of future directions in coral microatoll sea level research.

Chapter 2 Review of coral microatoll sea level studies and the Holocene sea-level history of Sundaland

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Abstract

Coral microatolls are an important sea level proxy which have been used to reconstruct relative sea levels, with various degrees of temporal and vertical precision, for over 100 years. Here I review the development of the coral microatoll sea level methodology over that period, paying particular attention to key contributions which have shaped our understanding of the sea-level proxy, and its application in studying a variety of sea level related problems. This chapter also discusses microatoll terminology, morphology, indicative meaning and other key concepts related to successfully applying the methodology. We highlight issues such as ponding whose full implications are sometimes underestimated or poorly constrained. The chapter concludes with a section reviewing the Holocene sea level studies on the Sunda Shelf focusing on the limited geographical spread of previous studies and outlining where the work in this thesis was conducted and the scientific aims proposed to advance the use of coral microatolls in the region.

Introduction

Coral microatolls (Figure 2.1) are coral colonies which grow in the lower part of the tidal zone, their vertical growth is constrained on sub-decadal time periods by unusually low water levels and, as long as sourced from open water locations, they can be used to reconstruct relative sea level from their lifetime. Today they are regularly employed to study sea level, both former (e.g.: Woodroffe et al., 1990; Scoffin and Le Tissier, 1998; Nunn, 2000; Meltzner et al., 2017) and to a lesser extent present (e.g.: Woodroffe and McLean, 1990; Spencer et al., 1997; Flora et al., 2009; Weil-Accardo et al., 2016b). Microatolls can also be used to reconstruct climatic ocean interaction such as the El Niño Southern Oscillation (ENSO) cycle (Woodroffe and Gagan, 2000; Woodroffe et al., 2003) and in tectonic reconstructions (Taylor et al., 1987). This review will concentrate on the relative sea level applications of microatolls and for more information on tectonic applications readers are referred to: Taylor et al. (1987); Zachariasen et al. (2000); Natawidjaja et al. (2004); Sieh et al. (2008); Meltzner et al. (2010); Meltzner et al. (2012); Philibosian et al. (2014); Weil-Accardo et al. (2016a).

Figure 2-1 Large fossil coral colony, demonstrating the predominantly horizontal growth form of a microatoll. Microatolls start their growth as hemispheric colonies growing upwards and outwards, upon reaching limiting water level the polyps on their upper surface are killed, but horizontal growth continues. The series of concentric rings on the surface of this microatolls result from the microatoll growing up and being periodically limited by sea level. Microatolls in this image grew on a site in Sarawak, Malaysia where the 18.6-year tidal cycle is the main control on microatoll morphology.

Scientists first noted microatolls 200 years ago (von Chamisso, 2013: original publication 1821; Darwin, 1842; Dana, 1846). The potential of fossil microatolls in sea level research was noted, and first demonstrated at the beginning of the 20th century by Sollas (1904) who used them to make the first observation of a former, higher than present, sea level, on Funafuti Atoll in the Pacific. Later scientific advances, in particular the development of Radiocarbon (Libby et al., 1949) and U-Th series dating (Edwards, 1987), and the discovery that coral bands grow annually (Knutson et al., 1972; Buddemeier et al., 1974) allowed for reconstructions of past sea levels not just in relative terms but also in terms of age. The full value of microatolls as sea-level

indicators and many of the issues pertinent to coral microatoll methodology (e.g. ponding) was first laid out in detail by Scoffin et al. (1978) and was followed by Woodroffe and McLean (1990) who provided the first example of a sea-level study in which a slab was cut through a coral microatoll to reconstruct its sea-level history.

Although the use of microatolls in sea level research is well-established, and methodology is continually developed, the full potential of the method is not always employed and limitations of the method are not always appreciated or acknowledged. The purpose of this review is to present a brief history of microatoll studies, outline the methodology, its current state and highlight recent advances in understanding microatoll morphology and significance. Finally, this chapter addresses limitations which will be the focus of deeper investigation in following chapters. In particular, the underappreciation of ponding issues which will be investigated in chapter 3.

Microatoll growth and morphology

Definition of a microatoll

The specific term 'microatoll' was first coined by Wood-Jones (1912). However, a variety of other terms based on physical descriptions were also used: "broad cylinder with a flat top" (Dana, 1846), miniature atolls (Guppy, 1886), diminutive atolls (Agassiz, 1895), dwarf atolls used by Krempf (1927). The lack of a concise definition of the term 'microatoll' meant that some confusion persisted, Kuenen (1933) defined it as a colony

of corals with a raised rim, surrounding a lower flat surface of dead coral, but others also used it to mean either a circular group of coral colonies or a larger, circular, patch reef with a central depression (Doty and Morrison, 1954; Newell and Rigby, 1957). These issues persisted into the nineteen seventies with some authors still describing patch reefs as “taking the form of microatolls” (Kinsey and Domm, 1974: 51). Scheer (1972) proposed a concise definition, reserving the term ‘microatolls’ only for single coral colonies and proposing other terms (such as: mini-atoll, faro and atoll) for larger structures, similar in shape, but of larger size and composed of many individual colonies. The various terms used for microatolls in the history of publications about them, as well as alternative uses for the term were reviewed by Stoddart and Scoffin (1979). The 1979 review, and an important study published a year earlier by some of the same authors (Scoffin et al., 1978), which outlined the significance of microatolls, cemented the usage of the term to mean:

“...a single coral colony, commonly massive and circular in plan, with a dead, predominantly flat, upper surface and a living lateral rim.” Scoffin et al. (1978: 100)

[Coral species capable of forming microatolls](#)

Many early publications report on which genera and species of corals form microatolls, some of the earliest of these were Dana (1846), Guppy (1886), Sollas (1904), Krempf (1927), Stephenson et al. (1931) and Abe (1937). In the 1970s a detailed appendix listing Great Barrier Reef species was published in Scoffin et al. (1978: appendix by Rosen) and a review of literature on the subject was also published by Stoddart and

Scoffin (1979). The majority of microatoll forming corals are massive or branching corals of the Scleractinia order: *Acropora*, *Coeloseris*, *Cyphastrea*, *Diploria*, *Echinophora*, *Favia*, *Favites*, *Galaxea*, *Goniastrea*, *Goniopora*, *Hydnophora*, *Leptoria*, *Lobophyllia*, *Montipora*, *Oulophyllia*, *Pavona*, *Platygyra*, *Pocillopora*, *Porites*, *Psammocora*, *Siderastrea*, *Turbinaria*. Some coral not of the scleractinia order also form microatolls, among them: *Heliopora*, *Millepora*, *Tubipora*. The majority of coral microatoll sea-level studies in the Indo-Pacific focus on massive species, particularly *Porites* (e.g.: Woodroffe and McLean, 1990; Nunn, 2000; Yu and Zhao, 2009; Meltzner et al., 2017), a genus which is relatively common on most reefs throughout the Indo-Pacific and the Atlantic Oceans (Veron, 1993). In the Caribbean Weil-Accardo et al. (2016b) have also used *Siderastrea siderea* and *Diploria strigosa* microatolls to study sea level.

Annual banding

Coral growth is banded, with high and low density bands that alternate. Although early naturalists were aware of the banding (e.g.: Dana, 1846) the nature of coral annual banding was only described in detail by Knutson et al. (1972) and Buddemeier et al. (1974). While it is now commonly accepted that coral bands generally comprise one high and one low density band per year, there are rare cases where banding may exhibit other patterns such as four bands instead of two. Corals, which normally exhibit the usual two band couplet can be perturbed by external conditions to alter the pattern temporarily: producing more bands than usual or producing high density stress bands or growth hiatuses (Scoffin et al., 1989; Cantin and Lough, 2014). The timing of

the formation of the hi and low density bands too is subject to variability, in Phuket, Thailand, Brown et al. (1986) noted asynchronous deposition of high and low density bands at neighboring reefs as a result of high sedimentation rates at different times of the year that likely reduced light levels locally. The exact reasons for the formation of high density and low density bands remain under debate, with suggestions that they are the result of combined local climate variables such as cloud cover, rainfall and temperature (e.g.: Lough and Barnes, 1989), internal coral growth patterns influenced by external factors (e.g.: Barnes and Lough, 1993), reproduction (e.g.: Gagan et al., 1996), light levels (Klein and Loya, 1991), temperature (e.g.: Buddemeier et al., 1974; Highsmith, 1979), rainfall (Supriharyono, 2004), salinity (e.g.: Scoffin et al., 1989), wave energy (Scoffin et al., 1992). Tanzil et al. (2016) argues that factors controlling density banding may vary across different coral reefs. For our work on the Sunda Shelf the most relevant study, based on geographical proximity to the Mapur site, may be Tanzil et al. (2016) who studied the nature, timing and causes of density banding on a data set of 52 corals from six coral reefs around the Malay Peninsula (and Singapore). They correlated seasonal density differences to changes in wave energy (Fig. 2.2), and to a smaller degree by rain, though emphasizing that correlation is not causation, leaving the possibility that the banding is caused by another parameter, possibly also wave-energy related.

Figure 2-2 Partial effects plot showing relationship between skeletal density anomaly/ g cm^{-3} and anomalies in significant wave height/m (SWH) and rainfall / mm month^{-1} (Rain). Dashed line denotes 95% confidence interval of model; tick marks on the inside of the x-axis of each partial plot denote the location of the covariate values that apply to the plot. Figure and caption from Tanzil et al. (2016)

Figure 2-3 Comparison of sea level measurements from a tide gauge in Tarawa, Kiribati (a, thin line 3 monthly, bold line annual average) with coral annual growth heights (b) based on X-radiography of a *Porites* microatoll from Abemama, Kiribati between from 1974 to 1988. Demonstrating good agreement between the two. Distance between the tide gauge and microatoll site was 140 km. Figure from (Woodroffe and McLean, 1990).

The discovery of the annual nature of coral banding, debate on the causes of the density bands notwithstanding, opened up new possibilities for microatoll sea level studies. This was demonstrated by Woodroffe and McLean (1990) who compared a 15-year record of tide-gauge measurements with the growth of a contemporary microatoll, and demonstrating their agreement (Fig.2-3).

How microatolls form

Microatolls form when a coral colony grows upwards and radially outwards until their upward growth is limited by exposure at low water levels (Scoffin et al., 1978; Meltzner et al., 2010; Meltzner and Woodroffe, 2015). When a microatoll is limited by low water levels the polyps on the upper surface of the colony die, however those which are lower, below the water level, continue to grow. The low water event which causes the highest polyps to die, and its evidence sometimes preserved in microatoll structure, is called a diedown. The level of polyps surviving the diedown is called the highest level of survival (HLS) (Taylor et al., 1987).

Coral HLS

The exact relationship between the height of coral HLS and low water levels is not well constrained, though it appears that HLS of open water microatolls tends to lie between lowest astronomical tide and mean low water (Scoffin et al., 1978: Fig. 29; Smithers and Woodroffe, 2000; Meltzner et al., 2017). Although it should be noted that the HLS of different coral genera (and species), even within the same tidal range, vary, for example Meltzner et al. (2017: Figure 3) shows that *Porites* sp. coral microatolls on

Belitung Island, Indonesia tend to grow lower in the tidal range than a coral microatoll identified to family level as *Favidae* (Fig. 2.4). Implying that fossil microatolls should only be compared to living representatives of the same species.

Some studies do not provide enough information to demonstrate this was the case, reporting only that fossils, of different genera, were compared to living microatolls, but not elaborating whether the living microatolls were of the same species for each fossil. In such cases, it is not clear to the reader if the need to compare fossil and living microatoll of the same species is assumed to be intrinsic to the methodology or if the issue had not been considered.

Figure 2-4 Plot of living microatoll HLS on two sites (TKUB and TBAT) on Belitung Island Indonesia. Demonstrating differences in the relationships of different coral families (*Porites* and *Favidae*) with the tidal range on those sites. Figure from (Meltzner et al., 2017).

Variety of coral microatoll morphologies

The morphology of a microatoll is ultimately controlled by water levels (Scoffin et al., 1978). The water levels, however, may be controlled not just by the sea level but also by other intervening factors which vary considerably from site to site. In tectonically active areas microatolls may take on stepped forms: with low center and high outside rings if subject to subsidence, or with a high center and lower outside rings if subject to emergence (e.g.: Taylor et al., 1987). More complex morphologies may develop on sites with tectonic histories which include abrupt co-seismic uplift/subsidence and a gradual opposite inter-seismic trend (e.g.: Natawidjaja et al., 2004; Meltzner et al., 2010; Philibosian et al., 2014). Such morphological complexity is not restricted to tectonically active areas and in tectonically stable locations microatoll morphology may develop similar patterns, but tends to have more gradual elevation changes (Scoffin et al., 1978; Hopley, 1982).

Sea-level fluctuations may also result in, rarely seen, but important types of morphology. In Belitung Island, Indonesia, Meltzner et al. (2017) slabbed a microatoll which documents a significant sea-level fluctuation in its morphology (Fig. 2.5). The microatoll recorded the sea level rising from 0.8 m RSL up to 1 m RSL followed by a drop of ~ 0.6 m, recovery and a second rise to almost 1.2 m above present, all within a period of ~300 years. The importance of such unequivocal evidence of sea-level fluctuations will be emphasized in the “Holocene relative sea level on the tectonically stable Sundaland” section.

Figure 2-5 Sea level fluctuation reconstructed from two slabs of the same microatoll (TBAT-F01 Belitung, Indonesia) demonstrates RSL fluctuating by more than 0.6 m in a period of ~300 years.

Discerning sea-level history from microatolls

Noise from periodic and semi periodic fluctuations on annual to decadal time scales

The periodicity of coral microatoll growth and diedowns in many open-water settings results from a nodal 18.6-year tidal cycle. In other settings oceanographic phenomena such as the Indian Ocean Dipole (Fig 2.6) (e.g.: Meltzner et al., 2010; Meltzner et al., 2012; Philibosian et al., 2014) or the El Nino Southern Oscillation (Fig 2.7) (e.g.: Taylor et al., 1987; Goodwin and Harvey, 2008) may also shape the morphology. These cycles should not present a problem to the reconstruction of the longer-term sea levels so long as data series longer than the duration of respective cycles can be recovered to filter out short-term noise. Though, to do this, the periodicity, and scale of the short

term oceanographic or tidal phenomena must be established for each individual research location.

Figure 2-6 An example of a microatoll from West Badgugu, Sumatra, Indonesia growing under the influence of periodic sea level anomalies, caused by the Indian Ocean Dipole (blue lines marked by triangles) and tectonic movements (blue lines without triangles). Figure from Philibosian et al. (2014)

Figure 2-7 Microatoll whose morphology was shaped by sea level anomalies caused by 3-5-year variability of the El Niño/Southern Oscillation. Microatoll from Blackrock reef, Rarotonga, Southern Cook Islands. Figure from Goodwin and Harvey (2008).

The three studies presented in this thesis (chapters 3-5) are all conducted on sites on the Sunda Shelf. Figure 2.8 shows the tectonically stable part of the Sunda Shelf, established through a 10-year long GPS study by Simons et al. (2007). Chapter 3 presents results of living microatoll studies from Mapur, and Belitung, both islands in Indonesia. Chapter 4 presents a study of fossil microatolls from three islands and one site on the mainland of west Sarawak, Malaysia. Finally, chapter 5, presents a fossil microatoll study from Mapur, one of the sites also used in chapter 3.

Figure 2-8 Study sites from this thesis marked on a map of the Sunda Shelf. Microatolls from two locations from Mapur, two locations from Belitung, and four locations from west Sarawak were studied as part of this thesis. We chose to study sea level on the Sunda Shelf because a large part of it has been inferred to be tectonically stable (blue dashed outline) by a 10-year GPS study (Simons et al., 2007). Map modified from Meltzner et al. (2017).

On the Sunda Shelf, in particular close to its center where Mapur Island lies, oceanographic phenomena such as ENSO have limited influence of ± 5 cm (Tkalic et al., 2013). The main control on coral microatoll diedowns appears to be the 18.61-year tidal cycle. During each cycle the tidal range increases for 9.3 years, then reverses and decreases for the following 9.3 years. The scale of this variation depends on the tide range of a particular location. For example, in Belitung (Indonesia) for a tidal range of 2.9 m the elevation of the low tide was calculated to change by 0.35 m (Meltzner et al. 2017). Using predictions from the same tidal model used by Meltzner et al. (Egbert and Erofeeva, 2002) at Mapur the site of the studies in chapters 3 and 5, we calculate a tidal range of 2.33 m, and that the lowest annual tide changes by 0.26 m. The year-to-year changes in the levels of the lowest tides over the 18.6-year tidal cycle commonly exceed the coral's annual growth rates of $\sim 1\text{-}3$ cm/yr (Tanzil et al., 2013). As a result, for part of the cycle, during which elevation of the low tide levels is rising, microatoll growth is un-constrained vertically. When the 18.6-year cycle reverses and the level of lowest tides drops, the upper part of the microatoll, that which grew over the previous 9.3 years, will eventually be exposed resulting in a diedown. Thus, in the settings where this cycle is dominant, we expect to see one or more diedowns for each cycle the microatoll lived through after it had first reached the surface. Chapter 3 explores the relationship between coral microatolls and the 18.61-year tidal fluctuation in considerably more detail.

Ponding of Microatolls

Ponding, if unrecognized, can seriously affect the outcomes of a microatoll sea-level study (Scoffin et al., 1978; Smithers and Woodroffe, 2000; Meltzner and Woodroffe, 2015). Ponding occurs when a barrier of sand, rock or coral (living or fossil) prevents the complete draining of all water from a particular area during low tide. Ponds may form on the reef at various elevations throughout the tidal range, though corals are less likely to grow in ponds elevated above mean high water neaps due to the need for the water in the ponds to be regularly refreshed (Scoffin et al., 1978). Corals living in ponded settings will record changes in the local water levels of the pond they live in rather than the open sea. In studies of fossil microatolls, unless ponding can be excluded, any raised fossil microatolls can only be considered evidence of a former higher sea level if they are measured to have grown above the elevation of the highest ponds where corals could theoretically survive today. Meaning they can only be considered evidence for higher than present RSL if they are above the high-water neaps in present day tidal regime. Even then, they should only be treated as a maximum bound on former sea level, unless it can be demonstrated they were not ponded during their life. This issue has been recognized and explained in detail by Scoffin et al. (1978), here we present it schematically in Figure 2.9.

Smithers and Woodroffe (2000) conducted a detailed survey of 282 microatolls on the Cocos Islands, an atoll in the Indian ocean, and concluded that even on a micro-tidal site with no obvious moats, the combined gradual effect of smaller pools may cause the level of the highest living coral (HLC) to be distributed over 30% of the spring tide

range, ~40 cm in the case of the Cocos islands (Fig 2.10). The importance of this range lies in the fact that only the microatolls in the lower, free draining, part of the HLC range respond to moderate RSL changes resulting from inter annual variability as demonstrated in the same study (Smithers and Woodroffe, 2000).

Figure 2-9 An illustration of the full implications of ponding on interpretation of fossil microatoll RSL. Only open water microatolls at B should be used as modern HLG/HLC for comparison with fossils. Among fossil microatolls D and E can only be used to infer a higher former sea level if it can be confirmed that they were not ponded while alive. While fossil microatoll F can be used to infer a higher former sea level regardless of ponded/open water morphology because it lies above high water neaps, too high for modern corals to survive. Although, unless it can be shown that they were not ponded they are still only a maximum bound on RSL. A- unconstrained corals growing below tidal range, B- living open water/free draining microatolls growing below low water neaps, C- living microatolls ponded up the reef flat up to high water neaps, D-E fossil microatolls found below high water neaps, F- fossil microatoll above high water neap, G- modern reef crest, H- fossil reef crest. 1- total modern HLG/HLC range on site, 2 – open water modern HLG/HLC on site. Illustration schematic only, not drawn to scale.

Figure 2-10 Plot of surveyed microatoll heights (HLC) on the southern Cocos Islands, showing a ~40 cm range, nearly 30% of the tidal range. Figure from Smithers and Woodroffe (2000).

Unfortunately, the full implications of this issue are rarely discussed in detail. For example in a study from the Cook Islands, Goodwin and Harvey (2008) compare fossil microatolls to the HLC of living microatolls within a moated location. Though the authors state that: “The moat is free draining...” (Goodwin and Harvey, 2008: p18), data on HLC of living microatolls in an open water location, outside the moat, is not included, thus making it impossible to confirm this assertion. When, as in this case, the object of investigation is fossil RSL on a micro-tidal site, corrections of error ranges can be made to account for possible ponding. In some cases, however, ignoring the possibility of ponding can have more serious consequences. In a study of modern sea level change on the Abaiang atoll in Kiribati (Flora et al., 2009), authors conducted a survey of the surface annuli of 57 microatolls. Unfortunately, a photo from the study location (Figure 2.11) clearly shows the site was ponded; the pond around the surveyed

microatolls was separated from the open sea level at low tide. In this case the average rate of sea level rise of 0.2 mm/year, calculated by the authors, reflects changes in the elevation of local ponding, rather than the sea level, and any correction of error range is impractical. Chapter 3 of this thesis investigates this issue in detail.

Figure 2-11 Ponded microatolls on the reef flat of the Abaiang Atoll, Kiribati. Note the distance and lack of connection between the open sea (breaking waves near horizon) and the microatoll field. None of the microatolls visible in this photo are suitable for reconstruction of modern sea level trend, a better, although more difficult, location to look for open sea microatolls would have likely been several meters beyond the breaking waves.

Approaches to RSL reconstruction from fossil microatolls

Surveying the top of fossil coral microatolls and comparing this to their living counterparts was the earliest approach to fossil RSL reconstruction, as demonstrated on the Funafuti microatoll by Sollas (1904). The approach, developed somewhat

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accidentally, as Sollas was on the island for a reef drilling expedition but frequent equipment breakdowns gave him time to explore the atoll. This approach remains the most utilized method for coral microatoll sea-level reconstruction. Notably, at the time there was no way of establishing chronology of the changes outside of a purely stratigraphic approach.

The development of radiocarbon (Libby et al., 1949) and U-Th (Edwards, 1987) dating methods researchers to develop more detailed absolute chronologies. This approach, sometimes referred to as the 'coring' approach because of the cores required to date the fossil microatolls (Meltzner and Woodroffe, 2015), was and continues to be utilized widely. Coral microatoll sea level studies have now been applied in the Indo-Pacific for example: Great Barrier Reef, Australia (Chappell et al., 1983; Yu and Zhao, 2009), Cook islands (Yonekura et al., 1988; Goodwin and Harvey, 2008), Phuket, Thailand (Scoffin and Le Tissier, 1998), Fiji (Nunn, 2000), Makassar, Indonesia (Mann et al., 2016), Java, Indonesia (Azmy et al., 2008), Cocos Islands (Woodroffe et al., 1990), Christmas Island, central Pacific (Woodroffe et al., 2012).

Reconstructions of relative sea levels from the structure of slabbed microatolls first demonstrated by Woodroffe and McLean (1990), who compared a 15 year record of tide measurements with the growth of a contemporary microatoll, measured from a slab of the microatoll, as shown in Figure 2.3. The annual changes in water levels constraining coral growth could now be discerned by examining the internal structure of a coral microatoll. This approach was explained in detail and compared to the

‘coring’ approach by Meltzner and Woodroffe (2015). The slabbing approach allows for better constraints on diedown timing and elevation and many more data points useful for sea-level reconstruction. Despite the notable advantages the slabbing approach is not utilized as often as the ‘coring’ approach. This is primarily due to the higher cost of equipment and logistics involved, and in some locations, due to regulations concerning the sampling of fossil or living microatolls. Despite this, several studies utilizing this approach have been carried out: on corals from the Cocos Islands/Maldives and Christmas Island by Woodroffe and McLean (1990), Tongareva Atoll, Northern Cook Islands, (Spencer et al., 1997) Cocos Islands, Indian Ocean (Smithers and Woodroffe, 2001), Abaiang Atoll, Kiribati (Flora and Ely, 2003), Christmas Island, Kiribati (Woodroffe et al., 2012: this study utilised both approaches), Haiti, Caribbean (Weil-Accardo et al., 2016b) and Belitung Island, Indonesia (Meltzner et al., 2017). A somewhat similar approach, where the microatoll was cut onsite, (without recovery of slab) and detailed analysis of banding, was also used in the Leizhou Peninsula, China (Yu et al., 2009).

[Chronological span of sea level evidence from coral microatoll studies](#)

Coral microatolls are used to extend the record of sea level change beyond that offered by instrumental records. In tectonically stable tropical regions, few tide gauges were installed before 1950s and practically none before 1900 (Church and White, 2006). For this reason, living microatolls can be utilized to extend this record. The advantage of using living microatolls is that annual bands can be counted back, thus reconstructing sea level with annual precision for as long as the coral growth allows. Although care

must be taken when interpreting annual bands because, as noted earlier, annual bands are not always equal to calendar years and in some cases anomalous bands may form representing shorter periods of time. Relatively few attempts to do so have been published so far, with these notable exceptions Woodroffe and McLean (1990) who reconstructed a 15 year record from the central Pacific (Kiribati), comparing it with a tide gauge 150 km away, and Spencer et al. (1997) who reconstructed a 57-year sea level record from Tongareva Atoll, Northern Cook Islands. The Spencer et al. paper compared the coral data to a tide gauge record from American Samoa (1500 km away) noting that particularly severe diebacks resulted from a ENSO warm phase event that disrupts the relationship between a microatoll and sea level, Flora and Ely (2003) demonstrate a 5 year match between a microatoll from Abaiang Atoll and a tide gauge installed on Tarawa, about 40 km away, both in Kiribati. Weil-Accardo et al. (2016b) reconstruct a ~100-year series from Haiti and compare it with a 24-year satellite altimetry record and a 60-year tide gauge record. At present, there has only been one study of living microatolls which extended the record beyond 1900 (Smithers and Woodroffe, 2001).

Fossil microatoll studies tend to concentrate on reconstruction of sea levels higher than present because of availability of preserved microatolls. Fossil microatoll studies rely on U-Th and radiocarbon dating and thus are characterized by more temporal uncertainty than studies of living microatolls. The original geomorphology of the setting is also subject to uncertainty, and ponding should be considered a possibility, as demonstrated by Chappell et al. (1983) who inferred that at least two of the eleven

study locations experienced ponding, the evidence for which has since been mostly eroded. The vast majority of fossil microatoll studies listed previously for both 'coring' and 'slabbing' approaches, reconstruct sea level from the mid Holocene highstand (e.g.: Chappell et al., 1983; Scoffin and Le Tissier, 1998; Nunn, 2000; Woodroffe et al., 2012; Meltzner et al., 2017).

Holocene relative sea level on the tectonically stable Sundaland

The tectonically stable Sundaland comprises large parts of Southeast Asia (Figure 2.8), from Thailand and Laos in the north, through the Malay Peninsula and eastern Sumatra to the north west of Java and west Borneo. In regards to the Holocene sea-level history and glacial cycles. Sundaland is considered a far field location and lies within zones IV/V as defined by Clark et al. (1978; Peltier, 2002; Woodroffe and Horton, 2005). Far field locations are expected to give the best estimate of eustatic sea-level changes, resulting purely from the Ice-Ocean water transfers. A Holocene highstand is predicted to have occurred here when the glaciers in high latitude ceased melting rapidly and ocean syphoning drew water from low latitudes into regions of the collapsing fore bulges (Mitrovica and Milne, 2002). However, the Sundaland is a wide continental shelf which, when submerged by sea level during the Holocene, experienced large hydro-isostatic changes resulting from continental levering, which occurred when newly flooded parts of the Sunda Shelf were depressed and the uncompressed regions were tilted upwards (Clark et al., 1978). As a result, the Holocene highstand across the region has a complex pattern and requires data of sufficient spread, temporally and spatially to reconstruct

the eustatic contribution (Peltier, 2004; Horton et al., 2005; Woodroffe and Horton, 2005; Bradley et al., 2016).

Reconstructions of Holocene sea levels on Sundaland are based primarily on studies from the Malay Peninsula (Geyh et al., 1979; Tjia et al., 1983; Tjia and Fuji, 1992; Tjia, 1996; Kamaludin, 2002; Parham et al., 2014), Singapore (Hesp et al., 1998; Bird et al., 2007; Bird et al., 2010) and Southern Thailand (Thiramongkol, 1983; Chaimanee et al., 1985; Somboon, 1988; Tiypunte and Theerarungsikul, 1988; Sinsakul, 1990; 1992; Somboon and Thiramongkol, 1992; Scoffin and Le Tissier, 1998; Horton et al., 2005) as well as a few other isolated studies from southern Vietnam (Stattegger et al., 2013), Java (Azmy et al., 2008) and Belitung, Indonesia (Meltzner et al., 2017). All data reconstructed before 2005 was reviewed by Horton et al. (2005), who updated the indicative meaning and vertical errors as well as calibrated or recalibrated the ages assigned to sea-level index points from those studies.

Despite the noteworthy effort of Horton et al. (2005) and the additional data gathered post 2005, reconstructions of the Holocene sea level on the Sundaland continue to show meter scale discrepancies. Much of the data constrains the relative sea level prior to, during, and shortly after, the mid Holocene sea level highstand, yet both the timing and height reconstructions of the highstand show large ranges. The highstand occurred sometime between 6500 and 5000 cal. years BP and reached 140 to 544 cm above present (Horton et al., 2005: and references therein; Bird et al., 2007; Bird et al., 2010; Bradley et al., 2016). The range of current timing and elevation reconstructions may

additionally not be representative of the entire Sundaland, because most of the sea level data comes from a relatively narrow band of either Southern Thailand or the Malay Peninsula and near-by areas. Additionally, there is debate as to the nature of the highstand, whether sea level reached a peak and declined smoothly, as suggested by some studies (e.g.: Scoffin and Le Tissier, 1998), to today's sea level or whether the rise and fall of RSL may have been stepped or fluctuating (e.g.: Geyh et al., 1979; Hesp et al., 1998; Bird et al., 2010). Many of the sea-level proxies used in the studies on the Sundaland do not have the resolution necessary to resolve the question, but new evidence from coral microatolls demonstrates that RSL fluctuated considerably (60 cm /100 years) during at least some periods (Meltzner et al., 2017).

Coral microatolls, particularly if studied with the higher precision slabbing approach, have the potential to resolve some of the most important remaining question relating to the Holocene highstand on Sunda Shelf and elsewhere. The proof of fluctuating sea level reconstructed on single continuous fossil microatoll, and corroborated by other fossil corals on a site 80 km away, by Meltzner et al. (2017) provides one example of the effectiveness of high precision coral microatoll studies. Questions regarding the timing and elevation of the peak of the Holocene highstand on Sunda Shelf as well as its spatial variability may also benefit from fossil microatoll studies if appropriate sites are explored. Finally, sea level trends prior to the installation of tide gauges in many tropical areas, may be extended by decades and in some case centuries, through the study of living coral microatolls on those sites.

Appendix of key coral microatoll, and coral related, papers discussed in this thesis:

Authors of study	Year	Title	Published in	Study Location	Subject	No. on map
Azmy K, Edinger E, Lundberg J, et al.	2008	Sea level and paleotemperature records from a mid-Holocene reef on the North coast of Java, Indonesia.	International Journal of Earth Sciences, vol 99, issue 1	North coast of Java, Indonesia	Reconstruction of temperatures, salinity and sea level from fossil coral microatolls (0.8 m a.s.l. at 7090±90 year BP and 1.5 m a.s.l. at 6960±60 year BP).	1
Barnes DJ and Lough JM.	1993	On the nature and causes of density banding in massive coral skeletons.	Journal of Experimental Marine Biology and Ecology, vol 167, issue 1	Central Great Barrier Reef, Australia	Coral staining and investigation of complexity of coral growth, including documentation of three growth processes (addition of new skeleton on surface, thickening and periodic uplift of the lower margin of the tissue layer).	2
Brown B, Le Tissier M, Howard LS, et al.	1986	Asynchronous deposition of dense skeletal bands in <i>Porites lutea</i> .	Marine Biology, vol 93, issue 1	Phuket, Thailand	Asynchronous deposition of high and low density bands in corals at neighboring sites. Demonstration that on some sites one years growth may regularly consist of four rather than the usual two bands.	3
Brown BE, Dunne RP, Scoffin TP, et al.	1994	Solar damage in intertidal corals.	Marine ecology progress series. Oldendorf, vol 105, issue 3	Phuket, Thailand	Investigation of solar irradiation effects on coral bleaching. Demonstrates that the sun altitude and azimuth have a direct effect on coral bleaching. For <i>Goniastrea Aspera</i> bleaching corresponds to periods of sub aerial exposure with high sun altitude and irradiance.	3
Buddemeier RW, Maragos JE and Knutson DW.	1974	Radiographic studies of reef coral exoskeletons: Rates and patterns of coral growth.	Journal of Experimental Marine Biology and Ecology, vol 14, issue 2	Eniwetok Atoll, Marshall Islands	Confirmation of the annual nature of coral banding through X-radiograph studies of 47 coral colonies (including: <i>Astreopora</i> , <i>Platygyra</i> , <i>Favia</i> , <i>Porites</i> ,	4

					<i>Oulophyllia, Goniastrea, Psammocora and Hydnoophora).</i>	
Cantin NE and Lough JM.	2014	Surviving coral bleaching events: porites growth anomalies on the Great Barrier Reef.	PLOS one, vol 9, issue 2	Central Great Barrier Reef, Australia	Investigation of the spatial complexity of <i>Porites</i> coral bleaching. Indicating partial mortality of coral was higher at inshore sites than at mid shelf and offshore sites.	2
Chappell J, Chivas A, Wallensky E, et al.	1983	Holocene palaeo-environmental changes, central to north Great Barrier Reef inner zone.	BMR Journal of Australian Geology and Geophysics, vol 8	Central and Northern Great Barrier Reef, Australia	Reconstruction of sea level from fossil coral microatolls indicating sea level at 1 m a.s.l. at 5500 year BP and smooth fall to present. Large data set including 45 radiocarbon dates from 11 sites.	2 and 5
Dana JD.	1846	Structure and Classification of Zoophytes: US Exploring Expedition During the Years 1838, 1839, 1840, 1841, 1842 Under the Command of Charles Wilkes.	Book	NA (multiple sites)	Some of the earliest descriptions of coral physiology. Including a physical description of coral microatolls and correct interpretation of the process forming them (periodic exposure).	NA
Flora CJ and Ely PS.	2003	Surface growth rings of <i>Porites lutea</i> microatolls accurately track their annual growth.	Northwest Science, vol 77, issue 3	Abaiang Atoll, Kiribati	A comparison of living microatoll surface morphology to X-ray of their structure and sea level records over a period of 2 years. Suggests microatolls from well drained reef flats may be used for low cost reconstruction of local sea level history.	6
Flora CJ, Ely PS and Flora AR.	2009	Microatoll edge to enso annulus growth suggests sea level change.	Atoll Research Bulletin, vol 571	Abaiang Atoll, Kiribati	Investigation of sea-level trend utilizing living microatolls from a reef flat between 1998 and 2008. Indicates 0.1 to 0.2 mm per year sea level rise over the period, however investigation is flawed due to insufficient understanding of ponding issues.	6

Goodwin ID and Harvey N.	2008	Subtropical sea-level history from coral microatolls in the Southern Cook Islands, since 300 AD.	Marine Geology, vol 253, issue 1-2	Southern Cook Islands	Reconstruction of sea level from fossil coral microatolls indicating sea level at 0.8 m a.s.l. at 1600 year BP and fall to 0.2 m below present at 200-300 year BP followed by rise to present.	7
Highsmith RC.	1979	Coral growth rates and environmental control of density banding.	Journal of Experimental Marine Biology and Ecology, vol 37, issue 2	Enewatok Atoll, Marshall Islands and Belize	Investigation of the causes of high and low density bands in coral (<i>Favia pallida</i> , <i>Goniastrea retiformis</i> , <i>Porites lutea</i>). Relates low density bands to low temperatures and inversely high density bands to periods when temperatures are higher.	4 and 8
Knutson DW, Buddemeier RW and Smith SV.	1972	Coral chronometers: seasonal growth bands in reef corals.	Science, vol 177, issue 4045	Eniwetok Atoll, Marshall Islands	First documentation of the annual nature of coral growth bands using X-ray radiography.	4
Lough JM and Barnes DJ.	1989	Possible relationships between environmental variables and skeletal density in a coral colony from the central Great Barrier Reef.	Journal of Experimental Marine Biology and Ecology, vol 134, issue 3	Central Barrier Reef, Australia	Investigation of the causes of high and low density bands in coral. Relates maximum annual density bands to high light levels and temperatures.	2
Mann T, Rovere A, Schöne T, et al.	2016	The magnitude of a mid-Holocene sea-level highstand in the Strait of Makassar.	Geomorphology, vol 257	Southwest Sulawesi, Indonesia	Reconstruction of sea level from fossil coral microatolls indicating sea level at no more than 0.5 m at 5600 cal year BP and decline to present sea level by 4000 cal year BP.	9
Meltzner AJ, Sieh K, Chiang H-W, et al.	2012	Persistent termini of 2004- and 2005-like ruptures of the Sunda megathrust.	Journal of Geophysical Research: Solid Earth, vol 117, issue B4	Simelue Island, Indonesia	Coral microatoll investigation of subduction zone segmentation in the last 1100 years. Indicates persistent boundaries of rupture patches on the Sunda Megathrust.	10
Meltzner AJ, Sieh K, Chiang H-W, et al.	2010	Coral evidence for earthquake recurrence and an A.D. 1390–1455 cluster at the south end of the 2004 Aceh–Andaman rupture.	Journal of Geophysical Research: Solid Earth, vol 115, issue B10	Simelue Island, Indonesia	Coral microatoll investigation of repeated earthquake occurrence on the Sunda Megathrust. Documents ruptures in 10 th and 13-14 th centuries before the 2004 rupture.	10
Meltzner AJ, Switzer AD, Horton BP, et al.	2017	Half-meter sea-level fluctuations on centennial	Nature Communications, vol 8, issue 14387	Belitung Island, Indonesia	Reconstruction of sea level from two independent fossil coral microatoll records indicating sea level	11

		timescales from mid-Holocene corals of Southeast Asia.			between 6850 cal year BP and 6500 cal year BP was higher than present and experienced two 0.6 m fluctuations.	
Meltzner AJ and Woodroffe CD.	2015	Coral Microatolls.	Handbook of Sea-Level Research Edited by Shennan, I. Long, A. J. Horton, B. P.	NA	Review of coral microatoll methodology approaches and terminology. First publication discussing both the HLS/HLG terms used primarily in tectonic microatoll studies and the HLC term used in many coral microatoll sea-level studies.	NA
Natawidjaja DH, Sieh K, Ward SN, et al.	2004	Paleogeodetic records of seismic and aseismic subduction from central Sumatran microatolls, Indonesia.	Journal of Geophysical Research: Solid Earth, vol 109, issue B4	Tanabala, Tanamasa and Pini Islands, Indonesia	Microatoll investigation of 20 th century paleogeodetic history of the region. Documents raptures in 1935 and 1965 CE.	12
Nunn PD.	2000	Significance of emerged Holocene corals around Ovalau and Moturiki islands, Fiji, southwest Pacific.	Marine Geology, vol 163, issue 1	Moturiki Islands, Fiji	Reconstruction of sea level from fossil coral microatolls indicating sea level at 1.6 m at 6000 and decline afterwards.	13
Nunn PD and Peltier WR.	2001	Far-Field Test of the ICE-4G Model of Global Isostatic Response to Deglaciation Using Empirical and Theoretical Holocene Sea-Level Reconstructions for the Fiji Islands, Southwestern Pacific.	Quaternary Research, vol 55, issue 2	Moturiki Islands, Fiji	Comparison between reconstructions of sea level from fossil microatolls and predictions by the ICE4G model. Show broad agreement of sea level higher than present occurring between 6000 and 2000 cal. year BP with a highstand of 1.5 m occurring between 5000 and 4000 cal. year BP.	13

Padilla-Gamiño JL, Hanson KM, Stat M, et al.	2012	Phenotypic plasticity of the coral <i>Porites rus</i> : Acclimatization responses to a turbid environment.	Journal of Experimental Marine Biology and Ecology, vol 434-435, issue	Moorea, French Polynesia	Investigation of phenotypic plasticity in <i>Porites rus</i> corals, indicating that there is significant variation in the physiology of the coral at colony level and at site level and that the species can acclimatize to condition changes at short time scales (weeks).	14
Philibosian B, Sieh K, Avouac J-P, et al.	2014	Rupture and variable coupling behavior of the Mentawai segment of the Sunda megathrust during the supercycle culmination of 1797 to 1933.	Journal of Geophysical Research: Solid Earth, vol 119,	Mentawai Islands, Indonesia	Coral microatoll investigation of the tectonic behavior of the Mentawai fragment of the Sunda Megathrust since the 18 th century. Producing maps of coseismic and interseismic behavior of the area.	12
Scoffin TP, Brown BE, Dunne RP, et al.	1997	The controls on growth form of intertidal massive corals, Phuket, south Thailand.	Palaios, vol 12, issue 3	Phuket, Thailand	Investigation of 'slanted' microatoll forms. Indicates solar damage and low water levels are the cause. Reconstructs three particularly low water events in 1982/83, 1986/87 and 1991/92 most likely related to El Nino.	3
Scoffin TP and Le Tissier MDA.	1998	Late Holocene sea level and reef-flat progradation, Phuket South Thailand.	Coral Reefs, vol 17	Phuket, Thailand	Reconstruction of sea level from massive coral fossils. Indicates that Sea level was 1 m above present 6000 years BP and fell smoothly since. Because the studied corals were not microatolls but hemispheric colonies the results may indicate only a minimum bound on sea level.	3

Scoffin TP, Stoddart DR and Rosen BR.	1978	The Nature and Significance of Microatolls.	Philosophical Transactions of the Royal Society B: Biological Sciences, vol 284, issue 999	Northern Great Barrier Reef, Australia	A fundamental study of the indicative meaning of coral microatolls inclusive of extensive discussion on ponding. A key paper in defining and cementing the usage of the term 'coral microatoll'.	5
Scoffin TP, Tudhope AW and Brown B.	1989	Fluorescent and skeletal density banding in <i>Porites lutea</i> from Papua New Guinea and Indonesia.	Coral Reefs, vol 7	Motupore Island, Papua New Guinea and Jakarta Bay, Indonesia	Study of fluorescence and skeletal density banding of shallow water corals. Indicates that distinct bodies of water differ in timing of banding with other areas. Fluorescence banding is, in some areas, clearest during periods of high fresh water run off from land. In the studied areas high fresh water input also coincides with the formation of low density bands.	15 and 1
Scoffin TP, Tudhope AW, Brown BE, et al.	1992	Patterns and possible environmental controls of skeletogenesis of <i>Porites lutea</i> , South Thailand.	Coral Reefs, vol 11	Phuket, Thailand	Investigation of factors controlling coral colony density across a range of sites with differing hydraulic energy. Higher hydraulic energy appears to correlate with higher density corals. While linear extension is inversely correlated with linear extension.	3
Sieh K, Natawidjaja DH, Meltzner AJ, et al.	2008	Earthquake supercycles inferred from sea-level changes recorded in the corals of west Sumatra.	Science, vol 322, issue 5908	Mentawai Islands, Indonesia	Relative sea level changes reconstructed from coral microatolls along a 700 km stretch of the Sunda Megathrust indicate sequences of raptures approximately every 2 centuries for at least the last 700 years. Suggesting a 2007 rupture was the first of a likely sequence of events.	12
Smithers SG and Woodroffe CD.	2000	Microatolls as sea-level indicators on a mid-ocean atoll.	Marine Geology, vol 168, issue 1-4	South Cocos (Keeling) Islands	Extensive study of <i>Porites</i> coral microatolls on a mid ocean atoll. Particularly large and valuable data set	16

					on HLC ranges and ponding which demonstrates 0.4 m range of HLC across an atoll.	
Smithers SG and Woodroffe CD.	2001	Coral microatolls and 20th century sea level in the eastern Indian Ocean.	Earth and Planetary Science Letters, vol 191, issue 1-2	South Cocos (Keeling) Islands	Reconstruction of sea level between 1895 and 1991 from living coral microatolls. Indicating sea level in the eastern Indian Ocean has risen slowly (<0.35 mm/yr) over the 20 th century.	16
Sollas WJ.	1904	Narrative of the expedition in 1896. The atoll of Funafuti.	Book	Funafuti Atoll, Tuvalu	First reconstruction of a former sea level from fossil microatolls at 1.2 m above present. No dating methods were available at the time to establish the timing of this sea level.	17
Spencer T, Tudhope AW, French JR, et al.	1997	Reconstructing sea-level change from coral microatolls, Tongareva (Penrhyn) Atoll, Northern Cook Islands.	8th International Coral Reef Symposium, vol 1	Tangareva Atoll, Northern Cook Islands	Reconstruction of sea level between 1936 and 1993 from living coral microatolls. Comparison of reconstruction based on surface morphology and x-rayed structure of microatoll slabs demonstrates that surface morphology may on some sites be insufficient to reconstruct sea level due to overgrown HLC changes from ENSO events.	18
Stoddart DR and Scoffin TP.	1979	Microatolls: Review of Form, Origin and Terminology.	Atoll Research Bulletin, vol 224	NA	Earliest review of microatoll methodology and terminology, one of the key papers to cement the usage of the term 'coral microatoll'.	NA
Tanzil JTI, Lee JN, Brown BE, et al.	2016	Luminescence and density banding patterns in massive Porites corals around the Thai-Malay Peninsula, Southeast Asia.	Limnology and Oceanography	Malay Peninsula and Singapore	Study of the causes of density and luminescent banding in corals around the Malay Peninsula. Correlates high density banding with periods of increased significant wave height and luminescent bands with low salinity due to fresh water input.	19
Taylor FW, Frohlich C, Lecolle J, et al.	1987	Analysis of partially emerged corals and reef terraces in the central Vanuatu Arc: Comparison of contemporary coseismic and nonseismic with quaternary vertical movements.	Journal of Geophysical Research, vol 92, issue B6	Central Vanuatu	One of the earliest coral microatoll investigations of relative sea level and tectonics utilizing the annual nature of banding to constrain timing of tectonic events. Introduces the HLS term.	20

Torres-Pérez JL and Armstrong RA.	2012	Effects of UV radiation on the growth, photosynthetic and photoprotective components, and reproduction of the Caribbean shallow-water coral <i>Porites furcata</i> .	Coral Reefs, vol 31, issue 4	San Cristobal Reef, Puerto Rico	Study of effects of UV radiation on growth and health of shallow water <i>Porites furcata</i> colonies. Indicates that increased UV radiation can debilitate the health and growth of coral colonies.	21
von Chamisso A.	2013 (1821)	Remarks and opinions of the naturalist of the expedition.	In Book: A Voyage of Discovery, into the South Sea and Beering's Straits, for the Purpose of Exploring a North-East Passage Undertaken in the Years 1815–1818, at the Expense of His Highness the Chancellor of the Empire, Count Romanzoff, in the Ship Rurick	NA (multiple sites)	First time coral microatolls are described in a scientific publication.	NA
Weil-Accardo J, Feuillet N, Jacques E, et al.	2016	Two hundred thirty years of relative sea level changes due to climate and megathrust tectonics recorded in coral microatolls of Martinique (French West Indies).	Journal of Geophysical Research: Solid Earth, vol 121, issue 4	Martinique, French West Indies	A reconstruction of 230 years of tectonic history based on fossil and living coral microatolls.	22
Weil-Accardo J, Feuillet N, Jacques E, et al.	2016	Relative sea-level changes during the last century recorded by coral microatolls in Belloc, Haiti.	Global and Planetary Change, vol 139,	Belloc, Haiti	First reconstruction of sea level in the Caribbean utilizing coral microatolls, indicates long term submergence of the area. Though disagreement in sea level trends from corals from different parts of the site may indicate some microatolls in the study were ponded.	23
Wellington GM and Glynn PW.	1983	Environmental influences on skeletal banding in eastern Pacific (Panama) corals.	Coral Reefs, vol 1, issue 4	Gulf of Panama and Gulf of Chiriqui, Panama	Investigation of the causes of high and low density bands in <i>Pavona</i> corals. Results indicate that light is the main control on band density and that the high	24

					density band formation correspond to lower light levels.	
Wood-Jones F.	1912	Corals and atolls		South Cocos (Keeling) Islands	Introduction of the 'coral microatoll' and HLC terms.	16
Woodroffe CD, Beech MR and Gagan MK.	2003	Mid-late Holocene El Niño variability in the equatorial Pacific from coral microatolls.	Geophysical Research Letters, vol 30, issue 7	Christmas Island	A reconstruction of ENSO variability using coral microatolls. Indicates that variability of ENSO was smaller than present from 3800 years BP to 2800 years BP, but more pronounced than present at 1700 years BP.	25
Woodroffe CD and Gagan MK.	2000	Coral microatolls from the central Pacific record late Holocene El Nino.	Geophysical Research Letters, vol 27, issue 10	Christmas Island, Kiribati	A reconstruction of ENSO variability over a 20 year period using living coral microatolls. Demonstrates three negative oxygen isotope anomalies attributed to warm El Nino events.	25
Woodroffe CD, McGregor HV, Lambeck K, et al.	2012	Mid-Pacific microatolls record sea-level stability over the past 5000 yr.	Geology, vol 40, issue 10	Christmas Island, Kiribati	Reconstruction of sea level from fossil coral microatolls indicating sea level stability at close to (within 0.25 m) present sea level for past 5000 years.	25
Woodroffe CD and McLean R.	1990	Microatolls and recent sea level change on coral atolls.	Nature, vol 344, issue 6266	South Cocos (Keeling) Islands and Abemama Atoll, Kiribati	One of the earliest (after Sollas and Taylor) demonstrations of coral microatolls being utilized for sea level reconstructions. The study documents a slight sea level fall over a 10 year period between 1979 and 1989.	16 and 6
Yu K-F and Zhao J-X.	2009	U-series dates of Great Barrier Reef corals suggest at least +0.7 m sea level 7000 years ago.	The Holocene, vol 20, issue 2	Great Barrier Reef, Australia	Reconstruction of sea level from fossil coral microatolls indicating sea level at least 0.7 m higher than present at 7000 cal years ago and at least 1.6 m higher than present at 5800 cal year ago.	2
Yu, Ke-Fu Zhao, Jian-Xin Done, Terry et al.	2009	Microatoll record for large century-scale sea-level fluctuations in the mid-Holocene	Quaternary Research, vol 71, issue 3	Leizhou Peninsula, China	Reconstruction of sea level from fossil coral microatolls indicating sea level 1.7 to 2.2 meters above present sea level and fluctuations of 0.2 to 0.4 m on century scale, over the period from 7050 to 6600 years BP.	26

http://d-maps.com/carte.php?num_car=3228&lang=en

Supplementary figure 1 Locations of sites discussed in the review chapter: 1- north coast of Java, Indonesia 2- Central Great Barrier Reef, Australia 3 Phuket, Thailand, 4- Eniwetok Atoll, Marshall Islands, 5- Northern Great Barrier Reef, Australia, 6-Abaiang Atoll, Kiribati, 7- Southern Cook Islands, 8- Belize, 9- Southwest Sulawesi, Indonesia, 10-Simelue Island, Indonesia, 12-Mentawai Islands, Indonesia, 13-Moturiki Islands, Fiji, 14-Moorea, French Polynesia, 15-Mutupore Island, Papua New Guinea, 16- South Cocos (Keeling) Islands, 17-Funafuti Atoll, Tuvalu, 18-Tangareva Atoll, Northern Cook Islands, 19-Malay Peninsula, Malaysia, 20-Central Vanuatu, 21-San Cristobal Reef, Puerto Rico, 22-Martinique, French West Indies, 23-Belloc, Haiti, 24-Panama Bay, Panama, 25-Christmas Island, Kiribati, 26- Leizhou Peninsula, China.

Chapter 3 Constraining the uncertainties of coral microatoll relative sea level studies

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Abstract

The ability of coral microatolls to record sea-level changes had made them a popular tool for a variety of scientific questions, they have constrained tectonic movements histories, El Niño/Southern Oscillation variability and mid-Holocene relative sea-level changes. Despite their long history of usage, questions over how reliable they are as a proxy for reconstructing sea level remain. In particular, very few studies have been conducted on relative sea level from living coral microatolls. As a result the ability of coral microatolls to reconstruct long term sea level trend has not been tested. Here we demonstrate that on the Sunda Shelf coral microatolls respond to the 18.61-year tidal cycle recording record relative sea level on time scales longer than one such cycle. We also demonstrate that they can be used to reconstruct long term sea level trends. We compare both lowest annual tides and mean sea level from tide gauges in Singapore and the Malay Peninsula with RSL reconstructed from of an open water microatoll from Mapur, demonstrating good agreement over a period of two decades of microatoll

record with three decades of tide gauge record. We also demonstrate that ponded microatolls cannot be used for sea level trend calculations and that ponding is widespread on the reef, affecting even lagoons which are partially open to the ocean. Here we also reconstruct a sea level trend from an open sea level coral microatoll in Mapur, Indonesia, it shows the sea level in the region has a long term (1915-2005) vertical change rate of 0 ± 0.88 mm/yr. We also calculate sea level trend from shorter coral microatoll records (1967 to 2005) for Belitung Island, Indonesia, resulting in a sea level trend from 1.6 ± 2.11 to 4.7 ± 2.16 mm/yr.

Introduction

Coral microatolls, are coral colonies that grow at the upper limit of the habitat suitable for coral growth. Found in the intertidal zones, they were first noted in 1821 by von Chamisso (2013: republished), Darwin (1842) and more fully described by Dana (1846). As Dana noted, vertical growth is limited by exposure, and the growth of the colony is predominantly horizontal. Disc-shaped coral microatolls found in tectonically stable areas are some of the most characteristic, but many morphologies can be observed depending on tectonics and sea-level changes in their growth region (e.g., Hopley, 1982; Taylor et al., 1987). Because they record water-level changes during their lifetime, which can last decades and in rare cases centuries, they are a valuable proxy for sea-level history.

Due to their ability to record sea-level changes coral microatoll have been used for a variety of purposes. In tectonically active areas they can be used as a proxy for sudden co-seismic and gradual interseismic land-level change (e.g., Taylor et al., 1987; 78

Zachariasen et al., 2000; Natawidjaja et al., 2004; Meltzner et al., 2010; Sieh et al., 2008; Meltzner et al., 2012; Philibosian et al., 2014; Weil-Accardo et al., 2016a). In non-tectonic settings fossil microatolls have seen use in studying Holocene sea levels (e.g., Chappell et al., 1983; Woodroffe et al., 1990; Yu et al., 2009; Meltzner et al., 2017) and oceanographic phenomena such as the El Niño/Southern Oscillation (Woodroffe and Gagan, 2000; Woodroffe et al., 2003). These studies are carried out with the assumption that coral microatolls track sea level over the course of their lifetimes, but comparisons of the sea-level trend from microatolls with tide gauges or satellite altimetry to establish their reliability are limited to only a handful (Woodroffe and McLean, 1990; Spencer et al., 1997; Flora and Ely, 2003; Flora et al., 2009; Weil-Accardo et al., 2016b).

None of these studies however, is entirely free of limitations. In some cases, record looks promising however, because a 50-year long record is required to reconstruct sea-level trend (Douglas, 1991), is simply too short to be used for a sea-level trend reconstruction with 14 (Woodroffe and McLean, 1990) and 7 years (Flora and Ely, 2003) analyzed. In other cases studied coral microatolls appear clearly ponded (Flora et al., 2009). Coral microatolls growing in ponds formed by a physical barrier of stone, sand or shingle which prevents or constricts water from draining during the lowest tides can grow to higher elevations than open-water microatolls. Ponded microatolls record changes in the elevation of the barrier around the pond rather than sea level (Scoffin et al., 1978). In other cases, limitations were those of the microatolls themselves for example particularly severe sea-level anomalies, i.e. ones which caused

the sea-level to be lowest in a couple of decades, resulting from oceanographic events caused unusually deep diedowns, following which, the microatolls took a decade or more to again reach an elevation constrained by low tides (Woodroffe and McLean, 1990; Spencer et al., 1997; Weil-Accardo et al., 2016b). The most recent, and comprehensive, effort by Weil-Accardo et al. (2016b) dealt with tectonically uplifted Belloc reef in Haiti, a tectonically complex region of the Caribbean Sea. They described two different morphologies, cup, suggesting sea-level rise, and hat, suggesting sea-level fall, among the *Siderastrea siderea* microatolls they studied. Weil-Accardo et al. infer that the falling sea-level morphologies resulted from the aforementioned problem of sea-level drops from oceanographic phenomena preventing microatolls from reaching the regular tide constrained levels. The sea-level trend of the cup shaped microatolls is consistent with tide gauge records for the area, however the authors also specify that microatolls of this morphology tend to grow in the middle of the Belloc reef, protected from surf and waves by those of the hat morphology which grow around the edges. If this is the case, the microatolls protected in the middle of the reef may have experienced slightly different water levels than the sea level of the area, raising the possibility that their record is influenced by ponding which is noted to affect microatolls growing at higher elevations on a reef (Scoffin et al., 1978; Smithers and Woodroffe, 2000; Meltzner et al., 2017).

The shortcomings and challenges experienced by these studies convince us that more unequivocal evidence is needed to constrain the exact relationship between coral

microatolls and the sea level. We have chosen to investigate three questions which are key to the application of coral microatolls as sea-level proxies:

- The first question is whether open-water corals record the regional sea levels, and whether they contain sequences long enough to reconstruct sea level through the 18.61-year nodal tide cycle. If open-water microatolls record sea levels we should be able to observe their HLS following the lowest tides of the year on inter-annual time periods while agreeing with instrumental records for the area on half century time scales.
- The second question we want to investigate is how much does ponding affect the record of sea level from microatolls. Our hypothesis is that ponded corals cannot be used to recover sea-level trends, because they are protected from the low tides and do not record RSL. If this is true we expect that most of the ponded coral microatolls will differ from open water microatolls in their sea-level trend. We also expect that ponded microatolls will have recorded at least some diedowns which cannot be explained by the 18.61-year tidal cycle.
- The last question we wish to answer is whether ponded microatolls register diedowns in time (even if not at the same elevation) with the open sea microatolls at all. We hypothesize that although they will likely record extra diedowns, not resulting from the 18.61-year tidal cycle, ponded microatolls will still record some diedowns which agree in timing with the 18.61-year tidal cycle because sills of sand or coral which cause ponding are unlikely to be entirely waterproof.

Background

Coral microatolls

At least several genera of coral form microatolls (Scoffin et al., 1978: Appendix by Rosen B. R.). We chose to study individuals from the *Porites* genus of which many species possess a massive structure which can be relatively easily recognized and interpreted from x-rays (Knutson et al., 1972; Buddemeier et al., 1974). The *Porites* genus is also abundant in the tropics of both the Atlantic and the Indo-Pacific Oceans (Veron, 1993). *Porites* microatolls have been utilized in studies of both fossil (e.g., Chappell et al., 1983; Scoffin et al., 1997; Meltzner et al., 2017) and living (e.g., Woodroffe and McLean, 1990; Spencer et al., 1997; Flora and Ely, 2003) corals. Corals exhibit banding in their growth structure (Dana, 1846: p. 53). In a similar way to tree rings, this banding is largely annual in nature forming one low and one high density band each year (Knutson et al., 1972; Buddemeier et al., 1974). The reason for the formation of high/low density bands at different times is the source of an ongoing debate. Linear extension and overall calcification rate is faster, though density is lower, during parts of the year when the coral is exposed to more sunlight (Highsmith, 1979; Wellington and Glynn, 1983). Some studies suggest this may change if the UV levels get too high (e.g., Torres-Pérez and Armstrong, 2012) which may explain the particularly dense stress bands formed by coral microatolls during diedown years. Some authors allow for the role of light but argue that it is the temperatures which are the key to the banding pattern (Highsmith, 1979). Finally, more recent work by Tanzil et al. (2016) appears to tie density banding to wave energy at different times of the year (high density forming during periods of increased wave energy), at least for areas

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proximal to the Malay Peninsula. Though the source of the banding was not one of the aspects we were investigating, our observations confirm that the low-density portion of our samples forms mainly during the dry season i.e. April to September when more sunlight is available and wave energy is lower in the study areas. Regardless of the primary cause, the bands in the microatolls we sampled are clearly distinguishable. Figure 3.1 shows an example of an x-ray of a fragment of a slab from PMPR-A-M2 from Mapur. The clear bands allow us to count back from the living edge to calculate the age of any portion of the sampled microatoll slab.

Figure 3-1 A fragment of an X-ray image of a coral microatoll slab (PMPR-A-M2 from Mapur) with clearly visible growth bands. One high density (dark) and one low density (light) band is formed in each year. White circle is a perforation of the slab drilled along a horizontal line for the purpose of linking the elevation of features within the slab structure with a site survey.

Coral microatolls develop from ordinary hemispherical colonies growing below the intertidal zone. They do this by growing upwards and outwards until they reach the water surface, in areas where the 18.6-year tidal cycle is the dominant influence on microatolls this is most likely to occur either while lowest annual tides are lowering or at the bottom of 18.6 year the cycle. When exposed for a long enough period the

polyps on the upper colony surface die, but those at lower levels survive. The extent of the required period of exposure is not well known factors such as light levels, temperatures and precipitation during exposure are all likely to contribute. However they are likely to be on the order of hours since the coral would rarely be exposed longer than that within normal tidal conditions. The upper limit of the surviving polyps is called the highest level of survival (HLS) (Taylor et al., 1987; Meltzner and Woodroffe, 2015). This level is not reached by the coral growth every year, in years when the upper growth is not exposed at low water levels and its vertical growth is limited only by the coral's growth rate we refer to the upper limit of growth as the highest level of growth (HLG) (Meltzner et al., 2010; Meltzner and Woodroffe, 2015). Some sea level studies refer to both HLS and HLG collectively as height of living coral (HLC) (Smithers and Woodroffe, 2000; Meltzner and Woodroffe, 2015). In this study, we shall use the former terms because they offer more precision in meaning. Each time the coral microatoll is exposed and part of the upper growth around the whole perimeter is killed the microatoll has experienced a diedown. Diedowns, where the upper part of a living band is killed but growth continues at lower levels, may be on millimeter, centimeter or even decimeter scale. We distinguish two types of diedowns, termed "preserved diedowns" and "deduced diedowns", which we distinguish by the type of evidence which has allowed for their inference. Some diedowns are quickly overgrown by later growth, and such a diedown is clearly visible in the structure of the microatoll, these are termed "preserved diedowns". Figure 3.2 shows an x-ray of a fragment of a microatoll slab (PMPR-A-M2), a preserved diedown is highlighted by a red line. The microatoll in the image grew from right to left, each yellow band marks a year's growth.

The growth (HLG) just prior to the diedown is ~6cm higher than that which continued after the diedown. The point above which all growth ceased due to the death of polyps is the depth of the diedown, and its elevation is the HLS of the coral in the year of the diedown. Timing of the diedown can often be narrowed down to approximately thirds of the band with which roughly equal 4 months in most situations where annual bands are close to calendar year. Because growth recovered quickly after the diedown its elevation was clearly preserved in the structure of the slab. Other diedowns are never overgrown, but the raised ring of coral on the upper surface of the microatoll still allows them to be inferred. Figure 3.3 shows the upper surface of a microatoll (TKUB-M1) on which we can see a series of raised rings (annuli) and the depressions between them. The presence of the rings around the circumference of the microatoll leaves little doubt that after a period of upward growth a lowering of water levels occurred forming the feature. In those cases, we refer to the diedown as a deduced diedown. The two categories differ slightly in that deduced diedowns cannot be used as HLS markers, unless additional error terms are applied (because of possible erosion), and their timing is usually only constrained to a period of 1-3 years.

Figure 3-2 Fragment of an X-ray image of a coral microatoll slab (PMPR-A-M2 from Mapur) with annual growth bands (yellow lines) and a diedown (red line) marked. In this image the microatoll is growing from right to left. The red line illustrates a ~5 coral microatoll drop in HLG of a coral microatoll as a result of a diedown. In this case the HLS would be measured at the bottom point to which the growth unconformity reaches, i.e. the bottom of the red line.

Figure 3-3 Fragment of a microatoll (TKUB-M1 from Belitung) with visible surface rings marked with white dashed line. The crest of each ring is additionally marked with a red triangle. A green triangle marks the raised ring currently forming on the living edge. The presence of these rings allows us to deduce diedowns which were not preserved inside the slab structure.

Several cycles of predominantly horizontal growth and diedowns result in the coral colony gradually taking on the flat morphology we associate with microatolls. Typically, colonies can survive decades to centuries, provided the accommodation space does not diminish. Because of this many microatolls alive today started recording sea level long before any tide gauges were placed in their area. The filtered record of sea level over the life of the microatoll can be recovered from many open-water microatolls (Woodroffe and McLean, 1990; Smithers and Woodroffe, 2000).

Water levels

Coral microatolls can record information about lowest water levels, but these may be modulated by oceanographic phenomena such as the Indian Ocean Dipole (IOD) (e.g., Meltzner et al., 2010; Meltzner et al., 2012; Philibosian et al., 2014) or the El Niño-Southern Oscillation (ENSO) in the Pacific (e.g., Spencer et al., 1997; Woodroffe and Gagan, 2000; Woodroffe et al., 2003). Weather phenomena may also influence the observed sea levels and introduce disparities from the predicted low tide (on the Sunda Shelf the scale of these disparities may reach ± 5 cm while persistent monsoonal winds can draw water away from some coastlines or pile it up higher on others on the order of $+50/-25$ cm for several week at a time (Wyrski, 1961; Chen et al., 2011; Tkalich et al., 2013).

On the Sunda Shelf, the 18.61 nodal tidal cycle is key to understanding open-water microatoll diedowns because over the cycle it alters the elevation of the low tides by

more than 30 cm (e.g., Meltzner et al., 2017). During an 18.61-year cycle the tidal range increases for the first 9.3 years then reverses and decreases for the second 9.3 years. This results in the lowering of the elevation of the low tides while the overall tidal range is increased and a rise in the relative low tide level when the cycle reverses. On the Sunda Shelf during the stage when low tides are rising from year to year, the changes in water elevations are typically faster than the growth rate of corals, as a result the coral growth is not constrained for the majority of that portion of the cycle. When the cycle turns and low tides become increasing lower, the highest part of the microatoll growth, previously unconstrained, becomes exposed. Over several 18.61-year cycles this results in a sequence of elevated rings forming, on the upper surface of the microatoll. Although changes in sill elevation may also result in similar structure on ponded coral microatolls.

Local factors such as ponding and varied growth rates of corals on a site may also influence the water levels they record. Ponding occurs when a rampart or sill is formed in the intertidal zone separating an area from the open sea (Scoffin et al., 1978; Smithers and Woodroffe, 2000). When this happens, water levels may be different in the ponded area for part of the tide cycle because at the lowest tides the sill prevents water from draining fully. Coral can often survive and form microatolls in such ponds as long as they are below high water neaps and water is replenished daily (Scoffin et al., 1978). *Porites* growth rates can also vary widely, in the Sunda Shelf they range from less than 10 mm/y to more than 30 mm /y though they tend to average around 20mm/y (Tanzil et al., 2013). Individual coral microatolls, even at the same site, can

grow at different rates, thus even if they died down in the same year at one point of time, this is no guarantee that they will do so again during later low water events if they have not yet grown above the constraining low tide level (Fig. 3.4). Finally different species of coral, even different species and subspecies of *Porites*, and indeed different local populations of a single subspecies may also have different inbuilt resistance to adverse conditions (Padilla-Gamiño et al., 2012).

Figure 3-4 Previous page: A cartoon of the importance of varied growth rates on coral morphology. The cartoon sequence shows two corals of the same age developing microatoll morphology. The growth rate of the microatoll on the left is roughly half that of the microatoll on the right. Sea-level changes from previous panel marked with blue (rise) and orange (fall) arrow on the right. A-unconstrained hemispheric corals. B- a low water level causes diedowns (red line) on both corals, but living tissue continues to grow below water level (green line). C- both corals are unconstrained again and grow upwards and outwards. D- another low water event causes a diedown on the fast-growing coral (right), but the slow growing coral (left) has not grown up high enough to be affected. E- Both corals are unconstrained again, and continue to grow upwards and outwards. F- a third low water even, of similar elevation as that in panel B, causes a diedown on both corals. G- both corals continue to grow upwards and outwards from below the diedown level. Despite the same sea-level history, the difference in growth rate causes the fast-growing coral to record one more diedown than the slow growing coral. Note that the cartoon is schematic only, in reality all coral microatolls can stand some exposure above water level and diedowns are caused by water levels dropping below this normally tolerated level.

Regional setting

Tectonic setting of study areas

For our study we chose to sample coral microatolls from two islands (Figure 3.5), both of which lie within the part of the Sunda Shelf which was inferred to be tectonically stable based on a study of 10-years of GPS data (Simons et al., 2007). This is important because changes in land level due to tectonic deformation would be difficult to separate out from the relative sea-level change recorded by the microatolls. We acknowledge that complete tectonic stability is unlikely in almost any setting, particularly over the entire period since the Holocene highstand, however this evidence gives us confidence that the area of our investigation is at least relatively stable compared to those lying outside the dashed outline in figure 3.5.

Figure 3-5 Map of Sundaland with the Mapur and Belitung microatoll sites, and the site of the Tanjung Sedili tide gauge, marked with circles. Blue outline marks the edges of the portion of the Sundaland which has been inferred to be tectonically stable by a 10 year GPS study (Simons et al., 2007). Map modified from Meltzner et al. 2017

Mapur Island

Mapur is located 100 km south-east of Singapore at (0.99°N, 104.82°E, Fig. 3.5). The tides are semidiurnal and over the 18.61 year tidal cycle the tidal range varies from 2.33 to 1.97 meters (Egbert and Erofeeva, 2002). Water clarity there is better than around larger islands such as Bintan. We sampled three living microatolls from two sites, one along the northern coast and a second along the eastern coast of the island. We will refer to the sites as Mapur North and Mapur East, respectively. The Mapur North site (Fig. 3.6) comprised a shallow lagoon with many ponded microatolls and an outer rampart formed mostly by fossil microatolls in the west, and a sandy beach deepening rapidly with scattered coral colonies in the east. The Mapur East site (Fig. 3.7) has a fringing reef with extensive fossil reef flats in the northern part, deepening southwards into a living reef in a lagoon partially open to the east.

Radial slabs of coral microatolls PMPR-A-M1 and PMPR-A-M2 from Mapur North, were collected, respectively, from a fully open free draining setting and from a lagoon that was almost completely separated from the sea during low tide. A radial slab of coral microatoll PMPR-B-M1 was collected at Mapur East. This microatoll grew in a lagoon that was partially open to the sea, at no point in the tidal cycle appearing to be fully sequestered from the open sea. This setting was chosen to investigate if there are 'degrees' to ponding and how much the ponding issue may influence the information recorded by the coral microatolls.

Figure 3-6 Map of Mapur North site. Red points on the map show locations of living microatolls. Location of sampled corals labeled with black point and names. A mid Holocene fossil reef adds complexity to this site, ponding corals in a large lagoon above modern open-ocean HLS. Uniform blue color marks the modern reef slope which dropped in depth rapidly and was not surveyed. Modern living coral colonies grow in many parts of the fossil reef, the only open water microatolls are those growing on the seaward side of the reef crest at the top of the reef slope.

Figure 3-7 Map of Mapur East. Most of the surveyed living coral microatolls grow within a large lagoon partly separated from the open sea by the fossil reef crest. Throughout the time fieldwork was conducted in 2012 and 2013 the passage (marked by blue arrows) remained open and water flow was deep enough that waves were only rarely seen breaking over the sill of the lagoon. However, as far as we know, there are no open water microatolls within the surveyed part of this area.

Belitung Island

Belitung (Figure 3-5) (2.68°S , 107.66°E) has a diurnal tide regime, at the northeastern part of the island near to our sites (2.65°S , 107.60°E), the tidal range varies from 2.8 to 2.1 meters over the 18.61-year tidal cycle (Egbert and Erofeeva, 2002), half of this difference applies to the elevation of the low and half to the high tides. The island is located about 200 km east of mainland southern Sumatra, Indonesia. The island is 80 km wide, roughly circular. Two sites, both on the northwest coast of the island, were chosen for microatoll collection living coral microatolls were chosen along sites with good fossil microatoll preservation which were sampled for a separate study of Holocene RSL. Individual coral colonies were chosen for maximum size, good preservation of ring structure on dead part of the colony and regular circular colony shape. The TKUB site was a fringing reef with wide ($>250\text{m}$) sand covered coral reef flats behind it backing onto mangroves, and the TKEL site was a sandy beach with a fringing reef beyond it. Two microatolls (TKUB-M1 and TKUB-M2) were slabbed at the more southerly TKUB site and one (TKEL-M1) was slabbed at the more northerly TKEL site. The TKEL-M1 slab was collected from a free draining open coastline, as was TKUB-M2 at the southern site. TKUB-M1, on the other hand, grew on a reef flat, behind a low but wide ($>50\text{ m}$) rampart of coral and sand (Figure 3-14), at low tide fully separated from the open sea. Similarly, to the Mapur sites, the different settings were chosen to show how ponding may influence the information recorded by the coral microatolls.

Methods

Sites were determined from satellite photos and field reconnaissance, based on the health, size and number of microatoll colonies. We chose the largest and least visibly eroded or damaged colonies in order to get the longest and least perturbed sea-level record. Ponded and open-water microatolls were sought out separately with the reef flat being the main site of search for ponded and the reef slope being the site for open-water microatoll search. Site bathymetry and corals were surveyed with a Leica total station to provide context for understanding the hydrodynamics of the site and to ensure that sampled microatolls were not tilted. Screws were inserted into the microatoll slabs and surveyed to ensure the internal structure could be correlated to the surveys and that the original horizontality of each slab was preserved. A radial slab from the outside edge to the center of the colony was then extracted from each microatoll, at the side where all rings noted in the colony were clearly visible, with a chainsaw, producing a ~8 cm thick coral microatoll slab.

The slabs were recut on a large rotary saw into several thinner ~8 mm slices and x-rayed on a standard hospital x-ray machine. We then adjusted contrast and brightness of the images, this was done only to parts of the images which were not clear, care was taken to avoid creating any artifacts, for example fragments for contrast or brightness corrections were never delimited parallel to growth bands. We then traced annual bands on the x-radiographs (by eye). We chose to mark the line on the inside of the denser sub-band because our observations have shown that, at our sites, this is roughly

the start (± 2 months) of the calendar year. To ensure we are marking the banding contacts correctly we also considered the coral growth lines, which are visible on the x-ray (Fig. 3.8). The coral growth lines should always be orthogonal to the annual growth bands. Diedown unconformities are also marked. The highest elevation attained in each year's growth (the HLG) is tabulated along with measurements of the HLS following each diedown. We then plot the results and compare the relative sea-level histories recorded by the various coral microatolls with one another and with the lowest annual tide, extracted from hourly tidal prediction from the Oregon State University Tidal Inversion Software (Egbert and Erofeeva, 2002).

Figure 3-8 *Fragment of an X-ray image of a coral microatoll slab (TKUB-M1 from Belitung) showing 6 years of growth. Annual bands marked with black lines. Yellow dashed lines mark the direction of growth lines. Note that where you trace the annual lines they should always cross the growth bands at right angles.*

Coral banding can exhibit sub-annual patterns for example when monsoon patterns in a given year differ from the norm (Scoffin et al., 1989). Some studies report corals in which several high/low density band couplets may be exhibited in a single year (Brown et al., 1986; Scoffin et al., 1989). However, Brown et al. (1986) also state that where

this was observed “there were no significant differences in annual linear extension values.” The same can be deduced from figures in (Scoffin et al., 1989: their figure 8) where some bands contain more than one couplet of high and low density bands but the over-all extension rate of annual growth remained relatively constant. Therefore, during our interpretation of the coral bands, we made an assumption that the thickness of each annual band should be approximately the same as those around it. This assumption is supported by the fact that among the coral microatolls we analyzed, where we saw very clear annual banding, we never saw significant (>50%) changes in the annual extension rates. The only areas where we do see significant changes in band thickness are near parts of the coral affected by diedowns. Where diedowns occur, we usually see characteristic gradual narrowing of the band from normal thickness several (~1-4 cm) centimeters below the diedown right up to a point at the diedown’s bottom edge.

The tidal predictions were performed using the Oregon State University Tidal Inversion Software (Egbert and Erofeeva, 2002) that assimilated various altimetry data (e.g. TOPEX/Poseidon, TOPEX Tandem and ERS). Instead of utilizing a global tidal model (e.g. TPOX7.2), a regional version for Indian Ocean (China Seas, resolution: 1/30° from <http://volkov.oce.orst.edu/tides/YS.html>), which covers our study sites, was used to extract harmonic constituents because of lower misfit values and better quality in coastal regions and shallow waters. The Ind2016 regional model consists of eight tidal constituents (m2, s2, n2, k2, k1, o1, p1 and q1). The tide at each site was then hourly predicted with Tidal Model Driver Matlab toolbox (TMD v2.03) developed at Earth

Space Research (https://www.esr.org/ptm_index.html). Hourly predicted tide at each site was then used to find the lowest annual tides. This step allows the comparison of the lowest tidal values with the diedowns from coral microatoll slabs.

Because the 100-km distance may make the comparison of Singapore/Malaysian tide gauges directly to Mapur corals inappropriate we initially made a comparison of the tidal model with the lowest yearly tides recorded by a tide gauge record from Tanjong Sedili, Malaysia (Caldwell et al., 2015), which lies 50 km north of Singapore, and 120 km Northwest of Mapur, on the east coast of the Malay Peninsula. The record cited is hourly tide observations from the tide, from which we then extracted the lowest tides for each year. The result of the comparison can be seen in Figure 3.9 where the lowest annual tides from the tide gauge record and the tide model are plotted. The tidal modal data shows good correlation with the main trends of the tidal gauge, though we note reports that monsoonal sea level anomalies can reach as much as +50/-20 cm in Singapore and south Malay Peninsula (Tkalic et al., 2012). Despite monsoonal effects it is noteworthy that over the 25-year tidal record of the Sedili tide gauge the difference in the low tides between the tide gauge observations and model predictions does not exceed 10 cm. This observation gives us confidence we can use the tidal model to make tidal predictions for Mapur and Belitung, and compare them with the coral microatoll growth series from those sites.

Figure 3-9 A comparison of the Tanjung Sedili tide gauge (Malaysia) lowest annual measurements (blue line) and Keppel tide gauge (Singapore) (light blue) with predictions from the tidal model (orange line) demonstrate good general agreement. Diedowns from PMPR-A-M1 also plotted (green diamonds) to demonstrate first order agreement. Although sea level anomalies of 20-50 cm have been reported for the Sunda Shelf (Tklich et al., 2012), they do not appear to have affected the low tides over this 25-year sequence by more than 10 cm at any point. This observation gives us confidence we can use the tidal model to make a prediction for our microatoll sites.

Matching the 18.61-year tidal cycle

In order to comment on the results, it is first necessary to constrain exactly what constitutes a match between coral growth and the 18.61-year tidal cycle. The 18.61-year tidal cycle comprises a 9.3-year period when tidal range expands followed by a 9.3-year period when it contracts. As a result of these changes the elevation of the low tides lowers (when tidal range is expanding) and rises (when the tide range is contracting). Apart from the general rising or falling trend in the low tide over each

18.61-year cycle, smaller tide drops can be seen in some years. However, we note that not all of them are equally likely to be registered by a coral microatoll in the form of a diedown. Oceanographic may add complexity to the record however their effects which have been constrained from the tide gauge records to be within a ± 5 cm range are unlikely to disrupt a large part of the record. Monsoonal effects have a larger vertical range (+50 cm and -25 cm) however they tend to be constrained to periods of a few weeks in time, hence they are unlikely to perturb the record because tides close to (within 5 cm) the lowest annual tide occur at several times over the course of the year.

Figure 3.10, shows the lowest annual tides predicted for the Mapur site, extracted from hourly predictions of a tidal model (Egbert and Erofeeva, 2002) for two full 18.61-year tidal cycles. A ‘synthetic’ coral microatoll following the 18.61-year tide cycle is also plotted. Its behavior is laid out in a simple excel IF function, where the synthetic coral growth elevation S is determined as follows:

$$\text{if } (S_{-1} + G < T), \text{ then } (S = S_{-1} + G); \text{ else } (S = T)$$

Where:

S is HLG of the coral microatoll at the current time step.

S_{-1} is the HLG of the coral microatoll at previous time step.

$G = 1.21$ cm (the value of the annual vertical growth rate of the coral 1.21 cm/y).

T is the predicted tidal elevation at the current time step.

Put another way, if the previous year's synthetic coral elevation plus annual growth rate is below the current year's predicted minimum tide, then the previous year's coral elevation plus annual growth rate will be plotted, otherwise the current year's predicted minimum tide plotted, effecting a diedown. As shown in figure 3-10 below not all periods when tides are lower from one year to the next are equally likely to result in a diedown being registered by a coral microatoll. For example small lowest-annual tide drops seen roughly half way through the rising part of the cycle occur at a time when coral microatoll have not yet had time to grow upwards enough to be affected by these drops.

Figure 3-10 Periods when coral microatolls are increasingly likely to register diedowns in agreement with the 18.61-year tidal cycle. Blue line shows a prediction of a low tide for two full 18.61-year tidal cycles. A synthetic coral series demonstrates when the coral is unconstrained (green diamonds) and periods when diedowns occur (red diamonds). A diedown occurred in each year following a red diamond. Red/white shaded bars with vertical guidelines demonstrate periods during which low tide levels are lowering increasing the likelihood of a coral microatoll registering a diedown.

Results

Open water/ponded

Microatolls PMPR-A-M2 and TKUB-M1 were chosen from ponded locations, which can be easily confirmed by comparing their elevation to the open water microatolls from the same sites (PMPR-A-M1 and TKUB-M2 respectively). Sample PMPR-B-M1 was chosen from a lagoon area which did not appear to be fully cut off from the open sea at any of the low tides when we visited the site, and which were ~ 14 cm above the lowest tides for the year (2013). The ponding is not, therefore, obvious to anyone visiting the site for a brief visit and with no knowledge of the bathymetry. However, the lagoon is separated from open sea on three sides and at least some of the corals growing within its deepest part are ponded, we chose PMPR-B-M1 to investigate whether such partial separation from the sea will influence the sea level it records.

Open water coral microatolls were chosen carefully from locations where no barrier of any kind was found to prevent or slow water drainage from the location at low tide. Finding open water microatolls is more challenging, time consuming and at times dangerous than finding their ponded kin further landwards. In all cases where open water microatolls were sampled the water depth begins to increase rapidly seawards from the location of the slabbed microatoll such that surveying more than a few steps beyond them was impractical because of water depth. Thus, their open water status appears well constrained.

Table 3-1 Diedown timing on Mapur corals

Mapur Diedown timing -->	Late 1915	Early 1943	Mid-1947	1964-1966	late 1972	Late 1973	1978-1979	1980-1981	Late 1982- Early 1983	Late 1986	1987-1988	1994-1995	1995-1996	1999-2000	2004-2005	Late 2008	Early 2009	Early 2012
PMPR-A-M1																		
PMPR-A-M2 Poned																		
PMPR-B-M1 Poned																		

Preserved diedown
 Deduced diedown
 Clearly no diedown
 No data

Table 3-2 Diedown timing on Belitung corals

Belitung Diedown timing -->	1938-1939	1959-1960	Late 1968	Late 1970	Late 1971	Late 1976	Late 1981	Mid-1985	Early 1988	Mid/late-1990	Late 1995	1999-2000	Late 2004	Mid-2005	Late 2006	Early 2009
TKEL-M1																
TKUB-M1 Poned																
TKUB-M2																

Preserved diedown
 Deduced diedown
 Clearly no diedown
 No data

Diedown and growth sequences from Mapur

Sample PMPR-A-M1 revealed a sequence of over 130 years of growth (Fig. 3.11). Its first diedown occurred in late 1915. Later diedowns occurred in early 1943, mid 1947, 1964-66, 1972, 1980-1981, late 1986 and late 2005. It appears to have died down in at least five out of seven of the 18.61 year cycles it lived through, though we have no conclusive evidence of diedowns in two cycles whose lowest parts fall in the 1890s and 1930s (comment on this below). All of the diedowns recorded by this coral can be explained by low tides resulting from the 18.61-year tidal cycle. The diedown in 1972 occurs during the period when the 18.61-year cycle allows the low tides to rise, but a small dip in the tidal levels of that year (and the year before) may be enough to cause a diedown. This is an important observation because in studies based purely on fossil microatolls dated by U-Th or radiocarbon it is not possible to directly use tidal predictions for the period to check that a coral microatoll growth sequence is following the 18.61-tidal cycle. Rather the sequence needs to first be aligned to the 18.61-tidal cycle/tidal prediction using the diedown timing, hence, knowing that some diedowns occur in the half of the tidal cycle when generally speaking the tidal range is decreasing and the elevation of low tides is rising is important.

Figure 3-11 Coral microatoll growth sequences from Mapur (PMPR-A-M1, PMPR-A-M2 and PMPR-B-M1) and the timing of diedowns which they registered (vertical lines) compared to the lowest annual tides extracted from a tidal model prediction (Egbert and Erofeeva, 2002) for the same site. While most diedowns on the open water (PMPR-A-M1) microatoll occur in years when tides are close to the bottom peak of the 18.61-year tidal cycle or lowering, several diedowns on the other two corals do not appear to be correlated with the tidal cycle in the same way. Microatolls PMPR-A-M1 and PMPR-A-M2 are plotted in the same elevation frame demonstrating how much higher ponded microatolls can grow. PMPR-B-M1 is not plotted on the same elevation reference frame and neither is the tidal prediction.

Sample PMPR-A-M2 revealed a 44-year sequence of growth. Diedowns are recorded in late 1973, early 1983, 1995-1996, 1999-2000 and in early 2009. Despite growing in a clearly ponded location, the coral microatoll does register diedowns in each of the 18.61-year cycles it lived through. However, the diedowns in 1973, 1995-1996 and 2009 come in years in which the low tides do not reach as low as in the previous year, and cannot be explained by low water levels resulting from the lowest stages of the

18.61-year cycle. These diedowns may have resulted from changes in the elevation of the sill of the pond where the coral microatoll grew.

Sample PMPR-B-M1 revealed a 50-year sequence of growth. Diedowns occurred in 1978-1979, late 1982, 1987-1988, 1993-1994, 1999-2000, 2004-2005, late 2008 and early 2012. PMPR-B-M1 does record diedowns in years when the low tides are lowering, despite growing in a lagoon partially separated from the open water, however diedowns in 1978-1979 and 1994-1995 are not anticipated from the 18.61-year cycle.

Of the three samples taken from Mapur (Figure 3.11) the open water PMPR-A-M1 shows the best match to the 18.61-year tidal cycle in that it does not appear to record any diedowns which cannot be explained by the cycle. All observed diedowns occur either during the lowest parts of the 18.61-year tidal cycle or when the tides are lowering. The correlation with the tidal cycle is not perfect though. Diedowns for two 18.61-year cycles that the coral microatoll lived through in the 1890ties and 1930ties are not recorded in the slab. In my view, there are two possible explanations: erosion or modulation of the diedown timing. Much of the PMPR-A-M1 sequence consists of bands which have an eroded upper surface (eroded HLG). Figure 3.12 demonstrates a 'synthetic' coral microatoll which demonstrated what the growth of PMPR-A-M1 could have looked like under ideal conditions (plotted according to the same rules as for figure 10, for PMPR-A-M1 the average annual growth rate is 1.21 cm/y, that is also the value used for the synthetic coral). It is important to note that this does not represent what the coral really did look like, rather, the synthetic sequence is an

oversimplification of our current understanding of how coral microatolls react to tides.

Figure 3-12 A synthetic, microatoll growth sequence for an annual growth rate (1.21 cm/yr) and starting elevation similar to those of PMPR-A-M1. The synthetic coral sequence is not meant to replicate what PMPR-A-M1 would have looked like if it was un-eroded, but it helps to illustrate where the most erosion occurred and its maximum vertical extent.

The synthetic coral calculation takes into account only the tide elevation, it does not make any provision for temperature, light levels, wave splash, rain, sea level anomalies or genetic resistance to adverse conditions of the particular coral, which are known to vary even within local populations of *Porites* (Padilla-Gamiño et al., 2012). Any and all of these may affect coral growth and how it dies down. The synthetic coral is a gross oversimplification but a useful one because it shows us that a coral microatoll growing at the same average rate as PMPR-A-M1 may have grown several cm higher than what is preserved, and gives us some indication which portions may have been higher. If HLG of PMPR-A-M1 was indeed a few cm higher originally then erosion of diedown evidence appears to be a reasonable explanation for not demonstrating a response to the two 18.61-year tidal cycles.

Other possibilities include modulation of diedown timing by low temperatures, cloudy or rainy weather coinciding with the low tide and lessening the impact of exposure on the coral. This mechanism could have protected the coral during low tides causing it not to have a diedown when expected. Corals are known to suffer less damage from heat and UV related stresses if these occur at a time when the sky is largely overcast (Mumby et al., 2001), same may be expected if low tides occur at night.

In the case of PMPR-A-M2 and PMPR-B-M1 the correlation to the 18.61-year tidal cycle is not as good. This was largely expected as neither of the corals grew in a fully open-water environment. Despite the relatively short lifespan of PMPR-A-M2 it shows five diedowns, three of which occur during parts of the tidal cycle when the trend was such that coral should have been gaining, not losing, accommodation space. It is important to note that apart from the timing of the diedowns the elevation of the coral is important. PMPR-A-M2 grew more than 50 cm above open-water microatolls at the same site. Despite growing much higher than its open-water counterpart, PMPR-A-M1, we note that the slab still shows a diedown for each of the 18.61-year cycles it lived through. PMPR-B-M1 exhibits three diedowns that cannot be explained by low water levels resulting from the lowest/lowering stages of the 18.61-year cycle, though it does record a diedown for each 18.61-year cycle it lived through.

As stated previously, many other factors (rain, cloud cover, temperature, monsoon wind sea-level anomalies) could affect the timing of diedowns in some circumstances. Hence one or more diedowns which appear to not come from the tidal cycle might not

be an indication of ponding. Rather it is multiple such diedowns on PMPR-A-M2 and PMPR-B-M1 and the higher elevation in comparison with open water microatolls, as seen with PMPR-A-M2 compared to PMPR-A-M1 in Figure.3.11, which are indications of ponding. In the case of PMPR-B-M1 we do not have an open water coral microatoll to compare it to, hence relative elevation cannot be used to establish if it is ponded. However, apart from two diedowns which cannot be explained with the 18.61-year tidal cycle we have other indications of ponding for example the small (<3 cm) reach of each diedown into the slab structure suggests some protection from the low tides, and appears to be more consistent with our hypothesis that ponded microatolls would still record diedowns which agree in timing with the 18.61-year tidal cycle.

[Diedown and growth sequences from Belitung](#)

Slab TKEL-M1 on Belitung Island revealed a 64-year sequence of growth (Fig.3.13). The first preserved diedown occurred in late 1968, and three more diedowns followed in mid-1985, mid/late-1990 and mid-2005. All of the diedowns are coincident with the 18.61-year tidal cycle. Though the diedown in 1990 appears to result from only a minor lowering of the low tide, overall the correlation with the 18.61-year tidal cycle appears robust.

Slab TKUB-M1 revealed an 85-year sequence of growth. Diedowns occurred in 1938-1939, 1959–1960, mid-1970, 1976, 1982, early-1988, late 1995, mid-2004, late 2006 and early 2009. The coral microatoll is ponded up on the reef flat, ~30 cm above its open water counterpart (TKUB-M2) at the same site. The ponding, apart from becoming apparent at low tide in the field (Fig. 3.14), is evidenced by the multiple

diedowns in 1938-1939, 1958-1960, 1976, 1995 and 2009 which are all inconsistent with the 18.61-year tidal cycle. Factors other than the tidal cycle may cause extra diedowns which do not fit the tidal cycle, however multiple such diedowns on one coral suggest ponding.

Figure 3-13 Same as **Figure 3-11**, for Belitung. Again, open water microatolls (TKUB-M2 and TKEL-M1) tend to have diedowns when low tides are falling or reach their lowest elevations. The ponded microatolls (TKUB-M1) records additional diedowns not anticipated considering the 18.61-year cycle. Microatolls TKUB-M1 and TKUB-M2 are plotted in the same elevation frame demonstrating how much higher ponded microatolls can grow. TKEL-M1 is not plotted on the same elevation reference frame and neither is the tidal prediction.

Slab TKUB-M2 revealed a 79-year sequence of growth. Diedowns occurred in late 1971, early 1988, late 1990 and mid-2005. Two more diedowns may have occurred sometime around 1964 and 1986; however due to later regrowth obscuring the tops of these areas it is not possible to confirm the HLG drops in the slab are ring features that are

continued in other parts of the microatoll. Therefore, we cannot exclude the possibility of these being irregularities in HLG which occurred in the part of the microatoll which was slabbed. Two of the diedowns (1971 and 1990) occur at times when only small drops in low tides occurred during the half of the 18.61-year tidal cycle, therefore when elevations of low tides were rising. One diedown, 1988, occurs near the bottom of an 18.61-year cycle but in a year when the predicted low tide is 3.1 cm higher than the previous year. Thus, although diedowns on TKUB-M2 appear to first order appears to anticipated by the 18.61-year tide cycle, the correlation is not as robust as for TKEL-M1. The imperfect fit may either be a result of variability in coral behavior which we do not fully understand: for example, successive daily low tides occurring during a particularly hot or sunny period may cumulatively stress coral more than one low tide which dips a few cm lower but comes on a cloudy day. Other possibilities are either temporal (band counting) uncertainty, or the tidal prediction for Belitung may not be as well constrained as that for Mapur.

Figure 3-14 Microatoll (TKUB-M1) Belitung, Indonesia, which is growing in a pond clearly separated from the open ocean on the horizon. All microatolls growing in the foreground of this photo are likely ponded to some degree. The reef crest cannot be seen in this photo but while searching for open water microatolls we followed it along the site, roughly 10-30 meters seaward from where the last corals visible in the photo break the water surface. Note that the part of the coral growth is exposed above the water level. All corals can withstand some exposure above water without severe negative effects. Diedowns on both ponded and open water microatolls occur as a result of water level dropping below this tolerated level, with other factors such as temperature, UV rays, precipitation and time of day all playing a role.

The open water microatolls from Belitung appear to diedown in each 18.61-year cycle, as expected, but the fit is not perfect, particularly for TKUB-M2. This indicates either a mismatch between the coral and the tidal prediction, or more variability in the diedown behavior than we generally understand. It is perhaps, not an observation we should make too much out of, considering the fact that all diedowns on the open water corals from Belitung do still occur near the low point of the 18.61-year tide cycle, hence they could also be explained by sea level anomalies.

In the case of TKUB-M1, diedowns are recorded when low tides are near their lowest elevations 1970, 1988, 2004, 2006, but other diedowns in 1938-1939, 1959-1960, 1976, 1995 and 2009 are not anticipated from the 18.61-year tidal cycle, suggesting the microatoll is ponded. It is intriguing that, although ponded, the microatoll is nonetheless influenced by the lowest tides of the 18.61-year cycle. This may be because the pond in which it grows is not completely isolated from the open ocean and during the lowest tides of the 18.61-year cycle it too has more time for the water to seep out. It is worth mentioning that the elevation loss as a result of these diedowns is small (<3 cm). We find this to be consistent with our hypothesis that a coral microatolls growing in at least some ponds would still record diedowns at times of particularly low tides but that the amplitude would be dampened by the ponding.

Sea level

The only coral we sampled from an open water location in Mapur was PMPR-A-M1. This coral shows little or no sea level change over its lifetime (Fig 3.11). Neither of the ponded coral microatolls from Mapur shows the same or even similar result nor are they in agreement with each other, which may be expected if each microatoll grew in a separate local pond. PMPR-A-M2 indicates that the sill of the lagoon at Mapur North is getting higher rapidly, rising more than 4 mm annually, while the sill of the lagoon in which PMPR-B-M1 is building up at a more modest 1.44-2.08 mm annually. Although I note that the same effect may possibly result from cementing of pond sills which would lead to less water loss during low tides. What is interesting about the sea level signals

at Mapur is that sea-level rise recorded by tide gauges in the Singapore Straits has been reported at 1.2-1.7 mm between 1975 and 2009 and increasing to 1.9-4.6 mm/y in the most recent (1993-2009) part of that period (Tkalich et al., 2013). Had ponding not been identified, both of the ponded corals could be treated as evidence for this. While the only coral we sampled in an open water location indicated no net sea-level rise over its ~90-year record.

Both open water microatolls from Belitung demonstrate a trend of rising sea level, though they record slightly different rates of sea-level rise. The ponded coral again does not record the same sea level record as the open water coral microatolls. Its record shows that over the years the diedowns i.e. the water levels around the coral microatoll actually drop, though this drop is <1 mm/yr in scale. The sea-level rise recorded by TKUB-M2 and TKEL-M1 vary between 1.6 ± 2.11 and 4.7 ± 2.16 mm/yr. This is within the range of 2-5 mm/yr reported around the island of Belitung (Cazenave and Llovel, 2010). It should be noted however, that the four recorded diedowns on each of the open water microatolls from Belitung cover periods of 35-38 years and may be insufficient to establish a precise sea-level trend

Table 3-3 Sea Level Record from sampled Microatolls, Sea level change calculated separately from diedown elevations and from highest HLG elevations shortly prior to diedowns following methodology of Meltzner et al. (2012).

Microatoll	Sea level change mm/yr Diedowns	Error in mm	First year of record	Last year of record	Duration of record in years	Sea level change mm/yr HLG	Error in mm	First year of record (first diedown)	Last year of record (last diedown)	Duration of record in years
PMPR-A-M1	0.01	±0.89	1915	2005	90	0.00	±0.87	1912	2004	92
PMPR-A-M2 Ponded	3.98	±2.22	1973	2009	36	3.39	±2.22	1973	2009	36
PMPR-B-M1 Ponded	2.08	±2.67	1982	2012	30	1.44	±2.50	1979	2011	32
TKUB-M1 Ponded	0.39	±2.05	1970	2009	39	0.50	±1.95	1968	2009	41
TKUB-M2	3.79	±2.29	1970	2005	35	4.70	±2.16	1968	2005	37
TKEL-M1	2.97	±2.16	1968	2005	37	1.60	±2.11	1967	2005	38

Discussion

The hypothesis, that coral microatolls record changes of water level around them appears to be well supported by the results of our study. We can see in the comparison of microatolls from both Mapur and Belitung, the corals appear to respond to every 18.61 year cycle they live through. With the exception of two earliest cycles from PMPR-A-M1's record, the evidence of which has likely been destroyed by erosion.

This hypothesis is further bolstered by a comparison of the actual sea level record of TKEL-M1 and TKUB-M2. Despite the fact that the two corals come from sites close to 20 km apart their record is remarkably consistent. Not only is the overall shape of both coral growth curves very similar but both corals show similar sea levels within error range. A ~1-2.5-millimeter difference in the mean annual sea-level trend between the two microatolls is likely the maximum precision we can achieve with this method without longer coral records, 50 years being minimum time to record a sea level trend (Douglas, 1991).

PMPR-A-M1 from Mapur shows negligible (0.01 ± 0.89 mm/yr and 0 ± 0.87 mm/yr) sea-level change over the 91 and 93 year periods (1915-2005 and 1912-2004), there are no tide gauges with long enough records to serve as a comparison near to Singapore. Church and White (2011) calculated a sea-level trend for a similar (1900-2009) period globally at 1.7 ± 0.2 mm/yr. On the other hand a lower rate ($0.23-0.33$ mm/yr)

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calculated by Smithers and Woodroffe (2001) is in agreement (within error) with that calculated from Mapur. Caution is necessary when comparing the three calculations, Church and White (2011) calculated a global sea level trend while both the Smithers and Woodroffe rate, calculated for the Cocos Islands, and the Mapur calculations are for local sea level. There is no reason to believe the two local trends should agree with a global trend, particularly since much of the data for the first 40 years of the Church and White (2011) calculations is mainly from temperate regions. It is also difficult to claim the match between Cocos Islands and Mapur is more than a coincidence.

Figure 3.15 shows a comparison of RSL from four tide gauges in Singapore and southern Malay Peninsula (Holgate et al., 2013; Permanent Service for Mean Sea Level, 2017) with that of PMPR-A-M1. Because only diedowns represent HLS the five records in the figure are all normalized with their observation from 2005 set as 0. Unfortunately, only one other diedown from PMPR-A-M1 (in 1986) was recorded in the period from which tide gauge records were available, but it matches the records within its error value (1 sigma). A sea level trend calculated from the microatoll over just this period (1986-2005) based on the two diedowns is 2.08 ± 4.44 mm/yr and matches a trend calculated for 1984-2009 from Singapore tide gauges by (Tkalic et al., 2013) of 2.05 ± 0.25 mm/yr. Of course, over such a short period the microatoll error is very wide, still this raises the possibility, if the PMPR-A-M1 record is to be believed, that sea level rise near to Singapore may have begun much later than the global average. We did not sample another open water microatoll near enough to PMPR-A-M1 to allow a verification of the sea-level trend, but if we look at the shape of the

growth curve of PMPR-B-M1 we will see a lot of similarity. The two coral microatoll's do not exhibit marked similarity in timing of diedowns (only 2005 may be a direct match), despite this the overall rise and fall of HLG on the two sequences is similar in timing. This may be an indication that these two coral microatoll's, eight kilometers apart and in different settings, show some similarity despite not matching in the timing of most diedowns. Such a similarity of morphology may indicate some open water signal is being preserved in the ponded PMPR-B-M1 although the small scale of elevation loss at each diedown (<3cm) suggests that that signal is being dampened by the ponding.

Calculating a sea level trend based on coral microatolls may be challenging. In locations where water levels are controlled by the 18.61 year tidal cycle an absolute minimum length of record would have to span a period of more than one such cycle, and be bounded by at least two preserved diedowns. This, however, only assures that the recovered record tracks the sea levels. Recovering the sea level trend usually requires records of at least 50 years (Douglas, 1991), thus, to recover the sea level trend from a coral microatoll a sequence longer than 50-years bounded by diedowns would be required, as in the case of PMPR-A-M1. In the case of PMPR-A-M1 we have demonstrated that it is in good agreement with the 18.61– year tidal cycle, and that over the period tide gauge records are available the microatoll is in agreement with them. We have also recovered a sea level trend, however there are no tide gauge records long enough near Mapur to confirm the entire length of the record.

Our second hypothesis was that the record from ponded corals cannot be used for sea-

level reconstructions. For Mapur the open water coral microatoll (PMPR-A-M1) shows little or no sea level change while both ponded coral microatolls show the water level around them is rising. If we compare only that part of PMPR-A-M1 which overlaps with the ponded corals then their rates overlap, however, because of the wide error, at that point PMPR-A-M1 overlaps within error with every other coral in the study. Such wide errors emphasize the fact that longer records are need in order to extract reasonable trends which can be compared with tide gauges or other microatolls. Conversely in Belitung the open water coral microatolls both show clear sea-level rise while the ponded coral microatoll shows almost no change in water levels around it over its lifetime.

Figure 3-15 Comparison of RSL from tide gauges in Singapore and south of Malay Peninsula with RSL from PMPR-A-M1. On a coral microatoll growth sequence only diedowns (HLS) are observations of sea level, the other points on the sequence represent only a sea level minimum. However, the overall similarity of the microatoll shape to the annual mean sea level of the tide gauges suggests a robust match between the two data sources.

One of the issues with using ponded coral microatolls' sea level record is the extra diedowns they exhibit. All of the ponded coral microatolls exhibit diedowns which cannot be explained easily by the tidal record. These may result from changes in the level of the sill of the pond the corals live in, or from other factors such as periods of particularly hot weather or wind driven water level anomalies. Ponded coral microatolls growing on the reef flat, at higher elevation, tend to be separated from open-water sea level in smaller water bodies for longer periods than their open water counterparts. As a result, they may be affected by water-level anomalies more easily than open-water microatolls. The extra diedowns, not resulting from the 18.6-year tidal cycle, introduce data points in the record which do not reflect the open-water sea level thereby introducing artifacts into their sea-level record. As a result, these corals should not be used for sea-level trend calculations.

Finally, ponded corals should not be used to reconstruct sea-level changes because they can grow tens of centimeters above the level of the open water coral microatolls. In Mapur this difference is about 50 cm at the start of the record, between PMPR-A-M1 and PMPR-A-M2, and actually grows by nearly 20 cm over its forty-year life time (Fig 3.11). In Belitung, the difference between TKUB-M1 and TKUB-M2 is ~40 cm in the 1960ties and decreases by 15 cm by the time the coral microatolls were sampled (Fig 3.13).

The confirmation that ponded microatolls should not be used to reconstruct sea-level trends is important because ponding is not always easy to recognize in the field. For example, although the PMPR-B-M1 microatoll grew in a lagoon which did not appear to be cut off from the sea at any of the low tides (some of that lowest that year) in either 2012 or 2013, based on the extra diedowns it is likely that the coral was indeed ponded, and its sea-level trend is different to that from an open water microatolls 8 km away at Mapur North. It is likely that any constriction of water outflow during lowering tides alters the timing of tides experienced by microatolls, potentially shortening the periods of or raising water levels of the lowest tides at the site. Such complexity has been previously reported for microatolls growing within the lagoon of the Southern Cocos Islands (Smithers and Woodroffe, 2000). Of the studies which attempted to study modern sea level change, some appear to have run into the problem of unrecognized ponding resulting in a variety of sea-level trends recovered from the same site (Flora et al., 2009). This variety is more likely to be representative of the changes in ponding heights of the individual microatolls measured.

Our final hypothesis was that despite the differences, the ponded coral microatolls would show some diedowns which do correlate with the 18.61-year tidal cycle, though only temporally. We hypothesized this because it is unlikely that a pond sill made of materials such as sand or loose coral would be fully water tight. During lower excursions of the tides the pond would be above the open water level for longer, thus there would be more time for water to leak out. Which means that we would still expect a diedown for the lowest sections of each 18.61-year cycle, though dampened

by the ponding. This hypothesis appears to be true. All three ponded microatolls appear to still respond to each 18.61- year tide cycle they live through. This observation is important because the coral's apparent adherence to the pattern expected from the 18.61-year tide cycle could be confused for proof that they are not affected by ponding. Thanks to the comparison with the tidal prediction however, we also see that these microatolls also show a series of extra diedowns which do not result from the tidal cycle and we infer that, a sea-level trend cannot be recovered from such microatolls.

Conclusions

Our evidence demonstrates that open ocean microatolls do track the sea-level history of the region where they are growing. Numerous other factors may alter the timing of diedowns so good knowledge of individual sites, the tidal and oceanographic processes, and local bathymetry is necessary.

Further, our evidence shows that ponded coral microatolls can respond to the 18.61-year tidal cycle, however, the elevation element of such diedowns is dampened, hence, unreliable as a sea level proxy. Additionally, the diedown record from ponded microatolls is 'polluted' with additional diedowns which do not result from the tidal cycle. Our evidence also shows that ponded microatolls also grow significantly above the elevation of the open water microatolls. These observations suggest that while using ponded microatolls may in some cases be possible, with regards to RSL heights, provided a sufficiently large error range is applied, the use of ponded microatolls for

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reconstruction of sea-level trends is ineffective.

The effects on local sea level of the IOD, ENSO, and the monsoon must be understood at each site for a realistic interpretation of the results. More research is necessary to fully understand the duration of a low water event necessary to cause a microatoll diedown, including under different atmospheric and light conditions.

Ponded microatolls do not show an accurate sea-level history, great care should be taken to ascertain that the corals sampled were not ponded. Signals from one coral should be confirmed with others which are not within the same local setting, including lagoons, no matter their size. In cases where this cannot be done the possibility of ponding should be assumed. For fossil microatoll studies where a comparison to living HLS is required we recommend the full HLS range on a site is surveyed and the open water (usually lowest) growing microatolls are used, unless it appears they have tilted or slumped down. The outside, seaward, side of a reef crest is a good place to look for coral microatolls with an open water signal. As far as we are aware, all coral microatolls growing landward of the reef crest at both Mapur and Belitung sites are currently ponded to some degree, regardless of reef flat or lagoon setting.

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Supporting Information for Chapter 3

Supplementary figure 2 Section of coral microatoll PMPR-A-M1 after the annual bands and diedowns have been marked

Supplementary figure 3 Section of coral microatoll PMPR-A-M2 after the annual bands and diedowns have been marked

Supplementary figure 4 Section of coral microatoll PMPR-B-M1 after the annual bands and diedowns have been marked

Supplementary figure 5 Section of coral microatoll TKEL-M1 after the annual bands and diedowns have been marked

Supplementary figure 6 Section of coral microatoll TKUB-M1 after the annual bands and diedowns have been marked

Supplementary figure 7 Section of coral microatoll TKUB-M2 after the annual bands and diedowns have been marked

Chapter 4 Relative sea-level proxy records from fossil coral microatolls in Western Borneo, South China Sea: Sea-level stability around 7 ka and possible Holocene faulting

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Abstract

The spatial variability of Holocene relative sea level (RSL) in the South China Sea is poorly known, with data restricted to Thailand, the Malay Peninsula, and a few other isolated sites. In this study, we present new continuous RSL proxy records for Borneo using surveyed and U-Th dated fossil coral microatolls from four sites in western Sarawak. We present a continuous 450-year record of RSL from ~7450 to 7000 years BP. Our data suggest that RSL was higher than present and rapid RSL rise had ceased by 7450 years BP. We compare these RSL reconstructions with a regional model of glacio-isostatic adjustment (GIA). The RSL reconstructions from three sites off the coast

of Sarawak show a gradient sloping in the opposite direction to that predicted by the GIA model. This disagreement can best be explained by tectonic deformation since 7000 years BP, which was previously unrecognized: we propose vertical offset of ~1.1 m due to slip on the Serabang fault, which runs between our four sites. This slip may have occurred in response to the loading of the Sunda Shelf by rising sea level.

Keywords

Coral microatolls, Borneo, Holocene highstand, GIA models, relative sea level, Serabang fault, Borneo tectonics

Introduction

Reconstructions of Holocene relative sea level (RSL) provide context for projections of the magnitude and rate of future sea-level rise (Dutton et al., 2015). Changes in RSL, which is defined as the height of the ocean surface relative to the land surface or ocean floor (Khan et al., 2015), are not globally uniform (Milne et al., 2009). RSL is influenced by a combination of factors that act over a variety of spatial and temporal scales (Shennan and Horton, 2002). At regional scales, glacio- and hydro-isostasy, ocean dynamics, and tectonics are the main processes driving the RSL signal over Holocene timescales. At local scales, tidal regime changes and sediment consolidation can influence RSL records. Reconstructions of RSL in low latitudes, far from major glaciated locations, are referred to as far field (Pirazzoli and Pluett, 1991); in these locations, eustatic contributions to RSL change generally exceeded glacio-isostatic contributions during the early and mid Holocene (e.g., Lambeck et al., 2014). The RSL reconstructions

of many tectonically stable far-field locations are characterized by a mid-Holocene RSL highstand, at the time meltwater production decreased (e.g., Angulo and Lessa, 1997; Baker and Haworth, 2000; Grossman et al., 1998; Hanebuth et al., 2011; e.g., Lambeck et al., 2014). The timing and magnitude of the highstand can be used to provide information about the nature of the end of melting of the global ice sheets. Following this highstand, the fall in RSL to present is due to a combination of hydro-isostatic loading (continental levering) and a global fall in the ocean surface due to equatorial ocean siphoning, i.e. a flow of water away from far-field regions and into collapsing forebulges near formerly glaciated regions (Mitrovica and Peltier, 1991; Milne and Mitrovica, 2008).

The Sundaland is located in Southeast Asia, comprising the Malay Peninsula and parts of Thailand, Borneo, Sumatra and Java. It is assumed to be relatively tectonically stable, based in part on GPS studies (e.g., Simons et al., 2007). Over this region (Fig. 4.1), there is considerable variability in the timing and amplitude of the Holocene highstand (Fig 4.2), with estimates of the timing between 7000 and 4000 years BP and amplitudes of 1 to 5 m above present (Horton et al., 2005: (and references there in); Bird et al., 2007; Bird et al., 2010; Parham et al., 2014). The variability of the mid-Holocene highstand is supported by a glacial isostatic adjustment (GIA) model of Bradley et al. (2016) which showed variability in RSL of more than 4 m at different locations on Sundaland at 7000 yr BP. The model is calibrated to RSL reconstructions from China, Thailand, and the Malay Peninsula and it is unknown whether it is applicable elsewhere in the South China Sea.

Figure 4-1 Map of Southeast Asia with the approximate borders of the tectonically stable Sundaland outlined, after Simons et al. (2007). Roman numerals show study sites, arranged by regional grouping. I – Sarawak sites: this study; II – Malay Peninsula and Singapore studies: Geyh et al. (1979), Tjia (1996), Hesp et al. (1998), Kamaludin (2002), Horton et al. (2005), Bird et al. (2007, 2010); III – Strait of Makassar: Mann et al. (2016); IV – Belitung: Meltzner et al. (2017); V – northern Java: Azmy et al. (2010). Solid circles show locations of sites discussed while circles with dark outline represent other RSL studies on or near Sundaland not discussed in this paper (Chaimanee et al. 1985; Scoffin and Le Tissier, 1998; Sinsakul, 1990; Somboon, 1988; Somboon and Thiramongkol, 1992; Thiramongkol, 1984; Tiyaipunte and Theerarungsikul, 1988). White arrows are rates of motion, based on GPS velocities over a ten-year period from 1994 to 2004. Inset shows detailed locations of our sites (solid circles) and approximate location of the Serabang Line (dashed line) based on Hutchinson (2005).

Figure 4-2 RSL history on the Malay Peninsula is characterized by a spatial difference in the timing and height of the mid-Holocene relative sea-level (RSL) highstand: note higher RSL on the west coast of the Malay Peninsula. Original data from Geyh et al. (1979), Tjia and Fuji (1992), Bird et al. (2007, 2010), and Kamaludin (2002). Indicative RSL meaning of some data and errors plotted as reinterpreted by Horton et al. (2005).

Here, we produce a continuous 450-year proxy RSL record (~7450 to 7000 years BP) using coral microatolls from three sites in western Sarawak, Borneo (Fig. 4.1). This record is supplemented with additional proxy RSL data from younger (~6230 to 6040 years BP) microatolls at a fourth site. We compare RSL reconstructed from fossil microatolls with RSL elevations predicted by a GIA model. The comparison, along with predictions of the gradient of RSL heights in the region, implies that the sites were subject to post formation elevation changes. We discuss potential sources for the changes and deduce that they are likely related to previously unknown tectonic

movement on the Serabang Fault. Finally, we correct the RSL data for the tectonics and present a new RSL record for this previously unexplored region.

Study area

The western Sarawak coast of Borneo is located on the Sundaland block (Fig. 4.1 inset), and is considered to be tectonically stable with very small internal deformation based on a decade-long study of GPS motion records from Southeast Asia (Simons et al., 2007). This region is characterized by broad coastal/alluvial plains, wetlands vegetated by nipa palms, mangroves, and intermittent bedrock headlands (Mumby et al., 2001). The spring tidal range in Sarawak ranges from 2.9 to 5.8 m (Staub and Gastaldo, 2000) and tidal influence extends far inland in estuarine and fluvial systems. The tides have a dominant semidiurnal component (Staub and Gastaldo, 2000; Lim and Koh, 2010). Regional rainfall averages 3700 mm year⁻¹ and primarily falls on the steep interior slopes of the major river drainages (Staub and Gastaldo, 2000), which build extensive deltas at the coast. Where bedrock headlands and islands occur along the western Sarawak coast, they comprise bedded sedimentary rocks of Jurassic to Neogene age, and some metamorphosed, as well as igneous intrusive and extrusive rocks (Hutchison, 2005).

We reconstruct RSL using microatolls from three islands off the coast of Sarawak (Satang Besar, Talang Besar, and Talang Kecil) and a fourth site on the northwestern Sarawak mainland (Tanjung Datu) (Fig. 4.1 inset). The largest of the three islands is Satang Besar, with an area of approximately 0.5 km², whereas the smallest is Talang

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Kecil, with an area of 0.1 km². On all three islands, fringing reefs are developed on the southwestern shores. Fossil microatolls are located on the modern (living) reef flats, with each microatoll growing directly on a rock platform; higher parts of the reef flats are exposed at low tide, and the lower parts are today colonized mainly by *Coelastrea aspera* and soft corals. Unponded living *Porites sp.* microatolls occur in a narrow (>25m) band along the seaward edge of these platforms.

The fourth site (Tanjung Datu) is on the Tanjung Datu peninsula, northwestern Sarawak, approximately 21 km northwest of the Talang Islands (Fig. 4.1 inset). Unlike the three islands, the fringing reefs at Tanjung Datu face northeast and more frequently exposed to higher energy waves and stronger currents which result in increased seawater turbidity. Consequently, while there is healthy coral growth, surveying corals at this site proved challenging. As at the other three sites, the microatolls here established directly on solid rocky substrate, and reef zonation and structure appear to be similar to those found at the island sites. Unlike other sites, however, the reef flat at Tanjung Datu is relatively narrow (>50 m) (i.e. limited platform for horizontal coral growth). *Coelastrea aspera* and soft corals can be found growing highest along the shoreline and are hence exposed first during low tides, followed by *Porites sp.* microatolls seawards at the edge of the reef flat. All sites are located away from large rivers and on the seaward edges of the reef flats, ensuring an abundance of well-preserved microatolls from which clear RSL histories can be extracted.

Reconstruction of relative sea level

Coral microatolls

Fossil coral microatolls are an accurate and precise RSL indicator (Scoffin et al., 1978; Meltzner and Woodroffe, 2015) and have been applied globally (Woodroffe and McLean, 1990; Smithers and Woodroffe, 2000; Nunn and Peltier, 2001; Woodroffe and Murray-Wallace, 2012) and regionally in the South China Sea (Azmy et al., 2008; Yu et al., 2009; Mann et al., 2016; Meltzner et al., 2017) to produce sea-level index points (SLIPs). A coral microatoll is formed when a coral colony reaches a vertical growth limit constrained by a combination of exposure to ultraviolet (UV) light, heat and desiccation during low tides (Scoffin et al., 1978; Brown et al., 1994; Scoffin et al., 1997). The level up to which a coral microatoll grows is called highest level of growth (HLG), while the elevation above which its polyps die during low water, is called the highest level of survival (HLS). If polyp death occurs at a uniform elevation around the perimeter of the microatoll, it is a clear indication that it was caused by low water levels (Taylor et al., 1987; Meltzner et al., 2017; Meltzner and Woodroffe, 2015). While the upper surface of the coral dies and vertical growth is halted, horizontal growth continues, over time producing a variable surface morphology (Meltzner and Woodroffe, 2015).

The exact morphology of the upper surface of a microatoll is controlled by RSL. If RSL is rising, the coral polyps will not be vertically constrained and will grow upwards until they are limited again. Microatolls growing in rising RSL tend to have lower centers

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(the oldest part of the coral) and higher outer rings, and vice versa in conditions of falling RSL. If water levels remain stable the microatoll will tend to form a flat surface. Microatolls can continue recording the RSL for decades or centuries as long as there is accommodation space for their continued growth. Using fossil microatolls it is possible to reconstruct RSL change through a comparison of the elevation of living and fossil specimens at the same site, in the same manner as other fixed biological indicators (Laborel and Laborel-Deguen, 1996; Rovere et al., 2015).

Superimposed on the long-term RSL trends are periodic fluctuations in the lowest tides that are related to the 18.6-year nodal tidal cycle. In places where the nodal tidal cycle is significant, these fluctuations result in concentric rings on a microatoll's upper surface (Meltzner et al., 2017). The nature of this cycle typically results in at least one diedown and raised ring on the microatoll surface per 18.6-year cycle.

HLS is influenced by physiology of the coral, as well as wind, insolation, ponding and other factors which affect polyp survival during low tides (Brown et al., 1994; Scoffin et al., 1997). Because of these influencing factors, HLS is not uniform throughout a reef, but rather exhibits a range. Ponding refers to instances whereby coral microatolls growing in lagoons and ponds are cut off from the open sea for part of the tidal cycle, and are thus protected from the lowest water levels. As a consequence, the growth patterns of these ponded microatolls do not reflect the full tidal cycle and sea level, but rather record the water level changes of the pond or lagoon in which they are growing (Scoffin et al., 1978).

Field surveys.

We selected 27 living and 10 fossil massive *Porites* *sp.* microatolls from our four field sites to reconstruct RSL. Locations of selected fossil and modern microatolls were determined using a Garmin GPSMAP 64 global positioning satellite system. Elevations of the surface morphology of the living and fossil microatolls at all three island sites were surveyed using a Leica TCRP1203 total station. The microatolls from Tanjung Datu were surveyed (relative to living microatolls) with a low-tech method devised by Emery (1961) using measuring staffs and the horizon as a back sight. Later work by Krause (2004) demonstrated that the accuracy of the 'Emery method' is comparable to instrumental surveys on short (<60 m) distances.

U-Th dating of microatolls

We collected a ~10 cm core (2 cm diameter) from the top surface of each targeted fossil microatoll. The cores were then fragmented and the cleanest, deepest part of the cores were sampled for U-Th dating. Only samples that did not have visible recrystallization were used. All samples underwent ultrasonic cleaning at least three times in deionized water before further chemical cleaning. Procedures for chemical separation and purification of uranium and thorium are similar to those described by Edwards et al. (1986) and Cheng et al. (2000). The samples were dated at the Earth Observatory of Singapore, Nanyang Technological University, on a Finnigan NEPTUNE plus MC-ICPMS following the procedures by Cheng et al. (2013). We calculated

corrected ^{230}Th ages using an initial $^{230}\text{Th}/^{232}\text{Th}$ value of $6.5 \pm 6.5 \times 10^{-6}$ (atomic ratio) (Shen et al., 2008). This number is applicable to most of the corals in continental shelf settings (Shen et al., 2008; Clark et al., 2012). All the secondary electron multiplier biases, spectral interferences, chemistry and instrumental blanks, and corrections for spike composition are calculated in an off-line data reduction process (Cheng et al., 2013). Uncertainties in the U-Th isotopic data and ^{230}Th dates are calculated at 2σ level or two standard deviations of the mean, details of U-Th dates are shown in Table 4.1

Growth reconstructions of fossil microatolls (Fig. 4.3) were based on the dated samples from each microatoll and the detailed surveys of surface topography. The lifespan of each *Porites* microatoll was estimated based on its size, and an average linear growth rate of 1 cm year^{-1} as measured from several modern massive *Porites* sp. colonies cored from the Talang Besar and Tanjung Datu study sites.

Determining RSL from HLS

To reconstruct RSL, the HLS must be measured on both fossil and living microatolls at any given site. The difference in elevation between fossil and living HLS is then used as a proxy for past RSL. However, since HLS is also influenced by factors other than RSL that affect coral polyp survival during low tides (e.g. coral physiology, wind, insolation, ponding), a range of values for HLS is usually found for a reef (Brown et al., 1994; Scoffin et al., 1997). To minimize the likelihood of including ponded living microatolls in our study, we selected only microatolls along the outside edge of the reef flat i.e. where the reef crest begins. The HLS elevations of living *Porites* sp. microatolls were

measured at Satang Besar (n=10), Talang Besar (n=7) and Talang Kecil (n=10) to calculate an average HLS for each site, which was later compared to the elevations of fossil microatolls on each respective site. At Tanjung Datu we were unable to locate living *Porites* microatolls. Instead, we measured the elevation of the fossil *Porites* sp. in relation to a living microatoll of *Coelastrea aspera*. On all three island sites we surveyed, *Coelastrea aspera* corals consistently grew higher than any open water *Porites* sp. microatolls. Therefore, the difference between fossil *Porites* sp. HLS and living *Coelastrea aspera* HLS provides a minimum value for past RSL at Tanjung Datu.

Uncertainty in RSL includes errors from several sources, which were added together in quadrature. We did not have sufficient HLS measurements at each site to conduct a full statistical analysis; therefore we conservatively applied a wider vertical error of ± 0.18 m (2σ) calculated by Meltzner et al. (2017) for living microatolls on Belitung Island, Indonesia, 600 km to the southwest. We counted this variability in HLS (± 0.18 m) twice due to the fact that it applies both to living and to fossil microatolls, and added an additional uncertainty to account for surveying precision (± 0.01 m) and erosion (up to 0.15 m). Fossil microatolls are commonly eroded, by an unknown amount, after their death. However, we selected microatolls with clear ring structure (e.g., Fig. 4.4) and thus conservatively estimated the error to be 0.10 m for all microatolls from Satang Besar, Talang Besar and Talang Kecil islands. A value of 0.15 m was used for the two Tanjung Datu microatolls because they were more weathered. Erosion uncertainty was only added to the positive elevation error resulting in asymmetrical ranges. The coral microatolls are considered compaction free because they grew directly upon

bedrock. Errors are listed in Table 4.1 and shown on Figure 4.3. All errors (both temporal and elevation) are given at 2σ .

Data from the four study sites are shown in Table 4.1 and Figure 4.3. The dated samples were taken near the highest and youngest portion of each microatoll, and an estimate of the difference (in years) between the dated part of the microatoll and the point when highest growth was reached is listed in Table 4.1. These differences are generally a few decades or less. The lifespan of each microatoll was also estimated – we calculated this based on the radius of the microatolls and by assuming a linear growth rate of 1 cm year^{-1} for all the fossil corals (i.e. similar to that documented for modern corals at the sites). The RSL history of each microatoll (Fig. 4.3) was reconstructed based on the microatoll's size, the elevations of its various concentric rings, and, again, an average linear growth rate. The microatolls at Talang Besar, and to a lesser degree (due to more erosion) at other sites as well, show regularly spaced concentric rings that occur roughly once every two decades; this would be consistent with influence from the 18.6-year nodal tidal cycle. Similar influence is seen elsewhere on the Sunda Shelf (Meltzner et al., 2017).

Table 4-1 Summary of U-Th age results and HLS observations in relation to living coral microatolls. All errors given at 2σ . Positive error range for Tanjung Datu corals is larger because they were more eroded, and it was further extended by 0.83 m which is the difference between HLS of the *Porites* and *Coelastrea* microatolls surveyed in the field. Errors were added in quadrature.

Site name	Sample name	Location Lat/Lon (decimal degrees)	^{230}Th age, corrected* (years BP)**	^{230}Th dating error (years)	Highest achieved after dated sample (years)	HLS	Estimated lifespan of microatoll (years)	Estimated beginning of RSL record	Estimated end of RSL record	Height above modern HLS (m)#	Vertical error (m)	HLS change over lifetime (m)	RSL (Height above modern HLS Corrected for tectonics) (m)♣	RSL error (Vertical error corrected for tectonics) (m)♣
Satang Besar	SRSB-F1	1.7800° N 110.1604° E	7129	±60	~22		~86	7193	7107	0.72	+0.27/-0.25	+0.047	1.45	+0.78/-0.77
	SRSB-F2	1.7801° N 110.1606° E	7182	±62	~36		~107	7252	7145	0.75	+0.27/-0.25	+0.042	1.48	+0.78/-0.77
Talang Besar	SRTB-F1	1.9125° N 109.7750° E	7026	±29	~16		~316	7325	7009	1.38	+0.27/-0.25	+0.090	0.65	+0.78/-0.77
	SRTB-F2	1.9126° N 109.7749° E	7016	±66	~10		~129	7135	7006	1.27	+0.27/-0.25	+0.063	0.54	+0.78/-0.77
	SRTB-F3	1.9122° N 109.7753° E	7094	±33	~10		~137	7221	7084	1.42	+0.27/-0.25	+0.016	0.69	+0.78/-0.77
Talang Kecil	SRTK-F1	1.8936° N 109.7677° E	7148	±26	~23		~314	7439	7125	1.50	+0.27/-0.25	+0.139	0.77	+0.78/-0.77
	SRTK-F2	1.8932° N 109.7676° E	7040	±26	~19		~256	7276	7020	1.50	+0.27/-0.25	+0.031	0.77	+0.78/-0.77
	SRTK-F3 ##	1.8935° N 109.7677° E	7046	±28	NA		NA	NA	NA	1.74	+0.27/-0.25	NA	NA	NA
Tanjung Datu	SRTD-F1	2.0593° N 109.6467° E	6128	±37	~20		~120	6228	6108	1.65	+0.88/-0.25	+0.2	2.38	+1.14/-0.77
	SRTD-F2	2.0593° N 109.6467° E	6062	±25	~20		~120	6162	6042	1.65	+0.88/-0.25	+0.2	2.38	+1.14/-0.77

* Age corrections were calculated using an estimated initial $^{230}\text{Th}/^{232}\text{Th}$ ratio of $6.5 \pm 6.5 \times 10^{-6}$ in atomic ratio.

** BP stands for “before present” where the “present” is defined as the year 1950 AD.

The height of the highest point on a microatoll, not the height of the dated sample.

##SRTK-F3 is not considered reliable and cannot be used as a SLIP but is included in the table for sake of completeness.

♣ For details of tectonic correction see discussion

Predictions of relative sea level

Bradley et al. (2016) extended a previously published global ice sheet model (Bassett et al., 2005), which was unconstrained from 10,000 yr BP to present. The new model was developed by comparing RSL predictions from the GIA model to SLIP data from China and the Thai-Malay Peninsula. Data-model misfits were examined for a range of eustatic sea-level scenarios and earth model parameters. The model is characterized by a slowdown in melting at ~7,000 yr BP, associated with the final deglaciation of the Laurentine Ice Sheet, followed by a continued rise in eustatic sea level until ~1,000 yr BP of ~5.8 m associated with melting from the Antarctic Ice Sheet. We chose to look at a wide array of plausible RSL predictions for seven earth models in the following range: (1) lithospheric thickness of 96 km; (2) upper mantle viscosity values from 1×10^{20} Pa s to 1×10^{21} Pa s; and (3) lower mantle viscosities of 1×10^{21} Pa s to 5×10^{22} Pa s (Table 4.2).

Table 4-2 Parameters of the six Earth models chosen for comparison with data.

Earth model parameters	96p28	9611	96p38	96p250	96p130	96p510
lithosphere thickness	96km	96km	96km	96km	96km	96km
Upper mantle viscosity	2×10^{20} Pa s	1×10^{21} Pa s	3×10^{20} Pa s	2×10^{20} Pa s	1×10^{20} Pa s	5×10^{20} Pa s
Lower mantle viscosity	8×10^{21} Pa s	1×10^{21} Pa s	8×10^{21} Pa s	5×10^{22} Pa s	3×10^{22} Pa s	1×10^{22} Pa s
CHI sq. Misfit*	15.61	16.99	18.75	20.72	22.05	25.47

* 95% confidence limit is 25.20, the misfit is calculated for Malay Peninsula - Thailand data set from Bradley et al. 2016

We predict RSL for the four study sites. The Talang Besar and Talang Kecil islands are treated as one region, because of their proximity to each other, whereas Satang Besar

and Tanjung Datu are predicted separately. We then compare the model predictions for the four sites with the RSL proxy results.

Results

Our samples from western Sarawak plot in three distinct groups: Satang Besar; Talang Besar and Talang Kecil; and Tanjong Datu (fig. 4-3). The Satang Besar and Talang groups overlap in time but not in elevation, whereas Tanjung Datu is both younger and higher than the others. The two fossil coral microatolls from Satang Besar grew between ~7253 and 7107 yr BP, and their HLS ranged between 0.64 and 0.76 m. Each microatoll shows almost no sea-level rise (<0.05 m) over its lifetime. The sampled corals from the two Talang sites grew over a longer period of time and partially overlapped with the corals from Satang. The oldest microatoll started to grow at ~7439 yr BP and the youngest grew until ~7006 yr BP. The Talang microatolls (excluding SRTK-F3) show little vertical spread of HLS, from 1.27 to 1.50 m, but each microatoll again shows sea-level stability, gaining at most 0.14 m over its lifetime. SRTK-F3 grew higher than other samples but it is considered unreliable (see discussion). Finally, our fossil coral microatolls from Tanjung Datu were roughly 1000 years younger than those at the other sites, growing from ~6228 until 6048 yr BP. They show the highest average HLS at 1.65 m and they gained the most (0.2 m) elevation over their lifetimes.

Figure 4-3 Relative sea-level (RSL) plots of 10 fossil microatolls from Sarawak, based on a dated sample from each microatoll, marked with black circles on plots (b) and (c), a detailed total station survey of each microatoll, and an estimated growth rate of 1 cm/y. Panel A shows the 2σ error bars for each data series; the error shown for each microatoll applies uniformly as absolute error to all points on the relevant curve in panel (b) or (c) (relative chronological and vertical errors between two points on the same curve are much smaller). Panel B shows data from Tanjung Datu (SRTD) and panel (c) shows data from Satang Besar (SRSB), Talang Besar (SRTB) and Talang Kecil (SRTK).

Satang Besar

The sample from *Porites* microatoll SRSB-F1 is ~7129 years old, and based on the width and estimated growth rate the coral appears to have had a lifespan of ~86 years, from ~7193 to ~7107 yr BP. At its highest the coral grew to 0.72 m above HLS of modern *Porites* on Satang Besar. It has a low center and higher outside rings indicating rising RSL. During its lifetime, the coral HLS rose by 0.05 m.

The sample from *Porites* microatoll SRSB-F2 dated to ~7182 yr BP making this the oldest dated sample of the study. This microatoll is also bigger than SRSB-F1 and grew for ~107 years, from ~7253 to ~7145 yr BP. At its highest the coral grew to 0.75 m above HLS of modern *Porites* on Satang Besar. It has a low center and higher outside rings indicating rising RSL. During its lifetime, the coral HLS rose by 0.04 m.

Figure 4-4 A six-meter-wide fossil microatoll (SRTB-F1) on Talang Besar Island shows clear rings resulting from many successive diedowns driven by the 18.6 year tidal cycle (Meltzner et al. 2017). Note that the outer rings are slightly higher than the center. A U-Th age of 7026 ± 29.1 years BP (before AD 1950) was obtained from the outer ring. With a growth rate of ~1 cm/yr. this microatoll likely holds a RSL record spanning ~320 years. Photo by Chiew Tyiin Ng.

Talang Besar

The SRTB-F1 (*Porites*) sample dates to ~7026 yr BP, but the microatoll has a radius of ~3.16 m (Fig. 4-4), suggesting it grew for ~316 yr, from ~7326 to ~7010 yr BP. At its highest the coral grew to 1.38 m higher than modern HLS at Talang Besar. It has a

slightly lower center than the outside rings, indicating rising RSL; over its life time the HLS rose by 0.09 m.

The sample from SRTB-F2 (*Porites*) dates to ~7016 yr BP. This coral lived for ~129 years, from ~7135 to ~7006 yr BP. At its highest the coral grew to 1.27 m higher than modern HLS at Talang Besar. The microatoll surface indicates a RSL rise during its lifetime. The measured HLS change over this period is 0.06 m.

The sample from SRTB-F3 (*Porites*) dates to ~7094 yr BP. The microatoll grew for ~137 years, from ~7221 to ~7084 yr BP. At its highest the coral grew to 1.42 m higher than modern HLS at Talang Besar. Like the other microatolls from the site it indicates a rising RSL during its lifetime, but the HLS change is minimal at only 0.02 m.

Talang Kecil

The sample from SRTK-F1 (*Porites*) dates to ~7148 yr BP. Given its size the microatoll grew for as much as ~314 years, from ~7439 to ~7125 yr BP, making it the oldest microatoll in this study. At its highest this microatoll grew to 1.50 m above modern HLS on Talang Kecil. Its surface is quite worn, but, like the other microatolls, it indicates RSL rise, its HLS gaining 0.14 m over its lifetime.

The SRTK-F2 (*Porites*) sample dates to ~7039 yr BP, and it grew for ~256 years, from ~7276 to ~7020 yr BP. Like SRTK-F1 it reached an elevation of 1.50 m above modern

HLS on Talang Kecil. Like SRTK-F1 it indicates rising RSL with a smaller elevation gain over its lifetime of 0.03 m.

The sample from SRTK-F3 (*Porites*) dates to ~7046 yr BP. This was the highest *Porites* coral found on the Talang Kecil site, with its highest point 1.74 m above modern HLS at the site. This coral, however, was largely covered with sand and boulders, so its morphology and lifespan are not known. Given that it was contemporary to SRTK-F2 but 0.25 m higher, there is high likelihood of ponding. Because of this and our inability to examine its morphology (because of heavy boulders covering it) we consider this microatoll to be a less reliable sea-level marker than SRTK-F2.

Tanjung Datu

The SRTD-F1 (*Porites*) sample dates to ~6128 yr BP, and thus this microatoll is ~1000 years younger than the microatolls at the other sites. It grew for roughly ~120 years indicating a lifespan from ~6228 to ~6108 yr BP. It reached an HLS elevation of 1.65 m above modern HLS on the site. It indicates rising RSL, with elevation gain over its lifetime of ~0.2 m.

The SRTD-F2 (*Porites*) sample dated to ~6062 yr BP, again being significantly (~1000 yr) younger than microatolls from other sites in this study. Its HLS elevation was the same as SRTD-F1 at 1.65 m above modern HLS at the site. It was also of a similar size to the other sampled microatoll from this site, and its lifespan is also estimated to have been

120 years, suggesting it was growing between ~6162 to ~6042 yr BP. Again, similarly to SRTD-F1, it indicated rising RSL, with a change over its lifetime of ~0.2 m.

Model prediction results

The GIA model shows the influence of continental levering on RSL across the region. At 7000 yr BP, the model predicts a gradient in RSL with Tanjung Datu in the west being the lowest and Satang Besar in the east being the highest (Fig. 4.5). Figure 4.6 shows RSL predictions for a range of earth models, with RSL rising steeply up to 7000 yr BP, slowing thereafter, and peaking at 5000 yr BP with an elevation of 0.80 to 3.10 m above present for the sites in our study for different earth models. At 7000 yr BP, a height of -1.00 to 0.75 m above present is predicted for the Talang Islands, and -0.30 to 1.55 m is predicted for Satang Besar. The RSL height at Tanjung Datu at 6000 yr BP is predicted to have been -0.25 to 1.70 m above present. The model scenarios and results are compared to the microatoll results in Figure 6 and are discussed in the next section.

Discussion

Differences in elevation between sites

All the GIA model scenarios considered in the study predict that RSL of fossil microatolls will be highest on the Satang site, lower on the Talang sites and lowest at Tanjung Datu (Fig. 4.5). However, when we compare elevation data between sites (Fig. 4.3 and Table 4.1), the opposite trend is reconstructed. Satang Besar is predicted to have the highest RSL at 7000 yr BP, and it should be higher than the Talang sites regardless of which earth model parameters are assumed. The 96p510 earth model,

which is the closest fit to our data, predicts Satang Besar to be ~ 0.75 m higher than the Talang sites, but instead our microatolls indicate RSL at Satang was actually ~ 0.7 m lower than at the Talang sites. The combined discrepancy of ~ 1.45 m requires an explanation.

Figure 4-5 Relative sea-level (RSL) predictions for west Sarawak at 7000 yr BP, based on Earth model 96p28 (parameters in Table 2). RSL increases from the northwest (Tanjung Datu) towards the southeast (Satang Besar), which is opposite to observations from fossil microatolls. Dashed line marks approximate location of the Serabang Fault.

Model predictions should not be accepted as fact, indeed depending on the parameters of the chosen earth model the Talang Islands is predicted to be 0.4 -0.9 m higher than Satang Besar, however all models (including Ice 5G by Peltier (2004)) show the same RSL gradient direction. Indicating that the explanation to the offset of the two islands from model prediction must be found elsewhere. In principle, sediment

compaction, unrecognized ponding of microatolls or tectonic deformation could all explain the difference from prediction. The first of these possibilities, sediment compaction, is unlikely at our sites because, as stated earlier, all microatolls grew directly on bedrock. We therefore focus on the other two possibilities and discuss each in turn.

Ponding is a possibility that should be investigated at any microatoll site, both for living and fossil specimens. In a ponded setting, microatolls grow higher than in the open sea, giving false information about RSL and its change over time (Scoffin et al., 1978; Majewski et al., 2015). As a result, ponding can impact the accuracy of comparisons between living and fossil microatolls.

We investigated the possibility of ponding of the fossil microatolls at Talang Besar and Talang Kecil since erosion might have removed barriers of sand, shingle or other corals that once protected the fossils from the open sea. If this was the case it would make the RSL proxies from these sites appear higher than RSL was in reality. While the Talang Kecil microatolls grew at the back of the reef flat, where corals are more prone to ponding (Scoffin et al., 1978), our survey of their upper surface revealed large vertical changes (>10 cm) between the highs and lows of the ring structure. In contrast, our observations of living microatolls in Sarawak and at sites in Indonesia suggest that ponded microatolls tend to have a flatter morphology, experiencing smaller but more frequent diedowns than open-sea microatolls. Therefore, we argue that SRTK-F1 and SRTK-F2 on Talang Kecil were unlikely to have been ponded. As noted earlier however (Table 4.1), SRTK-F3 was measured to be 24 cm higher than the other two microatolls

on this site and further landward. This leads us to believe SRTK-F3 was likely to have been ponded. Additionally, there is little loose coral rubble or other sediment loose on the studied sites, making it difficult to see how ponding could occur anywhere but the most landward edge of the reef. As may have been the case for the most landward sample SRTK-F3, which was largely covered with sand and boulders during our field visit, preventing us from examining its morphology. Hence, SRTK-F3 was excluded from further analysis.

On Talang Besar the fossil microatolls exhibit clear ring structure with rings ~ 0.2 m apart, which would be in agreement with an 18.6-year tidal cycle modulation if a typical growth rate of ~ 0.01 m/yr is assumed, as was measured to be the case with living *Porites* sp. coral at the site. This would suggest these microatolls grew in open water. They also grew closer to the seaward edge of the reef than the microatolls on Talang Kecil, which suggests that ponding is even less likely on this site. We therefore conclude that ponding of fossil microatolls on the Talang sites is unlikely to be the explanation for the difference between predictions and observed data.

If ponding of fossil microatolls is not the answer could ponding of living microatolls be the cause? If living microatolls were ponded, their observed elevations would be higher than HLS of open-water microatolls, and the apparent elevation of the fossil microatolls (relative to the ponded living HLS) would be biased low. However, ponding is easier to recognize in living microatolls than it is in fossils, and we have paid particular attention to ponding, picking living microatolls for comparison only from the

outer edge of the reef crest with no barrier between them and the reef slope. Hence we surmise that this possibility is also unlikely.

Having ruled out sediment compaction and ponding, we postulate that the observed differences in RSL may be explained by tectonic deformation, specifically vertical displacement along a fault. Although western Sarawak is considered to be tectonically stable (Simons et al., 2007), tectonic movement occurred on several faults in the region during the Lower Cretaceous (~100 myr) (Haile, 1973; Hall et al., 2008; Hutchison, 1975; Hutchison, 2014). The closest of these is the Serabang Line (Fig. 4.1, Fig. 4.5), as mapped by Hutchison (2005), which may be a western extension of the better-known Lupar Line (Liu et al., 1999). The location is only approximate and is based on early studies of the Serabang Formation on Tanjung Datu (Hutchison, 1973; Hutchison, 1975). Few details regarding this feature are available, though Haile (1973) postulated it to be a Lower Cretaceous subduction zone. A more recent geological and geophysical study (Williams et al., 1988) supports Haile's (1973) hypothesis of a former Cretaceous subduction zone in Sarawak. Further support comes from a model of the buildup of Borneo published by Hall et al. (2008). Alternatively, Mazur et al. (2012) and Zahirovic et al. (2014) both interpret the Lupar and/or Serabang line as either a suture zone or an inactive fault.

These studies argue for the existence of a former subduction zone in western Sarawak, but none of the studies have suggested present-day activity on the Serabang or Lupar lines. We postulate that the ~1.45 m differential between our sites results from a reactivation of fault motion along the Serabang Line. If this is true, it is perhaps not

surprising that such motion has until now gone unrecognized. Evidence for limited recent movement along this structure would have likely been missed by the aforementioned studies due to the fact that they focused primarily on bedrock, whereas young fault movement is typically best recognized in Holocene deposits. Similarly, Simons et al. (2007) would have been unlikely to resolve deformation along the fault since the required vertical displacement rates of $0.21\text{--}0.36\text{ mm yr}^{-1}$ would have been within the noise, given that these GPS arrays have an accuracy of $\sim 1\text{ mm yr}^{-1}$ (Simons et al., 2007).

Having established the most likely explanation for the unexpected offset between our sites to be tectonic deformation, one question is: why was the fault reactivated? We propose that the fault may have been reactivated due to changes in the stress field resulting from the flooding of the Sunda Shelf following the Last Glacial Maximum. During the rapid sea-level rise in the early Holocene, large parts of the Sunda Shelf were flooded, and the added hydrostatic load depressed and flexed the lithosphere viscoelastically. The lithospheric stresses induced by this flexure have been modelled by Luttrell and Sandwell (2010), and they showed that rupture of faults near the coastline can be promoted through a reduction in normal stress. Neves et al. (2015) had similar results but showed that the magnitude of the stress change depended upon the geometry of the fault in question. Although there is currently insufficient information about the geometry of the inferred Serabang fault to attempt such analysis, the above-mentioned studies demonstrate the plausibility of Holocene reactivation of the Serabang fault due to rising sea level.

Another question posed by the implication of tectonic movement is: where did most of the movement occur? A detailed plot of predicted RSL for all sites in this study (Bradley et al., 2016) (Fig 4.6) reveals that RSL observations from microatolls at the Tanjung Datu site and the youngest microatolls at the Satang Besar site plot within error of predicted RSL for their age and locations, for a subset of reasonable earth models. In contrast, the RSL observations from the microatolls on the Talang Islands consistently plot ≥ 0.5 m above the predictions. Thus, if the model predictions are correct they suggest that the southern side of the proposed Serabang fault, including the Talang sites, has been uplifted. If this is the case the uplift must have occurred sometime in the past 7000 years, after the Talang microatolls grew.

However, we note a general inconsistency between the GIA models (Bradley et al., 2016) and proxy RSL observations in Sarawak: whereas all models suggest rates of RSL rise exceeding 7 mm yr^{-1} prior to 7000 yr BP and rates of 1 mm yr^{-1} or greater from 7000 to 6000 yr BP (Fig. 6), the observations suggest comparatively stable RSL just prior to 7000 yr BP. The inference of near RSL stability (e.g., ~ 0.09 m of RSL rise over ~ 316 yr, as recorded by SRTK-F1) is robust: the extended period of limited RSL rise is captured in individual fossil microatoll records (Fig. 4.3) and is reproducible on multiple microatolls at multiple sites. The reproducibility of the record strengthens the inference because if some sites were moated their record could be expected to vary randomly from each other, rather than show similarity as is the case.

Figure 4-6 A comparison of relative sea-level (RSL) proxy data from microatolls with model predictions for each of our three site locations. Panels (a), (b) and (c) show a full range of earth model predictions for each site. Panel (d) shows a comparison of earth model 96p510 with microatoll data from the three sites. Note the agreement of microatoll observations and RSL predictions for the Satang Besar and Tanjung Datu sites and the discord between predicted and reconstructed RSL from the Talang islands. Also, note the rapid RSL rise predicted prior to 7000 yr BP, which is inconsistent with the microatoll proxy data.

It could be suggested that apparent RSL stability in coral microatolls could be caused by RSL rise due to GIA being balanced by interseismic tectonic uplift. However, a near identical match of uplift rates and rates of RSL rise due to GIA would require a remarkable coincidence; furthermore, it is difficult to conceive of a mechanism by which both sides of the fault would have simultaneous interseismic uplift. We therefore consider this idea to be unlikely.

One possible explanation for the inconsistency between the model (Bradley et al., 2016) and the microatoll data is that differences in resolution of the model (1000 year steps for the model, compared to roughly two decades between successive concentric rings on the top of each microatoll) or the short window of the microatoll records (~450 years) make the comparison impractical. Another possibility is that the model resolution may be insufficient to precisely predict the timing of the cessation of rapid RSL rise. Specifically, a slowdown in eustatic sea level rise, and hence in RSL, may have occurred earlier than assumed in the Bradley et al. (2016) model, as is assumed in the ICE5G model (Peltier, 2004).

This reasoning suggests that we might consider shifting the predictions earlier in time and comparing the shifted RSL predictions with the observations. If we compare the microatoll elevations with RSL predictions that are shifted 500 years earlier, then there is better agreement between the predicted and observed rates of RSL rise, but it is then the Talang sites which plot closer to the shifted model-predicted RSL, while the Satang Besar site appears too low. If this is the case, the northern side of the fault would have been downthrown, in an absolute sense. This ambiguity highlights the

plausibility of any number of scenarios in between these two end-members, with vertical shifts possibly divided more evenly between the two sides of the proposed fault.

We note however that, regardless of which scenario is more realistic, the relative displacement of ~1.45 m between the Talang sites and Satang Besar can only be plausibly explained by tectonic deformation. This deformation must have occurred sometime after the corals lived and died. Therefore, our data strongly support our postulation that movement on the Serabang fault has occurred in the past 7000 years.

RSL due to GIA

Because of the likelihood of tectonic displacement in the study area, the RSL estimates presented here (Fig. 4.3) cannot be taken at face value to reflect a pure GIA signal. These RSL estimates include contributions from both GIA and tectonic changes. In order to estimate the contribution from GIA, we need to correct for tectonic effects. We do this by first assuming the vertical displacement along the proposed Serabang fault is divided evenly between the two sides, and then we add, in quadrature, 2σ elevation errors equivalent to half of the estimated tectonic displacement of 1.45 m. For simplicity, in Figure 4.7 we plot the data from the Satang and Talang sites with data from the Satang site shifted up by 0.73 m and data from the Talang sites shifted down by 0.73 m; vertical errors are increased as described above compared to those plotted on Figure 4.3 and listed in Table 4.1. This procedure extends the error bars but allows

us to estimate RSL at both sites without the tectonic influence. Table 4.3 presents data with this correction applied.

Figure 4-7 Fossil microatoll relative sea-level (RSL) data from the Satang and Talang sites, showing remarkable stability for a period of ~450 years. These data have the inferred tectonic signal removed, with the wider vertical errors accounting for uncertainty in which side of the proposed Serabang fault went up or down in an absolute sense. It is important to note that the error bars represent absolute errors about each point; relative vertical errors between all points are substantially smaller. Temporal errors are unchanged from Figs. 3 and 6.

Tanjung Datu is on the northern side of the inferred Serabang fault, along with the Satang site. Although we do not have concurrent microatoll growth at other sites, we have nonetheless made a tectonic correction for the Tanjung Datu corals in Table 4.1, just as we did for the Satang corals. Because Tanjung Datu microatolls are younger than those at the Talang and Satang sites, any movement that affected Tanjung Datu should be equal to or smaller than that between Talang and Satang: if the tectonic displacement occurred after the death of the Talang and Satang microatolls but before

the Tanjung Datu microatolls grew, then a tectonic correction is not appropriate for the Tanjung Datu site, and our correction would overestimate RSL there.

After adjusting for tectonics and propagating uncertainties, the results (Fig. 4.7) show that RSL due to GIA was fairly stable, with RSL in the range $0.4\text{--}0.8 \pm 0.78$ m above present at Talang and $1.4\text{--}1.5 \pm 0.78$ m above present at Satang, in the centuries prior to 7000 yr BP. Radiocarbon ages suggest this period of stability lasted at least from 7439 to 7006 yr BP (at Talang) and at least from 7252 to 7107 yr BP (at Satang), although radiocarbon uncertainties permit some of the individual coral records to have overlapped in time more than suggested in Figure 4.7; at minimum, microatolls SRTB-F1 and SRTK-F1 suggest this period of stability lasted at least ~ 315 years. One thousand years later, data from Tanjung Datu indicate RSL was in the range $2.2\text{--}2.4 +1.14/-0.77$ m above present, or $1.45\text{--}1.65 +0.88/-0.25$ m above present if we forgo the tectonic correction. These reconstructions agree, within error range, with other Sunda Shelf data from this period (Horton et al., 2005).

The microatoll evidence suggests that the RSL rise on the Sunda Shelf slowed earlier than modeled (Bradley et al., 2016) and earlier than seen in most published studies from the Sunda Shelf (Horton et al., 2005: and references there in). The only studies from the Malay Peninsula to show RSL stability prior to 7000 yr BP are those by Bird et al. (2007); (2010) from Singapore. The Bird et al. data show an earlier period of stability, between 7800 and 7400 yr BP; however, with many of the SLIP data in the Bird et al. studies having large chronological and elevation errors, and with our data spanning

only the periods ~7450 to ~7000 and ~6100 to ~6000 yr BP, it is difficult to compare the timing of the periods of stability at the Sarawak and Singapore sites.

Although it is possible that we missed corals that were younger and higher than those we found at the Tanjung Datu site, our data do not support a late (circa 5000 yr BP) RSL highstand as seen in some studies on the Malay Peninsula (Geyh et al., 1979; Tjia and Fuji, 1992; Bradley et al., 2016). Rather, our highest RSL observations date to ~6000 yr BP, similar to other sites including Kelang (Kamaludin, 2002) and Phuket (Scoffin and Le Tissier, 1998). A plot of all Malay Peninsula data (Fig. 4.8) shows that, apart from three high points from Malacca (Geyh et al., 1979; revised by Horton et al., 2005), both east and west coasts appear to reach a highstand between 7000 and 6000 yr BP and experience falling RSL thereafter.

The Tanjung Datu site is part of a 7-km long coastline with several microatoll sites, some of which stretched along the coast for hundreds of meters. Logistical constraints prevented us from exploring these sites further, hence future work at these sites may reveal stronger evidence for the mid-Holocene RSL highstand and its timing. However, it is clear at the Talang and Satang sites that there are no higher coral generations preserved that could yield evidence of a later and higher highstand.

Figure 4-8 Relative sea-level (RSL) history of the Malay Peninsula (from Fig. 2) with data from west Sarawak added. Note the period of stability between 7450 and 7000 yr BP. Sarawak data appear to be closer in elevation to the eastern coast of the Malay Peninsula, although the error bars allow some ambiguity, particularly for the data around 6000 yr BP. For reasons of clarity each fossil microatoll series plotted only as a beginning and an end point. Note that temporal errors of the microatoll dates are plotted but some may not be visible at this scale.

Although these results are speculative, the Serabang Line passes offshore Kuching, the state capital of Sarawak, an urban region with more than half a million residents. Our data are consistent with the mapped trace of Hutchison (2005) as a trajectory of the fault. Therefore, the seismic potential of this region may be underestimated, and current building ordinance for the State of Sarawak, while making provisions for fire and flooding hazards, makes none for earthquakes (Sarawak State Assembly, 2008).

To better understand the seismic hazard associated with the proposed Serabang fault, future investigations should (1) map the full extent of the Serabang fault with offshore

seismic chirp profiles and further studies of the geology onshore Tanjung Datu peninsula; (2) improve continuous GPS coverage of the region; and (3) conduct additional paleo-sea level investigations (such as this study) both on Tanjung Datu and on the islands off the Sarawak coast which were not investigated in this study.

Conclusions

We investigated four microatoll sites in western Sarawak to produce the first Holocene RSL record for Borneo. We document an early period of RSL stability, perhaps similar to that in Singapore, but in contrast to many studies elsewhere on the Sunda Shelf. Our data suggest rapid RSL rise was over by 7450 yr BP. This, in turn, suggests either an earlier end to rapid ice-sheet melting than is incorporated into the latest generation of GIA models, significant spatial differences in rheology on the Sunda Shelf, or both.

We compared the microatoll elevations and the gradients between the various Sarawak sites to predictions from a suite of GIA models (Bradley et al., 2016). Notably, the spatial gradients in RSL predicted by the GIA models are largely independent of the assumed ice history or rheology. A ~1.1-meter difference between the spatial gradient reconstructed from RSL proxy evidence and that predicted by the GIA models implies previously unrecognized tectonic movement along the Serabang Line, sometime after 7000 yr BP; the Serabang Line was previously thought to be inactive. We argue that the Serabang Line should be considered a Holocene-active fault and investigated further. This finding shows that the approach of comparing RSL models with local data

may be valuable not only for RSL studies but also for understanding tectonic processes and hazards in coastal regions.

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Chapter 5 Sea-level index sequences from coral microatolls reveal details of higher-than-present relative sea level in the Riau Islands, Indonesia, by 7.2 ka

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Abstract

In order to better estimate future sea-level change in Southeast Asia, the eustatic and the local glacio-isostatic and hydroclimatic contributions to relative sea level (RSL) must be constrained in both time and space. Many proxies currently used to reconstruct RSL have low (>1 m) precision, yielding ambiguous RSL reconstructions. Coral microatolls can be used to overcome these ambiguities because they can be used to reconstruct a large number of interconnected sea-level index points whose relative errors can be as low as ± 3 cm and ± 2 years per 100 years of record at 2σ . This precision allows long term changes of more than 6 cm between sea-level index points within a sea-level index sequence to be convincingly attributed to relative sea level change. Here we reconstruct RSL at Mapur Island, Indonesia, using nine coral microatolls and

define a new format for data defined from them: sea-level index sequences. A unique feature of the sea-level index sequences is that there is no ambiguity in the temporal order of reconstructed sea-level index points. The sea-level index sequence allows the continuous nature of sea-level to be investigated as the individual temporal errors of sea-level index points which contribute to the sequence do not allow for them to be rearranged in time. Where in a group of sea-level index points the temporal order is established through dating (usually radiometric) and their order may be ambiguous, within a sea level index sequence the order of individual points can never be changed. This feature not only allows unambiguous reconstruction of RSL trends but also a reduction of temporal errors. Using nine sea-level index sequences comprising 29 sea-level index points and 650 sea level minimum points, we reconstruct RSL for Mapur Island in Indonesia, for a period of 115 years between 7282 and 7166 cal yr BP revealing a ~0.5 m RSL rise from ~0.4 m to ~0.9 m above present, leveling off at 7200 cal yr BP. A single younger sea-level index sequence from 6795 to 6773 cal yr BP records RSL at ~0.7 m above present.

Keywords:

RSL, SLI sequence, coral microatolls, fossil coral microatolls, fixed biological indicators, sea-level proxies

Introduction

On local to regional scales, relative sea level (RSL) is largely a function of changes in global ocean volume (eustasy); changes in regional sea level that arise from ocean density changes, gravitational adjustments, regional hydroclimate oscillations; and changes in land level due to tectonics or isostasy (Peltier, 2002; Mitrovica and Milne, 2002; Milne and Mitrovica, 2008; Khan et al., 2015). Constraining how these processes have driven RSL change in the past will allow us to better quantify how the region will respond to rising sea level in the future. However, isolating the more important drivers of RSL requires an understanding of the spatiotemporal variability of past RSL, which in turn necessitates detailed knowledge of RSL spanning a range of times at a geographically distributed set of sites.

The Sunda Shelf in Southeast Asia is inferred to be relatively tectonically stable (Simons et al., 2007), though as chapter 4 demonstrates, this may not always be true for all of the area outlined by the Simons et al. publication (dashed blue line in figure 5-1). A mid-Holocene RSL highstand is predicted to have occurred there, when melting of high latitude glaciers stopped and before RSL began to drop as a result of water being drawn away from the low latitudes to the collapsing fore bulges of previously glaciated regions (Mitrovica and Milne, 2002). The spatial pattern of the highstand is made more complex by continental levering, which occurred when newly flooded parts of the Sunda Shelf were depressed and the uncompressed regions were tilted upwards (Clark et al., 1978). This results in an elevated highstand near to the main landmasses (e.g. Malay Peninsula, Western Borneo) and sea level below today's in the seaward margins of the shelf (e.g. eastern part of the South-China Sea) at the time when melting ceased

in glaciated regions during the mid-Holocene. Yet few studies from this region provide information about past RSL with precisions better than ~ 1 m and several hundred years. Studies that have been conducted on the Sunda Shelf do report a wide range of peak RSL during the highstand, from 140 to 544 cm above present, and variable timing of the highstand, from 6500 to 5000 yr BP (Horton et al., 2005: and references therein; Bird et al., 2007; Bird et al., 2010; Bradley et al., 2016) for different locations. However, the nature and rates of RSL rise, and its subsequent fall, remain ambiguous. Some studies argue the changes were smooth (Hesp et al., 1998; Scoffin and Le Tissier, 1998; Bradley et al., 2016), while others suggest they were punctuated, slowing at times (Bird et al., 2010), or even fluctuating (Tjia, 1996; Meltzner et al., 2017).

Despite a number of investigations of the Holocene RSL highstand on the Sunda Shelf, ambiguities in the height, timing, and particularly in the mode of RSL change on the Sunda Shelf remain. RSL changes are analyzed primarily through the reconstruction of sea-level index points (SLIP) which estimate unique positions of RSL in both time and elevation. On the Sunda Shelf the principal reason for the lingering uncertainties is that while there is now a growing database of SLIPs (Horton et al., 2005: , and references therein; Bird et al., 2007; Bird et al., 2010), most proxies yield only a few points per study, often separated by tens or hundreds of years. Where the errors are wide enough existing data may not be able to distinguish between a range of possible heights and timing options, and the nature of RSL change is thus likely to be poorly determined.

Coral microatolls are coral colonies whose upward growth is constrained by the sea level (Dana, 1846), they continue to grow predominantly horizontally and upwards

when changes in RSL allow, recording a filtered RSL record over their lifetimes (Scoffin et al., 1978; Woodroffe and McLean, 1990). Coral microatoll studies which reconstruct RSL from slabs cut from coral microatolls, as described by Meltzner and Woodroffe (2015), offer more precise reconstructions of RSL. Indeed, a recent coral microatoll study by Meltzner et al. (2017) illustrates that the true potential of the methodology lies not just in its vertical and temporal precision, but in its ability to deliver RSL records that span decades to centuries. Particularly long-lived fossil microatolls can document entire cycles of RSL fluctuations spanning several decades (Meltzner et al., 2017). Additionally, stitching together RSL histories from many fossil microatolls has potential to create composite records showing, with decimeter precision, the RSL fluctuations over hundreds to thousands of years.

In this study, we reconstruct RSL histories of nine fossil microatolls from Mapur Island in Indonesia (Figure 5.1). From the nine microatolls we reconstruct 28 Sea-level index Points (SLIPs) and 650 sea level minimum points. We utilize the Sea-level index (SLI) sequence methodology to reconstruct a continuous RSL records from the microatolls spanning their growth histories. We align similar parts of the RSL records between the microatolls and reconstruct a combined 115-year long record of RSL changes between 7282 and 7166 cal yr BP. The reconstructed RSL record demonstrates a ~70-year period over which RSL rises from ~0.4 to ~0.9 m above present; levelling off thereafter, though some evidence suggests it may have risen further. The reconstructed RSL suggests the Holocene highstand may have peaked as early as ~7200-7160 cal yr BP, in contrast with other studies (Geyh et al., 1979; Tjia and Fuji, 1992; Bradley et al., 2016).

Mapur is 100 km southeast of Singapore and the Malay Peninsula, the region that possesses the biggest concentration of SLIP data on the Sunda Shelf (Geyh et al., 1979; Hesp et al., 1998; Bird et al., 2007; Bird et al., 2010). Hence, reconstructions of the Holocene sea-level curve based on these data are some of the most complete anywhere on the Sunda Shelf and a good comparison for microatoll studies. We found two extensive fossil microatoll sites on Mapur Island, and its proximity to Singapore makes Mapur a good site for a comparison between microatolls and other RSL sites and proxies.

Study area

Mapur island (0.977°N, 104.830°E) is located in the Indonesian Riau Islands province, 100 km southeast of Singapore, on the Sundaland block (Fig. 5.1), an area inferred to be tectonically stable through a decade-long GPS study (Simons et al., 2007). Mapur is a granitic island, part of the East Malay block with bedrock of mainly Permo-Triassic age (Hutchison, 2014). The island has an area of ~25 km² and an elevation of 93 m at the highest point. Granites form several headlands with beaches lying between them. Mangroves grow along more sheltered parts of the coastline.

Figure 5-1 Map of Southeast Asia with the approximate borders of the tectonically stable Sundaland outlined, after Simons et al. (2007). Blue points: previous RSL studies, not using SLI sequences, near to the Mapur study site. Used as a comparison of traditional proxies with SLI sequences. Orange points: previous RSL studies based on fossil microatoll growth sequences. Inset shows Mapur Island and the locations of the two sites discussed in this study. Modified from Meltzner et al. (2017).

We reconstruct RSL using *Porites* sp. microatolls from two sites, on the northern and eastern coasts of the island (Fig. 5.1. inset), which henceforth will be referred to as Mapur North and Mapur East, respectively. Both sites are characterized as fringing reefs. At Mapur North, a 1.7-km long narrow band of coral (<400 m wide) lies seaward of a sandy beach with no major rivers draining nearby. The site contrasts with the more extensive reef at Mapur East, a wide (>500 m) coral platform. A large stand of coastal mangroves fringes several small fresh water streams that drain to the Mapur East site.

Tides are semidiurnal, and the tidal range at the sites varies between 1.97 and 2.33 m over the period of the 18.6-yr tidal cycle (Egbert and Erofeeva, 2002).

Both sites on Mapur have an abundance of healthy living coral for comparison with fossils. Extensive fields of well-preserved fossil *Porites* *sp.* microatolls on the northern and eastern shores of the island make for good study sites, and the moderate tidal range allows relatively long working periods.

Methodology

Microatoll background

A microatoll forms when a coral colony's growth reaches the water surface, and during extreme low tides, the polyps on the upper surface of the colony are killed, while those on the sides remain low enough to survive and continue growing in the following years. The microatoll then continues to grow horizontally while upward growth is periodically constrained by low tide. The elevation of the uppermost living polyps of the colony is called the highest level of growth (HLG) (Meltzner et al., 2010). This term can be applied to the upper limit of the colony in any particular year of growth. A related term, the highest level of survival (HLS) (Taylor et al., 1987), is only applied to the upper limit of growth in years when the low tides reach low enough to constrain the colony and kill some of the polyps, causing a diedown.

The tidal range is modulated over the 18.6-year nodal tidal cycle (Fig 5.2), and this influences microatoll morphology (Meltzner et al., 2017). In particular, during the

portion of the 18.6-year cycle when the tidal range is larger, the low tides are lower, and coral microatolls have less accommodation space for upward growth; when the tidal range is smaller, low tides are higher, and microatolls have space to grow a little higher. Near Mapur, from one year to the next, the rise in extreme low tide can sometimes reach 8 cm (Fig 5.2, panel A, change from 1974 to 1975), whereas *Porites* sp. annual growth rates on the Sunda Shelf tend to oscillate around 1.5-3 cm/yr (Tanzil et al., 2013). Hence, during certain portions of the 18.6-year cycle, the year-to-year rise in low tide exceeds the rate at which corals can keep up; during those years, the microatolls are unlikely to be exposed at lowest tides and their growth will be unconstrained by water level. Once the low tides reach their highest level of the 18.6-year cycle, the cycle reverses and the annual lowest tides fall from one year to the next. The highest portions of the microatoll will be increasingly exposed at extreme low tide, causing a diedown. Because the diedowns tend to occur either as the low tides are lowering or when the low tides fall to their lowest level, diedowns generally occur at the same stage of each 18.6-year tidal cycle. Thus, a comparison of the diedowns over a period longer than 18.6 years (one 18.6-year tidal cycle) allows us to filter out the cycle and concentrate on long term (>18.6 year) changes in HLS, which serve as a proxy for long-term changes in RSL.

In order to determine RSL at a particular time in the past, we compare the elevation of living microatolls and their fossil microatoll counterparts. The difference in elevation between the diedowns on the fossil and the HLS of living microatolls is a proxy for RSL change since the time when the fossil microatolls were alive.

Figure 5-2 on previous page: The 18.61 year tidal cycle model predictions for Mapur (Egbert and Erofeeva, 2002) for 1957-2025 CE. Red shading in panels indicates periods when the tidal range expands (lowering low tides), green shading indicates periods when the tidal range narrows (elevating low tides). Blue line in **Panel A** shows the change in the tide range. **Panel B** demonstrates changes in the high (blue) and low (black) tide elevations. **Panels C and D** demonstrate low tide levels (black) and the growth of a synthetic coral data series (blue line with maroon Diamonds). Whenever the coral grows high enough to reach the tide level it records a diedown. Coral growth is slower than change in low tides from year to year, hence for a period growth is unconstrained. Resulting in periods of ~11-12 years of the cycle when few diedowns occur and a ~7-year period when 2-3 major diedowns concentrate. During the period when the low tide levels are dropping the coral may record small diedowns annually, but only major ones will be recorded, either in the structure of the microatoll or as rings on its surface. Growth rates of 2.05 cm (panel C) and 1.26 cm (panel D) were chosen as these are the fastest and slowest growth rates, measured in the fossil microatolls in this study. There is a non-zero offset between the low tide level and the coral surface which is not shown here. Changes in growth rates can result in altered diedown timing e.g.: Panel C shows a potential diedown in 1998 while in panel D a diedown may occur in 1999. This suggests that coral diedowns should not always be expected to match year to year even when two corals are growing under the same tidal cycle.

Field surveys, sampling and slab processing

We selected four fossil microatolls from the northern and five from the eastern site in order to reconstruct RSL. Relative positions of selected microatolls were surveyed using a Leica TCRP1203 total station (± 1 cm), and locations were also determined using a Garmin GPSMAP 64s global positioning system handheld device (± 5 m). Microatolls were slabbed with an ICS® hydraulic chainsaw and one 10-cm wide slab was cut from the center to the outside of each fossil colony, following the procedure outlined by Meltzner and Woodroffe (2015). The slabs were then shipped to Bandung, Indonesia to be cut into 0.7 cm wide slices and radiographed directly to digital files (at ~250 DPI). The slices were radiographed in sections because they were too large for individual radiographic film plates. The images of each slice were then digitally mosaicked and annotated with annual banding and diedown unconformities as demonstrated in

Figure 5.3. The heights and timing of diedowns as well as HLG of each band were then recorded in a spreadsheet. The reconstruction of the microatoll carries different categories of information. The first is preserved HLG which is a sea level minimum, i.e. a point which must have been below mean sea level (though not necessarily water level at low tide) for the band to grow, but which gives no information about how far above it mean sea level was. The second category is eroded HLG, where the band is not overgrown by later growth the upper most part of it is usually eroded to some degree; in that situation, we can again use the point as a sea level minimum though we must additionally remember that un-eroded HLG for that year was actually higher. The third category is a diedown, the HLS immediately after it can be used as a SLIP. For clarity of figures after the information from a microatoll is recorded we plot two series, a continuous line, made up of all HLG points, both eroded and preserved, and the HLS of each diedown as a separate point on the figure.

Figure 5-3 An example of a small microatoll. A-mosaicked x-ray image. B-finished slab image after the annual bands have been marked with gray lines, and numbered from 1 to 45 representing the years of growth. Diedowns are marked D; these points represent the best control on HLS. Diedowns inferred from preserved raised rings along the upper surface of the microatoll but not preserved in slab, i.e. not protected by later growth, are marked DD; these points provide a minimum HLS estimate and their timing may be subject to ± 1 -year error. Both diedown categories are used in the study, although the final coral death is not considered necessarily as a diedown, as it may result from other causes for example disease, burial by sediment etc. The part of the record between the first and the last diedown on a microatoll slab is the most valuable for RSL reconstructions. For the sake of image clarity, a small living microatoll from Mapur North, not analyzed in this study, is shown here.

Radiocarbon dating

We collected up to four paired samples (~1 cm diameter, 4 cm long) from each slab for radiocarbon and U-Th dating. Samples were taken only from parts of the slab where banding was clearly visible and where there was no discoloration. A total of 14 samples were radiocarbon dated, with one or two samples per microatoll. Samples for radiocarbon dating were taken alongside (<2 cm away from) samples reserved for U-Th dating. Radiocarbon samples were dated at the Rafter Radiocarbon Laboratory in New Zealand. Radiocarbon ages were then modeled in the OxCal calibration program, version 4.2 (Bronk Ramsey, 2009). We applied the Marine13 radiocarbon calibration curve (Reimer et al., 2013). For the marine radiocarbon reservoir correction, a weighted average of *Porites* sp. ΔR values established at ten locations near Mapur, in the South China Sea and Indian Ocean (Southon et al., 2002; Dang et al., 2004; Hua et al., 2004; Bolton et al., 2016), suggests $\Delta R = -16 \pm 39$ yr in this region. Following the observations and reasoning of Meltzner et al. (2017) at sites elsewhere on the Sunda Shelf, whatever the actual value of ΔR at each of our sites, it is unlikely to have changed over the lifetimes of the mid-Holocene corals in our study. We therefore report calibrated and modeled ages in Table 5.1 assuming $\Delta R = -16$ yr, with zero uncertainty, in order to facilitate a comparison of the relative ages of each coral time series.

U-Th dating of microatolls

Only pristine (no visible secondary calcite) parts of the samples were selected for U-Th dating. All samples underwent ultrasonic cleaning at least three times in deionized

water. Procedures for chemical separation and purification of uranium and thorium are similar to those described by Edwards et al. (1986) and Cheng et al. (2000). The U-Th dating was performed on a Thermo Scientific *NEPTUNE Plus* MC-ICPMS following the procedures by Cheng et al. (2013) at the Earth Observatory of Singapore, Nanyang Technological University, Singapore. We calculated corrected ^{230}Th ages using a non-radiogenic initial $^{230}\text{Th}/^{232}\text{Th}$ value of $6.0 \pm 4.0 \times 10^{-6}$ (atomic ratio) (Shen et al., 2008). This number can cover most of the corals in continental shelf settings (Shen et al., 2008; Clark et al., 2012). All the SEM biases, spectral background, chemistry and instrumental blanks, and corrections for spike composition are calculated with an off-line data reduction process (Cheng et al., 2013). Uncertainties in the U-Th isotopic data and ^{230}Th dates given in this paper are at a 2σ level or two standard deviations of the mean ($2\sigma_m$).

Quantification of uncertainties in the microatoll RSL record

Coral HLS is affected by wind, wave splash, insolation, ponding, and other factors (Brown et al., 1994; Scoffin et al., 1997). For this reason, HLS of individual concurrent microatolls varies across a site. The standard deviation of coral HLS is site-specific and depends on a multitude of factors, including tidal range and the width and physiography of the reef; therefore, it is recommended that the error in HLS be determined uniquely for each site (Meltzner and Woodroffe, 2015). To determine an appropriate value for the standard deviation of HLS at each of the Mapur sites, we initially followed the methodology of Meltzner et al (2017). We surveyed HLG on all living microatolls found at each site, including open-ocean microatolls and those that

were clearly ponded (measurements at the northern site: N=124 points on 30 microatolls total; at the eastern site: N=115 points on 26 microatolls total). We measured only microatolls which have survived at least one previous diedown; if all the measured microatolls at a site have a similar growth rate, then the variability of their HLG can be used to represent the variability of their HLS. The resulting standard deviation for HLS on living microatolls was ± 33 cm at Mapur North and ± 12 cm at Mapur East. Both of these values are larger than the ± 9 cm standard deviation for living coral HLS determined by Meltzner et al. (2017) for sites on Belitung Island, Indonesia, and reflect the greater physiographic complexity of the reefs at the Mapur sites. In particular, the large value at the Mapur North site reflects substantial ponding of living microatolls at the site (Figure 5.4). If we ignore microatolls that are clearly ponded within the outer rampart of the reef at Mapur North site, the standard deviation for HLS on living microatolls reduces to ± 8 cm (N=48 points on 10 non-ponded microatolls total).

In light of the large standard deviation of living coral HLS at the Mapur North site, a relevant question is whether the large distribution of living microatoll elevations accurately reflects the distribution of HLS that we would expect for corals that grew at the site during the mid-Holocene. As we will show later, the outer rampart that results in substantial ponding of living corals at the site is itself composed of corals that grew approximately between 7500 and 6500 cal yr BP. No bathymetric features are preserved today seaward of the outer rampart that could have ponded the mid-Holocene corals (Figure 5.4), and no mid-Holocene corals were found that are higher

than those on the present outer rampart, supporting the contention that the mid-Holocene corals could not have been substantially ponded.

To test this assumption, we surveyed the outside rings of all 9 sampled mid-Holocene microatolls at the Mapur North site and extended this survey by including the outer rings of several other microatolls from each sampled generation (N=82 surveyed points on 16 microatolls total). The resulting standard deviation was ± 11 cm, despite the fact that the fossil microatolls spanned a 500-year period and were not necessarily coeval. The smaller standard deviation of fossil microatolls supports the argument that ponding was not a major issue at this site during the mid-Holocene. We conservatively adopt ± 11 cm as the standard deviation of fossil microatoll HLS for Mapur North. Because of the timespan and the sampling of a larger HLS range than at one particular moment in time, this value is a maximum for the HLS variability. For living microatoll HLS at that site, we exclude microatolls that were clearly ponded, adopting the previously described standard deviation of ± 8 cm for individual HLS points; we then use the mean, and the standard deviation of the mean ($\pm 8 \text{ cm} / \sqrt{48} = \pm 1 \text{ cm}$), of the HLS on all living microatolls that were not clearly ponded.

At the Mapur East site our HLS calculation revealed a standard deviation of ± 12 cm for all living microatolls. However, the surprisingly low standard deviation (± 4 cm) for HLS on individual microatolls that were not obviously ponded (N=97 points on 22 non-ponded microatolls total) suggests the survey did not capture the full variability of open-water HLS, and there remains a possibility that everything we considered to be “not obviously ponded” may nonetheless have been ponded. This hypothesis is

supported by our bathymetric survey (Figure 5.5), which revealed that all of the living microatolls on this site were growing within a lagoon and thus may not represent open-water HLS. Noting this we conservatively adopt the larger ± 8 HLS value calculated from Mapur North microatolls which were not clearly ponded, to be used for error range calculation as the standard deviation of HLS of living microatolls in Mapur East.

To establish fossil HLS for Mapur East we again calculated the standard deviation of HLS on the fossil microatolls (N=109 surveyed points on 19 microatolls total). The resulting value is ± 13 cm. This is a larger range than for the Mapur North site, there is no indication of any barrier which could have ponded the fossil microatolls while they were alive. However, the larger distribution of HLS on the fossil microatolls is unlikely to be indicative of a higher HLS for microatolls living at one time at Mapur East. More likely the higher range of HLS is the result of the coinciding of the lifespans of the fossil microatolls at Mapur East with a significant RSL rise that occurred during their lives (see results, and discussion). Because this ± 13 cm standard deviation of HLS likely includes HLS of both the start and

Figure 5-4 Map of Mapur North, demonstrating the complexity of the site. All of the living microatolls (red points) in the lagoon or within the main fossil field, where they grow in pools between fossil microatolls, appear to be ponded. Only those living microatolls growing on the modern reef slope record true open water HLS/HLG. No bathymetric features exist on the site which would be high enough to pond the mid-Holocene microatolls.

Figure 5-5 Map of Mapur East, demonstrating the complexity of the site. A fossil (mid-Holocene?) reef crest encloses a lagoon where HLG/HLS measurements are ponded to various degrees.

the end of the rapid RSL rise it is again a maximum value for HLS variability at one moment in time. As both the fossil standard deviation of HLS calculations, ± 11 for Mapur North, and ± 13 for Mapur East, are fossil HLS variability maxima, for error calculations of both sites we use the value from Mapur North which gives a better constraint on the true HLS variability.

To calculate the vertical errors for the proxy RSL elevations we add in quadrature the standard deviation for HLS on fossil microatolls, ± 11 cm; the standard deviation of the mean for HLS on living microatolls, ± 8 cm; a surveying error of ± 1 cm; and erosion error of 10 cm, erosion added only to the positive error, to account for erosion of the microatoll surface which occurred since the time it was alive; this erosion error results in asymmetrical errors. The resulting error for the relative elevation between two SLI sequences at a single site is $+17/-13$ cm at 1σ (2σ errors of $+34/-27$ cm are shown on all figures).

At both sites, the difference in elevation between the HLS of a fossil microatoll and the average HLS of living microatolls (excluding living microatolls that are clearly ponded) is a proxy for the RSL change between the time of the fossil microatoll growth and the present. At Mapur East, however, these values might be considered minimum estimates of past RSL because our calculation of the average living HLS at that site is likely influenced by ponded microatolls. If our estimate of living HLS at Mapur East was artificially raised because of ponding of living microatolls there, then our estimates of past RSL would be systematically biased low; this could be corrected by uniformly shifting all southern site RSL proxy elevations higher by an equivalent amount.

Fossil microatoll sea-level index (SLI) sequence

A fundamental limitation of most RSL proxy records is that traditional SLIP time series allow a wide range of possible RSL interpretations, due to large uncertainties about each data point. RSL proxy records from microatoll slabs can overcome this limitation to a large extent because they record SLIP data in a continuous sequence of uninterrupted growth of a coral microatoll colony. This leads to four important advantages: (1) vertical errors are reduced for relative elevations between two points on an individual microatoll slab, compared to the absolute vertical errors of two independent SLIP data points; (2) the relative chronological error for the difference in age between two points on an individual annually-banded microatoll slab is effectively reduced to the counting error on the number of annual growth bands between those points (Meltzner et al., 2017); (3) even if annual banding is unclear or absent, or when a slab cannot be obtained, the microatoll imposes an ordering, a priori, on the individual RSL proxy data points; for rapid RSL changes that are not resolvable by traditional RSL proxies with large chronological uncertainties, the microatoll morphology itself can indicate whether RSL was rising, falling, or fluctuating (Meltzner et al., 2017); and (4) traditional geochronological techniques can yield increasingly precise absolute ages of annually-banded microatolls if dates from multiple samples, taken a known number of annual bands apart, are combined (Meltzner and Woodroffe, 2015). As a result, the largest elevation and temporal errors are applied to an entire microatoll record as a whole, but can be ignored when considering only the relative uncertainty between two data points within a single microatoll record. Hence, RSL reconstructions based on the shape of a microatoll sequence are arguably more robust than those based on most other proxies. This feature of microatoll slab records makes

those records strongly advantageous, but requires a new format to record and track the nuanced information from microatoll slabs. Here we define a new format, a sea-level index (SLI) sequence:

A sea-level index (SLI) sequence comprises reconstructions of the timing and position of RSL from an ordered set of proxy data of sufficient duration to average over undesired high frequency RSL noise. This noise might arise from variability of RSL over the 18.61-year tidal cycle or the variability in the intensity of the Indian Ocean dipole or El Niño/Southern Oscillation.

SLI sequences can only be reconstructed from records continuous both physically and chronologically. Appropriate absolute errors defining uncertainty in the relationship between the whole of the SLI sequence and RSL, and errors defining uncertainty in the relative timing and elevation of any two points within the sequence, must be established for a particular site and proxy for which the format is to be used. A SLI sequence may contain both SLIPs and limiting data, but the most useful part of a SLI sequence is a portion bounded between two SLIPs.

The SLI sequence data format is currently only applicable to studies of microatolls, either those which were slabbed as described by Meltzner and Woodroffe (2015) or those where an effort has been made to survey the surface of a microatolls (e.g.: Yu et al., 2009), in particular if multiple samples from the microatoll were dated. However, there is no *a priori* reason why other proxies could not use the format, so long as they can fulfil the conditions of the SLI sequence definition. Indeed, it is hoped that in time

other proxies may be found or developed which can take advantage of the format. Figures 5-6 and 5-7 demonstrate some differences between SLI sequences and other proxies with two sets of hypothetical (synthetic) data. In Figure 5-6 we investigate the role of vertical errors, and in Figure 5-7 we investigate the impact of chronological errors. On each panel of Figures 5-6 and 5-7 there are two sets of observations: on the left, a group of SLIP data from a “traditional” proxy such as oysters; on the right, comparable SLIP data but in the form of a SLI sequence from a microatoll. Both the oyster SLIPs and the microatoll SLI sequence have the same timing and elevation, although the vertical and chronological errors for microatoll SLI sequences are typically smaller than those of an oyster SLIP. Panel (a) in both figures shows the raw data where everything but the errors are the same. In panels (b) through (h) we present a range of valid interpretations permitted by the data and their corresponding errors.

The primary difference between the left and right side of each panel of Figure 5-6 is that for time series consisting of discrete SLIP data, the relative errors between points are based on the absolute errors, but for time series comprised of SLI sequences, the relative vertical errors are smaller. For microatolls, the relative errors are calculated as the average standard deviation of HLS on individual microatolls. For Mapur, we surveyed a minimum of four HLS points on each of 45 individual living microatolls, and the average standard deviation is ± 1.5 cm. This value is supported by a similar survey of 282 microatolls by Smithers and Woodroffe (2000) who found the mean range of the height of living coral (equivalent to HLG used in this paper) to be 3.3 cm.

Figure 5-6 shows that the larger vertical errors of the SLIP data may result in broadly incorrect RSL interpretations over short intervals. If the RSL errors are the same for all data and every point is interpreted to be uniformly low or high within its error (panels (b) and (c)), the RSL curve can be lower or higher but its shape may not change. However, panels (d) and (e) show that while the data suggest an RSL peak, the SLIP data cannot reject interpretations of stable RSL or an RSL trough. In contrast, stable RSL or

an RSL trough are not supported by the SLI sequence, because the relative error between data points is an order of magnitude smaller than the RSL changes. Panel (f) shows the steepest RSL rise and steepest RSL fall supported by each data set. Panels (g) and (h) show, in turn, interpretations permitted by the SLIP data but not by the SLI sequence in which the RSL reconstruction is falling or rising at a linear rate. In all we see that in panels (d) through (h) the reconstruction of an RSL trend through a group of SLIPs is poorly constrained, allowing for a host of possible interpretations. In each of these cases we see that the SLI sequence has far less flexibility and its shape remains almost unchanged, reducing the range of possible RSL interpretations dramatically.

Figure 5-6 Comparison of a group of SLIPs on the left of each panel, with coral microatoll SLI sequences on the right. Panel a) through h) show possible RSL scenarios within the vertical error range: a) raw RSL data, b) lowest possible RSL, c) highest possible RSL, d) reversal of the trend suggested by the raw data, e) flattest possible RSL, f) steepest possible RSL fluctuation, g) falling RSL, h) rising RSL. In scenarios b) and c) where the RSL is plotted uniformly through the error ranges both SLIP data and SLI sequences behave similarly, though SLI sequences typically have smaller error bars. Panels d) through h) show the startling differences between the two data types when the RSL scenario is not plotted through all error ranges uniformly. SLIP points allow the error range of each point to be interpreted individually thus different scenarios change the shape of the RSL. An SLI sequence is composed of a continuous record of RSL in which all points respond to RSL changes uniformly (except a small error, ± 3 cm at 2σ in Mapur, related to HLS range on an individual microatoll), thus no matter the shift within the error range it must be applied uniformly and does not alter the shape of the interpreted RSL change.

Figure 5-7 explores the temporal aspect of a SLIP to SLI sequence comparison. As with Figure 5-6, the left side of each panel shows a group of synthetic SLIP data from a “traditional” proxy such as oysters, while the right side shows a synthetic SLI sequence from a coral microatoll. As with vertical errors, the relative chronological uncertainty between two points within a SLI sequence is typically much smaller than the absolute errors (Fig 5-8). This relative error, oftentimes only the band-counting uncertainty, may in rare cases reach ± 5 yr but is commonly below ± 1 year (Smithers and Woodroffe, 2001; Meltzner et al., 2017). In Figures 5-7 and 5-8 we adopt a more conservative error of ± 2 years per 100 years of record. Again, panel (a) shows the raw synthetic data, which indicate rising RSL. Panel (b) illustrates the effect of absolute age uncertainty, particularly if the chronological errors are the same for both the SLIP data and the SLI sequence: both RSL curves can be shifted along the horizontal axis. Panels (c) through (h) show a range of valid RSL interpretations permitted by relative age uncertainties among each data set.

As illustrated in panels (c) through (h), the relative chronological errors typical of “traditional” SLIP proxies support a range of RSL interpretations: slowed RSL rise (c), RSL fall (d), fluctuating RSL (e and f), an RSL peak (g), or an RSL trough (h). The overlapping temporal errors make it impossible to reject a number of contradictory RSL interpretations. The chronological order of individual SLIP data points cannot be established so long as their temporal errors overlap. Here, the SLI sequences have an advantage in a smaller relative temporal error within the sequence and a fixed ordering of individual SLIP data points determined from the annual banding or microatoll

morphology. This point is highlighted in a case of fluctuating RSL along the southern coast of China. Meltzner et al. (2017) reinterpreted data from an earlier study (Yu et al., 2009) based on discontinuous samples from coral microatolls. When microatoll morphologies were not considered, the large chronological uncertainties on individual U-Th dates prevented the resolution of details of the RSL history, including the number of RSL peaks and troughs and the rates of RSL rise and fall. However, consideration of microatoll morphology allowed Meltzner et al. (2017) to determine whether an individual U-Th dated sample belonged on one downward swing of the RSL curve or on the subsequent upward swing. This, in turn, allowed for the resolution of far greater detail than was possible in the original study.

An additional advantage of SLI sequences is that while working with a microatoll multiple samples can be taken for U-Th dating, radiocarbon dating, or both, and the absolute number of annual growth bands between the sample locations on the slab can be counted. Hence, a weighted date can be calculated or, for radiocarbon, dates can be modelled in OxCal to make the results more robust and reduce the error. The value of this potential comparison of ages from the same microatoll is fully demonstrated further on in this study (see discussion of U-Th RSL scenario). Because of this, and because the shape of SLI sequences cannot be altered significantly, they make an excellent tool for reconstructing RSL trends. SLI sequences reconstructed from fossil microatolls are arguably one of the most un-ambiguous proxies for reconstruction of RSL fluctuations during the Holocene highstand.

Figure 5-7 Similar as Figure 5-6, but the scenarios exploring temporal shifts within the error range. Panel b) again shows that when an RSL scenario is plotted through the error range of each point in a series both SLIP and SLI sequence data behave similarly. Panels c) through h) demonstrate again that when the RSL scenarios interpret each error range individually a number of possible contradictory RSL scenarios are possible. In an SLI sequence the SLIP points are connected in a sequence, the points can shift only 1-2 years (band counting error) relative to each other but aside from that any corrections or changes have to be applied to the error ranges of the SLIPs of the SLI sequence uniformly. Hence the shape of the RSL changes little. Additionally, an important feature of SLI sequences is that when temporal errors allow several SLIPs to overlap their chronological order cannot be altered. The same cannot be said of SLIP series from other proxies; where if there is temporal overlap between individual SLIPs then their order will remain ambiguous, supporting a wide range of possible RSL scenarios.

Figure 5-8 An enlarged part of panel (e) from Figure 5-7, showing the small internally relative error (red error bars) of an SLI sequence resulting from band count uncertainty (temporal error) and variability of HLS on a single microatoll (elevation error).

Results

We first present the SLI sequences from the two sites separately. Figure 5.9 shows the SLI sequences of the four microatolls from Mapur North. Based on radiocarbon results, three of the SLI sequences (PMPR-A-F3, -F4, and -F6) group together, spanning the period between 7314 to 7135 cal yr BP (excluding error bars of 47-69 years). All three SLI sequences show RSL rise of between 15 and 22 cm over their lifetimes. PMPR-A-F4 is the longest of the three sequences and spans 118 years. All three SLI sequences show declining elevations towards their outer perimeters, but as these portions of the record lack diedowns, we infer that these lower elevations result from substantial postmortem erosion of the outside rings of the colonies, and may not reflect lower RSL

during growth. A fourth microatoll (PMPR-A-F1) is younger and spans the period 6821-6757 (± 59) cal yr BP. It records only two diedowns over its 65-year lifespan, both at similar elevations, hence it suggests approximately stable RSL over that period.

Figure 5.10 shows SLI sequences from Mapur East. Based on radiocarbon results, all five microatolls cluster together between 7176-6994 cal yr BP (excluding error bars of 62-93 years). All five sequences show RSL rise (between 22 and 40 cm) over their lifetime. Four of the SLI sequences span more than 100 years of growth, with PMPR-B-F3 being the longest at over 153 years. Unfortunately, further analysis of the HLS survey revealed that PMPR-B-F3 likely tilted progressively during its lifetime, and we were unable to calculate an appropriate tilting correction for this problem. As a result, PMPR-B-F3 was removed from further analysis.

Figure 5-9 RSL proxy time series of fossil microatolls from Mapur North site. The age indicated for each microatoll is determined from the modeled radiocarbon dates in OxCal (Bronk Ramsey, 2009). Diedowns are sea-level index points; all other points on each curve are either preserved or eroded HLG and each point (1 per year) serves as a sea level minimum point.

Figure 5-10 RSL proxy time series suggested by fossil microatolls at the Mapur East site. The age indicated for each microatoll is that determined from the modeled radiocarbon dates in OxCal (Bronk Ramsey 2009) Diedowns are sea-level index points; all other points on each curve are either preserved or eroded HLG and each point (1 per year) serves as a sea level minimum point.

Table 5-1 Results of radiocarbon measurements of samples from Mapur, as well as calibration and modelling of dates, assuming $\Delta R = -16$ yr. ± 0 , in OxCal (Bronk Ramsey, 2009)

Rafter sample ID number	Microatoll/Sample Name	Radiocarbon Age (rcy BP)		Calibrated Age (yr BP), 2σ		No. of Younger Annual Bands	Calibrated Age of Outer Band (cal yr BP), based on single sample only, 2σ		Modelled Age (cal yr BP,) 2σ		Modelled Age		Age of outer band as shown in Figure 11/12	Age of outer band as shown in Figure 13	Age of outer band as shown in Figure 15
		Median	σ	From	To		From	To	From	To	Median	σ			
40333/30	PMPR-A-F1-A1	6304	20	6866	6702	14	6852	6688	6826	6709					
40223/16	PMPR-A-F1-b	6295	22	6853	6683	33	6827	6658	6845	6728					
	PMPR-A-F1 outer band								6812	6695	6754	29	6754	6754	6754
40333/32	PMPR-A-F3-C1	6654	21	7257	7149	43	7214	7106	7225	7129					
40223/17	PMPR-A-F3-b	6563	22	7181	7001	42	7139	6959	7224	7128					
	PMPR-A-F3 outer band								7181	7086	7134	24	7181	7177	7181
40333/33	PMPR-A-F4-B1	6686	20	7288	7164	42	7246	7122	7265	7170					
40010/20	PMPR-A-F4-b	6672	22	7275	7155	42	7233	7113	7265	7170					
	PMPR-A-F4 outer band								7223	7128	7176	24	7146	7142	7146
40333/35	PMPR-A-F6-B1	6744	21	7368	7230	19	7349	7211	7368	7230					
	PMPR-A-F6 outer band								7349	7211	7280	35	7217	7213	7217
40333/36	PMPR-B-F1-A1	6608	21	7236	7081	28	7208	7053	7198	7073					
40010/21	PMPR-B-F1-b	6579	22	7208	7020	50	7158	6970	7220	7095					
	PMPR-B-F1 outer band								7170	7045	7108	31	7122	7231	7047
40333/37	PMPR-B-F2-B1	6537	21	7152	6987	64	7088	6923	7152	6987					
	PMPR-B-F2 outer band								7089	6922	7006	42	7040	7149	6965
40333/38	PMPR-B-F3-A1	6536	20	7151	6988	51	7100	6937	7151	6988					
	PMPR-B-F3 outer band								7101	6936	7019	41	Not in fig.	Not in fig.	Not in fig.
40333/39	PMPR-B-F4-B1	6576	21	7203	7018	51	7152	6967	7203	7018					
	PMPR-B-F4 outer band								7152	6966	7059	47	7049	7158	6974
40333/40	PMPR-B-F5-B1	6508	20	7135	6955	71	7064	6884	7133	6993					
40010/22	PMPR-B-F5-b	6552	21	7163	6995	82	7081	6913	7144	7004					
	PMPR-B-F5 outer band								7062	6922	6992	35	6997	7106	6922

Developing SLI sequence histories

A principal advantage of SLI sequences is the possibility to combine several of them into a longer composite sequence, as shown by Meltzner et al. (2017). We adopt similar methods of matching coral growth sequences with one difference. The methods of Meltzner et al. (2017) follow previous work from western Sumatra (Meltzner et al., 2010; Meltzner et al., 2012; Philibosian et al., 2014) which documented that strong Indian Ocean Dipole events can cause sea level anomalies which lower the water levels below normal tidal levels. As a result, it is common for microatolls in western Sumatra to record concurrent diedowns over large areas. However, the diedowns on the Sunda Shelf are controlled primarily by the 18.6-year tidal cycle, where a similar concurrence of diedowns has yet to be demonstrated. As a result, we adopt a more conservative principle that diedowns should mostly match in periods of 7 years, which is suggested by the majority of diedowns occurring within 7 year periods on the synthetic corals shown by figure 5.2.

Below, we discuss each site separately first, attempting to slide the SLI sequences within their errors to overlap fragments which appear to have been responding to the same RSL trend, and that we interpret to have formed concurrently. Following this we compare the records from the two sites to determine whether they may have overlapped in time.

When comparing individual SLI sequences with one another, we rely on the number of annual bands between successive diedowns on each microatoll, and the general shape (elevation over at least two 18.6-year tidal cycles) of each microatoll (Meltzner et al., 2010, 2012, 2015; Meltzner and Woodroffe, 2015). Parts of the microatoll, however, are not elevation-limited by RSL, and the elevations reconstructed from those portions of the microatoll should be ignored when comparing SLI sequences. This includes the earliest part of a microatoll, which invariably shows at least several years of unconstrained growth as the coral initially grows up to HLS. Microatolls can also be eroded during and after their growth, by chemical, biological and physical processes. The outer (youngest) part of the microatoll is the most exposed and commonly shows a rapid HLG decline, which may not be related to RSL change. Hence the most reliable part of an SLI sequence to use in comparisons is the section between the first and last diedown.

Figure 5.11 demonstrates one possible scenario for the three clustered SLI sequences from Mapur North. All three SLI sequences appear to overlap. The last diedown of PMPR-A-F6 overlaps with the earliest diedown on PMPR-A-F4, and the coral HLG rises thereafter, on PMPR-A-F6, PMPR-A-F4 and the as-yet unconstrained PMPR-A-F3. The second (7209 cal yr BP) and third (7192 cal yr BP) diedowns of PMPR-A-F3 coincide with diedowns on the PMPR-A-F4 microatoll, which continues to grow for ~30 years after PMPR-A-F3 stops. The notable drop in the height of PMPR-A-F4 from ~7165 cal yr BP onwards may be due entirely to erosion of the perimeter of the microatoll and does not necessarily reflect a lowering of RSL.

As outlined previously, the growth of microatolls in Mapur is influenced by the 18.6-year tidal fluctuation. If the composite sequence is to be considered reliable it too should demonstrate that most of the diedowns align with periods of lowering low tides, while the higher parts of the sequences should mostly align with the periods when elevation of low tides was raised. The red and green bands on Figure 5.11 represent these two parts of the tidal cycle. Red bands indicate periods when low tides were lowered or lowering and corals were losing accommodation space, while green bands represent the periods when low tides were raised or rising and corals were able to grow upwards unconstrained. Hence, when a match of growth features and diedowns is achieved to form one composite sequence we compare it to the 18.6-year tidal cycle as shown in Figure 5.11. We can see that indeed the composite sequence can be aligned in such a way that most of the diedowns occur in the periods when low tide was lowered, while much of the upward growth occurs in the periods when the low tides were raised. On the basis of this comparison we can conclude that the reconstructed composite sequence follows the 18.6-year tidal cycle, and as such it is highly plausible.

Figure 5-11 Matching coral growth sequences from Mapur North by shifting them within their temporal errors. The amount of the shift for each series (in years) from its modeled age (Table 1) is indicated by letters in brackets: “E” indicates the series was shifted earlier, while “L” indicates the series shifted later. Red shading indicates presumed periods when the 18.6-year tidal cycle increases the tidal range, lowering the elevation of the low tides, while green sections mark periods when the elevation of low tides was rising. Note the timing of most diedowns during the half of the tidal cycle when low tides were depressed. Because various colonies started growing in different years and at different elevations, and because their growth rates differ slightly, the morphology and the timing of diedowns of microatolls growing alongside one another may be similar but are unlikely to be identical. The drop in coral height toward the end of each series (particularly PMPR-A-F4) is at least partly caused by erosion. Microatoll PMPR-A-F1 from the same site is not shown because it cannot be shifted within its temporal error to overlap with any other coral (from either Mapur North or

Mapur East).

Hypothetically it is possible to shift any one of the SLI sequences by 18.6-years in relation to the remaining SLI sequences and maintain a rough match of the timing of diedowns and periods when the microatolls appeared to grow unconstrained. However, the three microatolls grew on the same site, within 1 km from each other, and were not ponded as far as can be established. Therefore, it is unlikely they would show different RSL histories, hence it is important to note that in this alignment the diedowns match closely not only in timing but also in elevation. The rough elevation match is maintained not just in a pair of concurrent diedowns but also in subsequent diedowns on both sequences, indicating a match not just in RLS height but also in RSL change over time. Finally, given their temporal errors the alignment presented above is the only possible one which allows all three SLI sequences to remain within their errors. In order to make this scenario possible all three SLI sequences had to be moved within their temporal error. PMPR-A-F4 was moved 30 years later, PMPR-A-F6 was moved 62 years later, while PMPR-A-F3 was moved 47 years earlier. The entire sequence could be shifted up to 7 years later with all three microatolls still remaining within their respective error ranges, but PMPR-A-F6 could not be shifted the 18.6 years later required for its diedowns to align with the other microatolls. Nor could PMPR-A-F3 be shifted the 18.6 years earlier required to align in timing with the other microatolls. The rough match of diedown elevations, and timing, and keeping all three microatolls within their given error ranges convince us that we have made the best possible, most plausible, match within the given constraints. It is for this reason that the SLI sequences have to also demonstrate a rough match in diedown elevation. The narrow temporal window when the scenario is possible raises the possibility that overlapping several SLI sequences may make their dating more robust. The composite

record of all three SLI sequences spans nearly 80 years. During this time RSL rose by ~24 cm, possibly stabilizing and then falling by ~5 cm towards the end of this record. The same procedure was applied to SLI sequences from Mapur East (Figure 5.12). PMPR-B-F1 is the oldest microatoll in this group, and provides the earliest diedown in 7173 cal yr BP, its second diedown, in 7155 cal yr BP, coincides with a diedown on PMPR-B-F2 and PMPR-B-F4. The growth sequence of PMPR-B-F2 and PMPR-B-F4 is similar in their early years, after both sequences grow up to the limiting water level they follow each other closely. In 7138 cal yr BP both PMPR-B-F4 and PMPR-B-F2 record their second diedowns. Following this PMPR-B-F2 records a diedown in 7133 cal yr BP while PMPR-B-F4 records one a year later. As shown in Figure 5-2 different growth rates among corals on the same site may result in this kind of 1 or 2-year variability in diedown timing. Beyond this point diedowns on the two corals do not coincide in timing again, but their growth continues to rise and dip in time with each other at least until ~7090 cal yr BP beyond which PMPR-B-F2 registers no other diedowns and is generally lower in elevation, though the elevation difference may be due to erosion. PMPR-B-F4 records further diedowns in 7128, 7120, 7097 and 7078 cal yr BP while PMPR-B-F2 records only one more diedown in 7115 cal yr BP. PMPR-B-F5 did not preserve any clear evidence of diedowns, it is clear from at least two rings in its morphology that it was a microatoll but no direct evidence of diedown remains. The placement of PMPR-B-F5 is predicated upon a general similarity of the shape of its early growth to the final decades of PMPR-B-F4 and a drop in HLG which may be concurrent with the final diedown on PMPR-B-F4 in 7078 cal yr BP, both the diedown and the HLG drop are at similar elevation (<3 cm). With no clear diedowns on PMPR-B-F5 its placement is most open to debate out of all the microatolls, but a better fit

cannot be achieved without elevation shifts, and as elevation matches are one of the primary ways in which we reconstruct composite sequences such a shift is not permitted by our approach. The combined sequence from Mapur East is 187 years long, although diedowns which can serve as SLIPs bound only 95 years of this record. The rest of the period, represented mainly by PMPR-B-F5, comprises of sea level minimum points, although not supported by SLIPs from diedowns these sea level minimum points are still evidence that RSL likely continued to rise for at least another half a century. As with the composite sequence from Mapur North, the Mapur East composite shows agreement with the 18.6-year cycle with most diedowns occurring during the part of the cycle when elevation of the low tides is depressed. Though is important to note for any microatoll composite sequence reconstructions, that while fewer, some diedowns are also expected in the period when the low tide level is rising as demonstrated in Figure 5.2 (panels C and D).

The temporal errors of the composite records do not allow an overlap of the two composites presented in Figures 5.11 and 5.12. However, similarities in shape and RSL trend between the two groups of SLI sequences suggest an intriguing possibility that rather than representing two similar periods of RSL change they may represent the same period of time. Because of ongoing debate regarding the possibility of fluctuating RSL at the time of the mid-Holocene highstand (e.g.: Hesp et al., 1998; Scoffin and Le Tissier, 1998; Yu et al., 2009; Meltzner et al., 2017) it becomes important to investigate what the evidence from Mapur has to say about the question.

Figure 5-12 Matching coral growth sequences from Mapur East by shifting them within their temporal and elevation errors. The amount of the shift for each series (in years and centimeters) from its modeled age (Table 1) and surveyed elevation is indicated by letters in brackets: “E” indicates the series was shifted earlier, while “U” and “D” indicate vertical shifts up and down. The drop in coral height toward the end of each series is at least partly caused by erosion. Although PMPR-B-F3 (not shown) also aligns closely with these microatolls, further analysis revealed that PMPR-B-F3 was affected by tilting over its lifetime, and an appropriate correction was not possible.

The dates presented for each SLI sequence thus far are based on an assumption that the two sites, less than 10 km apart, share the same ΔR value for the marine radiocarbon reservoir correction. However, the ΔR in the region varies by more than 200 years from -121 ± 60 yr to $+89 \pm 70$ yr (Southon et al., 2002). There is no clear guide for choosing the ΔR value for a study, and the ^{14}C HRONO Marine Reservoir Database (Reimer and Reimer, 2001) has poor coverage in Southeast Asia. To test the hypothesis that the Mapur East RSL record overlapped in time with the earliest three corals at Mapur North, and that the apparent difference in age resulted only from different ΔR values at the two sites, we slid the composite SLI sequences from each site along the temporal axis, attempting to minimize the misfit between the two sites: if indeed the corals at both sites were growing over the same time period, their RSL proxy records should be consistent with one another.

The comparison between the sequences from Mapur North and Mapur East is presented in Figure 5.13, and discussed below. Comparing composites from different sites is more difficult than a comparison of individual SLI sequences within one site. This is because fossil microatolls on each site are compared to living HLS on the same site, and thus establishing a common reference frame for both sites is more difficult. RSL should vary little over the distance of just 10 km, but as much of our living HLS measurements on Mapur East were ponded it is likely that apparent RSL elevations from fossils on that site may be lowered. Thus, the composites from the two sites may not match in RSL exactly, hence RSL elevation cannot be used as a reliable feature of the comparison. Instead in the comparison we relied primarily on both composites responding in time to the 18.6-year tidal cycle and similarity of RSL change over time.

We begin the analysis with the first diedown of the composite sequence from Mapur North. For ease of reference we present this as a list in chronological order:

- The first diedown on PMPR-A-F6 in 7245 cal yr BP occurs only 2 years after the second diedowns on both PMPR-B-F4 and PMPR-B-F2.
- The second diedown on PMPR-A-F6 occurs in 7241 cal yr BP, same year as the third diedown of PMPR-B-F4 and one year after a diedown on PMPR-B-F2.
- The next two, third and fourth, diedowns of PMPR-A-F6 occur only two years apart, 7230 and 7228 cal yr BP, and either side of diedown five on PMPR-B-F4.
- The last, fifth, diedown of PMPR-A-F6 coincides in time, 7221 cal yr BP, with a diedown on PMPR-A-F4 and occurs three years after the fourth diedown of PMPR-B-F2.
- The first diedown of PMPR-A-F3 in 7209 cal yr BP coincides in timing with a drop of HLG on PMPR-B-F4.
- The second diedown of PMPR-A-F3 in 7204 cal yr BP coincides in time with a diedown on PMPR-A-F4, and comes 2 years after the sixth diedown on PMPR-B-F4.
- The third diedown of PMPR-A-F3 in 7187 cal yr BP again coincides with a diedown on PMPR-A-F4 but also with a diedown on PMPR-B-F4 and a concurrent dip in HLG on PMPR-B-F5.

The points listed above show that most diedowns on the two composite sequences are found within 1 or 2 years of each other, as may be expected even in comparisons between SLI sequences on the same site. It is necessary however, to also mention some apparent discrepancies between the two composite sequences. While PMPR-B-F4 and

PMPR-A-F6 both record a diedown in 7241 cal yr BP, only the former records another diedown four years later, while PMPR-A-F6 continues to grow upwards with no signs of being constrained. This may be due to the fact that in 7241 cal yr BP PMPR-A-F6 recorded a larger, ~7cm, diedown than PMPR-B-F4 (~1 cm). Another possible discrepancy, the last diedown on PMPR-A-F4, in 7166 cal yr BP does not coincide with any diedowns, but it does come at roughly the time when a diedown between growth rings on PMPR-B-F5 may be expected. While the other two microatolls still growing at this time PMPR-B-F2 and PMPR-B-F4 show no diedowns at all for more than two decades. It is likely that the two lower corals from Mapur East are simply too eroded at this point to be a reference.

The comparison demonstrates that in most cases diedowns on one composite sequence occur at a similar time (± 2 yr) as those on the other site. Where they occur without an equivalent this can be mostly ascribed to erosion. No significant problems suggesting the two sequences are incompatible have been found. Although RSL elevation may differ, as a result of previously described problems on the Mapur East site, it appears that the trend of RSL is similar. Throughout the comparison, where two concurrent diedowns occur their elevation agrees within 1σ error, there is only one exception to this in the comparison of the third diedown on PMPR-A-F6 and the fifth diedown on PMPR-B-F4, and in that case the two diedowns are only ~2 cm outside of 1σ error and well within 2σ error. Hence, although a uniform ~5 cm upward shift of the Mapur East sequence could be permitted, it was not necessary to demonstrate high degree of agreement between the two sites.

This alignment was only possible, however, by moving the Mapur East by more than the temporal errors allow (the errors on the calibrated ages in Table 5.1 were determined assuming zero uncertainty for ΔR). Although it was the Mapur East site which was moved outside of its error range, and one possible reason for doing that is discussed later, it is just as possible that it was Mapur North, or both sites whose ΔR value did not reflect the coral's true age.

Figure 5-13 Combining SLI sequences from the two sites while allowing for uniform but arbitrary shifts along the chronological axis of the composite sequence from each site. This scenario could be explained, for example, if the marine radiocarbon reservoir correction (ΔR) was different by 120 years at the two sites. The similarity of the resulting records from Mapur North and Mapur East, and the need to shift at least some of the individual SLI sequences beyond the dates permitted in Table 1, suggests different ΔR corrections are needed at the two sites.

Figure 5-14 RSL trend
(exponentially
smoothed average,
smoothing factor 0.3)
based on diedowns from
six SLI sequences from
both sites (excluding
PMPR-A-F1 due to large
chronological gap).

Figure 5.14 shows the RSL trend reconstructed based on the assumption that indeed the two sites (with the exception of PMPR-A-F1) span the same period. The plotted line is an exponential smoothing (smoothing factor 0.3) of the line plotted through all of the diedowns (in chronological order) from all the SLI sequences. The formula used for the exponential smoothing is as follows:

$$S_t = \alpha * x_t + (1 - \alpha) * S_{t-1}$$

Where S_t is the smoothed value, α is the smoothing factor (where $0 < \alpha < 1$), x_t is the current observation in the sequence and S_{t-1} is the previous smoothed value. Exponential smoothing has the disadvantage of starting each series of values with one unsmoothed value, hence it expresses a bias towards that value. To overcome the problem, we run the smoothing calculation in both directions (from youngest to oldest, and from oldest to youngest diedown), and we average the two to gain a more representative curve.

In Figure 5.15 we plotted an alternative interpretation of the data from the two sites. This time, we assume that the two groups of SLI sequences resulted from two separate RSL fluctuations. In this case, we moved the two sites' composite SLI sequences apart as much as their radiocarbon errors allowed, because the earliest, and lowest, of the Mapur East SLI sequences (PMPR-B-F1) would otherwise be difficult to reconcile with the high RSL proxy observations from PMPR-A-F4. Figure 5.16 shows the RSL trend this would entail, calculated in a manner similar to the RSL trend in Figure 5.14.

Figure 5-15 An alternative interpretation in which the SLI sequences from the two sites represent two separate but similar RSL fluctuations. In this case, none of the SLI sequences are shifted beyond the radiocarbon errors in Table 1. This scenario does, however, require a remarkable coincidence in the shape of two consecutive RSL fluctuations.

Figure 5-16 RSL
*fluctuations based on
 diedowns in the
 scenario shown in
 Figure 15 (exponential
 smoothing of average,
 smoothing factor 0.3).*

U-Th based RSL scenario

A comparison between ages of samples dated from each slab and consideration of the number of annual bands between the sample locations revealed internal discrepancies within the U-Th results. The calculated ages of samples from within the same microatoll slabs are non-reproducible; Figures 5.17 (Mapur North) and 5.18 (Mapur East) show a spread of dates calculated for the external (youngest) band of each microatoll, from all U-Th samples taken from the respective microatoll.

Figure 5-17 Mapur North. U-Th measurements from individual samples (Squares) adjusted through band counting to date the outside band of each microatoll. Weighted dates (Rhombi) of all U-Th measurements for each microatoll. The narrow error ranges appear to represent U-Th measuring uncertainties rather than true chronological uncertainty of the samples.

In the ideal situation where all samples are in agreement the symbols representing samples should form a vertical line similar to those from PMPR-A-F1 (Fig 5.17), instead

we see considerable spread of dates (in some cases >400 years). Age reversals and no overlap in error ranges of dates occur in some cases. There appears to be no consistency in the spread of these dates. The wide spread of dates is particularly telling when we consider the narrow error ranges on each date. It is clear that while the error bars may represent the U-Th measuring uncertainty, in most cases this underestimates true chronological uncertainties of the microatolls, in some cases by as much as ~400 years. It seems likely that the samples were subject to unknown processes, either during or post deposition, which are not in agreement with current assumptions of the U-Th dating methodology. Mapur lies in the southern part of the Southeast Asian Tin Belt, and one possibility is that the large variability is related to the high Uranium and Thorium concentrations reported for the region (Ramli et al., 2005; Sanusi et al., 2017). It is noteworthy that while the microatoll slabbing methodology with sample redundancy was able to show this problem, other proxies or even other microatoll studies, if based on single U-Th dates, may be underestimating their age chronology uncertainties and biasing the ages of their samples by as much as ~400 years.

Figure 5.19 shows the SLI sequences plotted according to weighted U-Th dates from respective microatolls. The narrow temporal errors make the reconstruction of a plausible RSL scenario impossible. With no clear procedure to estimate more realistic age uncertainties, we forego the attempt to align the SLI sequences into composite records or produce an RSL curve based on these. It is clear from these figures (Fig. 5.17-5.19) that in this case, dates from U-Th samples can neither form the basis for a reconstruction of RSL on the two sites nor do they distinguish if both sites represent the same period or two periods of similar RSL change.

Figure 5-18 Mapur East. U-Th measurements from individual samples (Squares) adjusted through band counting to date the outside band of each microatoll. Weighted dates (Rhombi) of all U-Th measurements for each microatoll. The narrow error ranges appear to represent U-Th measuring uncertainties rather than true chronological uncertainty of the samples.

Figure 5-19 Weighted U-Th dating of SLI sequences from Mapur. The narrow temporal errors likely represent only the precision of U-Th measurement, but not the true temporal uncertainty of the SLI sequences. Given these narrow temporal errors the construction of a plausible RSL scenario is not possible.

Hypothetically, both interpretations presented in Figures 5.14 and 5.16 are possible. In Belitung, Meltzner et al. (2017) have demonstrated RSL fluctuating by up to 60 cm on centennial scale. However, in that case the RSL fluctuations were, at least in one instance, captured in continuous growth of a single microatoll (Meltzner et al., 2017: Figure 5), and corroborated by another site. In the case of the two Mapur sites this is not the case, not only that, but if the two RSL fluctuations are both real and separate it is unlikely that each site captured only one of the RSL fluctuations and had no microatoll generations representing the other fluctuation. Additionally, the match in timing of diedowns, elevation and RSL trend on both sequences seems to be a very unlikely coincidence.

If, on the other hand, we are to believe that both sites represent the same period, the consistent difference in the apparent age of the corals at the two sites suggest that different ΔR values are appropriate for Mapur North and Mapur East, despite the relatively short (~10 km) distance separating them. Although ΔR variability over such short distances is not well understood it has been noted in some studies (Heier-Nielsen et al., 1995; McGregor et al., 2008). One possible explanation for a difference in ΔR values may be freshwater input at Mapur East; if freshwater zooplankton with younger apparent radiocarbon ages than its marine equivalent entered the food chain of the coral colonies at the site, then the reservoir age at that site might be smaller, necessitating a smaller reservoir correction. We propose that the differences in age between the two sites can be explained by a difference in ΔR of 60 yr from one site to the other and that this is more easily explained than the alternative proposition. This may not be surprising after all, given that ΔR in the region varies from -121 ± 60 yr to $+89 \pm 70$ yr (Southon et al., 2002). It is therefore our preferred interpretation that SLI

sequences from both Mapur North and Mapur East represent the same RSL trend, as presented in Figure 13, although the timing of that trend remains ambiguous since we have no definitive way of telling if the ΔR value used for calibration is correct for Mapur North, Mapur East or indeed for either of the sites.

Discussion

The last step is to compare the RSL trend reconstructed from SLI sequences with data coming from other proxies on the Malay Peninsula. In order to compare the SLI sequences with the more traditional proxies we first need to briefly take a look at the quality of the data from those proxies. Figure 5.20 shows all reliable SLIP points for the Malay Peninsula which overlap in time with the RSL reconstructed from SLI sequences. SLIPs from four studies overlap coincide in time with the data from Mapur Geyh et al. (1979); Hesp et al. (1998); Bird et al. (2007); (2010), data from the two older studies have been plotted following their reinterpretation by Horton et al. (2005).

For much of the period where the SLI sequences and the “traditional” proxies overlap there is a several meter range from the lowest to highest SLIPs. Part of that range may be ascribed to RSL change over time, but the range at any one point in time still appears to be 4-7 meters. Furthermore, it appears that there is a vertical offset between two groups of proxies, lower SLIPs, those based on oysters, bivalves and marine shells and a higher group those reconstructed from wood fragments and peat, with minimal overlap between the two groups. No RSL curve has been reconstructed from the other SLIP points because it is clear that due to the large error bars many different RSL curves

could be attempted. Furthermore, no single plausible RSL curve could be plotted which would be permitted by all SLIPs. Should we attempt to plot an RSL curve through the lowest and highest groups separately, there would be a 4 meter vertical gap between the two curves. The wide spread of data appears to be related to the assumptions underlying the indicative meaning of various proxies. However the discrepancy is not limited to inter proxy comparisons, when we look at the best represented proxy, i.e. wood fragments, there is still an internal range of ~4 meters and no overlap between the highest and lowest SLIPs reconstructed using the proxy. Having established that there are large discrepancies in the “traditional” proxy data set, let us now compare the data from “traditional” SLIPs and that based on SLI sequences.

A total of just 7 SLI sequences used in the final RSL reconstruction produced 28 SLIP points. One and a half times as many as all other proxies combined over this period (20 SLIPs). Despite the larger number of SLIPs the range of RSL observations from microatolls is only 1.02 meters while that of 20 traditional SLIPs is ~10 meters. Thus, not only do SLI sequences provide a much higher density of RSL observations but the vertical range of those observations is an order of magnitude more precise. Additionally, nearly half of that range (0.44 m) can be explained by the RSL change over the time the observations span.

Figure 5-20 Comparison of RSL reconstruction based on SLI sequences with SLIPs from other proxies from Singapore and Malacca Straits. Only SLIPs which overlap temporally with the reconstructed SLI sequences are shown. In the short span of RSL reconstructed from the SLI sequences 28 SLIPs are used, their vertical spread is only 1.02 m, 0.44 m of which is due to RSL change. In contrast, the SLIPs from other proxies are spread vertically over ~10 meters, and at any one point in time by 6-7 meters. Not only can a number of different RSL interpretations be plotted from “traditional” proxy SLIPs but no plausible scenario could account for all SLIPs. The precision of the RSL reconstruction from SLI sequences is an order of magnitude better than that of other proxies. A shorter 22-year reconstruction of RSL from SLI sequences of PMPR-A-F1 also shown. Yellow area shows possible timing range of the RSL

reconstruction.

The elevation of reconstructed RSL appears to be some of the highest reconstructed for the period. It comes closest to match the upper range of SLIPs reconstructed from wood fragments by Bird et al. (2007); (2010) and peat samples reported by Geyh et al. (1979). A single SLIP reconstructed from a coral head also from Bird et al. (2007) matches the short stretch of RSL reconstructed from PMPR-A-F1. However, the coral head is not identified as a microatoll and therefore its use for reconstructing a SLIP is questionable, rather it should have been used as a sea level minimum. None of the other SLIPs from marine samples from Bird et al. (2010) or Hesp et al. (1998) appear to match the SLI sequences, rather, our data is ~5 meters higher. Given that at least some of those points come from the same study as the wood fragments which do match our RSL, it is possible that the choice of a value of ΔR may be to blame. Moving the marine SLIPs 300 years earlier could perhaps bring them more in line with the SLIPs reconstructed from wood fragments.

The timing of the Holocene highstand is not conclusively demonstrated by our reconstruction of RSL because gaps remain in the Mapur record both before, and after, the fossil microatolls investigated here. However, since no higher fossil microatolls of mid Holocene age were found on either site it is likely that our reconstruction is of the peak elevation of RSL on the site. Hence the timing of the Holocene highstand at Mapur appears to be constrained to a period of ~270 years before 7000 cal yr BP. This timing suggests a slightly earlier peak to the Holocene highstand than that reconstructed by Bird et al. (2010) and a much, ~1000 years, earlier timing than that reconstructed by Hesp et al. (1998) and especially Geyh et al. (1979) who postulated a highstand closer

to 5000 cal yr BP, ~2000 years later than indicated by our data. However other microatoll studies on, and near, the Sunda Shelf have also noted the possibility of an early Holocene highstand between 7100 and 6500 (Yu et al., 2009; Meltzner et al., 2017).

Conclusions

In this paper, we have outlined a new approach to RSL reconstruction, using SLI sequences from fossil coral microatolls. By utilizing SLIPs from a continuous unbroken record, such as that provided by coral microatolls, the method reduces the relative vertical errors within an SLI sequence to ± 3 cm (2σ). Vertical gain or loss of as little as >6 cm between SLIPs on an SLI sequence can thus be decisively attributed to RLS change. A similar improvement of precision applies to the temporal scale of the SLI sequences, with only ± 2 years/100 years of record relative error within an SLI sequence. But even more importantly, within an SLI sequence there is no ambiguity about the temporal order of SLIPs i.e. their order can never be changed even if they occur close to each other in time and temporal errors indicate overlap. As a result, while the entire SLI sequence still has vertical and temporal uncertainties the shape of a reconstructed RSL scenario is more robust than any other RSL proxy currently in use.

Our RSL reconstruction supports increasing evidence that the mid Holocene highstand on the Sunda Shelf occurred earlier than previously thought. Although ambiguities in the available “traditional” RSL data remain due both to the lower precision of many

proxies and problems remaining to be solved both with U-Th and Radiocarbon dating on the Sunda Shelf.

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Supporting information for Chapter 5

Supplementary figure 8 Detail of PMPR-A-F1 coral microatoll structure.

Supplementary figure 9 Detail of PMPR-A-F3 coral microatoll structure.

Supplementary figure 10 Detail of PMPR-A-F4 coral microatoll structure.

Supplementary figure 10 Detail of PMPR-A-F6 coral microatoll structure.

Supplementary figure 11 Detail of PMPR-B-F1 coral microatoll structure.

Supplementary figure 12 Detail of PMPR-B-F2 coral microatoll structure.

Supplementary figure 13 Detail of PMPR-B-F3 coral microatoll structure.

Supplementary figure 14 Detail of PMPR-B-F4 coral microatoll structure.

Supplementary figure 15 Detail of PMPR-B-F5 coral microatoll structure.

Chapter 6 Summary and recommendations for further work

The five previous chapters in this thesis summarize a body of work that further demonstrates the utility of coral microatolls for building long composite sequences, at least in regions where the 18.6-year tidal cycle reliably imprints within the coral skeletal structure. The work presented also adds improved constraints on the relationship between coral microatoll growth histories and relative sea level.

In chapter 2 a review of the development of the coral microatoll sea level methodology is presented. Here, key contributions that helped to shape our current understanding of coral microatolls and their use as a sea level proxy are highlighted and discussed. This chapter also contains a description of the key aspects of microatoll methodology, and highlight those, such as ponding, whose full implications are sometimes underestimated or poorly constrained. The chapter concludes with a section reviewing the Holocene sea level studies on the Sunda Shelf focusing on the limited geographical spread of previous studies and outlining where the work in this thesis was conducted and the scientific aims proposed to advance the use of coral microatolls in the region.

The work presented in chapter 3 addresses ponding and shows that ponded coral microatolls do register diedowns due to the 18.61-year tidal cycle, however, the elevation element of such diedowns is dampened, hence, unreliable as a sea level proxy. Additionally, ponded microatolls record additional diedowns which do not result from the tidal cycle, they can also grow significantly higher than open water

microatoll, disqualifying their record from use as a proxy for RSL record. Using ponded microatolls may in some cases be possible, if not advisable, with regards to RSL heights, provided a sufficient error range is applied. However, the use of ponded microatolls for reconstruction of sea-level trends is not recommended. In order to avoid the ponding issue coral microatolls should ideally be chosen from locations on the seaward side of the reef crest, in places where no barrier of any kind exists between deeper water and the microatoll.

Chapter 3 also contains evidence that demonstrates that open ocean microatolls respond to the 18.61-year tidal cycle, tracking the local sea level. A first order comparison of mean sea level from tide gauges in Singapore and the Malay Peninsula with RSL of an open water microatoll from Mapur, shows good agreement of sea level data from the two sources. Here, though the sea level trend could only be compared with tide gauges over a ~30-year period, they show good agreement over the period. This suggests that sea level trends can be reconstructed from coral microatolls provided their record is long enough, though the temporal resolution of such a trend may be limited to minimum of 18.6 years. Here we also reconstruct a sea level trend from an open sea level coral microatoll, it shows the sea level in the region has a long term (1915-2005) vertical change rate of 0.01 ± 0.88 mm/yr.

Chapter 4 summarizes an investigation of four fossil microatoll sites in western Sarawak, Borneo, allowing the reconstruction of the first mid Holocene RSL record in Borneo. With the reconstruction, we demonstrate that rapid RSL rise in Borneo stopped by ~7450 year BP and RSL remained stable for at least the following 450 years.

This finding may imply an earlier end to rapid ice-sheet melt or significant spatial differences in rheology on the Sunda Shelf, or both.

While reconstructing RSL we also found a 1.1-meter vertical offset between our sites which is best explained by, previously unrecognized, tectonic movement along the Serabang Line, sometime after 7000 yr BP. The Serabang line is considered inactive, and our reconstruction suggests the fault may have been active within the Holocene and should be investigated to ascertain any potential hazard it may pose. This finding demonstrates that the approach of comparing RSL models with local data may be valuable not only for RSL studies but also for understanding tectonic processes and hazards in coastal regions.

In chapter 5, we define Sea-level index sequences, a new format for RSL data from continuous sea level proxy records such as coral microatolls. Utilizing data from an SLI sequence reduces the relative vertical errors within an SLI sequence to as little as ± 3 cm (2σ), although this value may vary across different sites. A similar improvement of precision applies to the temporal scale of the SLI sequences, with as little as ± 2 years/100 years of record relative error within an SLI sequence. More importantly, SLI sequences eliminate ambiguity in the order of sea-level index points from a proxy; their order cannot be changed even if they occur close to each other in time and temporal errors indicate overlap. As a result, while the entire SLI sequence still has vertical and temporal uncertainties the shape of a reconstructed RSL scenario is more robust than any other RSL proxy currently in use in the tropics.

The SLI sequence approach is then applied to fossil microatolls on Mapur Island, Indonesia, where a 115 year RSL sequence from ~7280 until ~7160 cal yr BP is reconstructed using the SLI sequence approach. The Mapur fossil sequence shows elevation rising from ~40 cm to ~90 cm above present and provides further support for an early mid Holocene highstand on the Sunda Shelf, closer to 7000 years BP than the 5000 years BP previously published.

Future Work

Throughout this study and particularly in chapters 2-5, this study identified several areas where future work may focus both in advancing our knowledge of coral microatoll as a sea level proxy and improving sea level records on the Sunda Shelf.

In Chapter 3 it was demonstrated that coral microatolls from open water locations respond to the 18.61-year tidal cycle, and record local sea levels. The match of tide gauge measurements of mean sea level with coral microatoll RSL records over a two-decade period suggests that the latter could be used to recover long term sea level trends, provided sufficiently long lived coral microatolls could be found and studied. Additional studies should be conducted where a microatoll slab is compared to a longer tide gauge record to test whether that the agreement holds for longer coral microatoll sequences in different regions. Following such a demonstration living coral microatolls may then be able to produce a number of records of sea level from low latitude locations stretching back several hundred years. The coral based approach has the

potential to extend sea level and sea level trend observations for locations where tide gauges were not installed until recently and have poor resolution.

An outstanding question for coral microatolls is the time and conditions required to cause a diedown. While chapter 3 demonstrates convincingly, that coral microatolls respond to low tides, more precise information of the time and conditions required to cause a diedown could help constrain anomalies in coral microatoll records such as diedowns not registered during particularly low tides, or diedowns registered when tides were not particularly low. As such robust field tests should be conducted to test the time and conditions (sunny, overcast, raining, night) required to cause or to prevent a diedown occurring.

In Chapters 4 and 5 we used fossil microatoll records to reconstruct RSL over 115 and 450 year periods. The potential is clear and many more records should be sought, particularly ones which partly overlap with the reconstructed periods. Allowing for the linking of the reconstructed periods. Such work will extend the temporal window of these observations and allow a composite record to be built which will likely be able to show RSL on the Sunda Shelf in decimeter precision over hundreds to thousands of years.

Chapters 4 and 5 also demonstrate there is a wide range of RSL observation on the Sunda Shelf, more sites should be investigated in new locations to constrain the spatial differences in RSL histories of the region.

Chapter 5 introduced the SLI sequence format for RSL data from continuous RSL proxy records. While slabbed microatolls may offer the most detail the SLI sequence format may also be applied to studies where the upper surface of a fossil microatoll is surveyed in detail (as was done in chapter 4). This approach could offer an additional layer of information from previously investigated fossil microatoll sites, without the need for costly or logistically difficult fieldwork. Particularly in situations where previously dated fossil microatolls could be relocated and resurveyed.

There remains much to do in sea level in the tropics and the promise of microatoll based sea level studies in the tropics shows great promise. New work and additional sites will likely provide better constraints on past sea level and information for the calibration of global ice models and predictions for future sea level change in the region.

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