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Investigating past earthquakes with coral microatolls

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Intertidal corals (microatolls) preserve evidence of past uplift or subsidence with annual precision. Microatoll records are particularly useful along subduction zones, and can reveal past earthquake ruptures at a level of detail that is ordinarily limited to the instrumental era.

The need for high-precision, widely distributed paleoseismic data

Decades of research have led to the realization that earthquake recurrence is complex, but nevertheless often follows a recognizable pattern (Philibosian and Meltzner 2020). Common patterns include rupture cascades (series of earthquakes on neighboring fault sections) and superimposed cycles (two or more neighboring fault sections with different recurrence intervals). To determine the types of recurrence patterns exhibited by a particular fault, it is necessary to establish details of past ruptures –timing, rupture extent, amount of fault slip –over several earthquake cycles. The required level of detail can be achieved only by using techniques with high temporal and spatial precision, as well as a wide distribution of study sites. The coral-microatoll technique, while limited in its applicability by the occurrence of reef-building corals above faults producing vertical movement, is perhaps the most precise among geologic-paleoseismic techniques.

The microatoll technique

The upward growth of corals in the intertidal zone is limited by relative sea level (RSL), as corals cannot survive for long out of the water. Reef-building coral species that grow radially outward generally form roughly hemispherical colonies underwater, but in the intertidal zone typically produce a colony with a flat, dead top, surrounded by a ring of living tissue that extends below the water.

The term "microatoll" was coined for these specimens based on their resemblance to ring-shaped coral reef atoll islands. As a microatoll grows outward, the height of the living outer ring responds to changes in RSL. Thus, the upper surfaces of microatolls record RSL over the lifetime of the colony, which in some species can reach hundreds of years. Furthermore, microatolls can be preserved in or near the intertidal zone for hundreds, or even thousands, of years after they die. Most coral species produce annual density bands analogous to tree rings. This combination of characteristics allows records of RSL to be reconstructed with annual precision over centuries, or millennia. Absolute ages of corals that died in the past are still limited by the precision of radiometric dating, but uranium-thorium disequilibrium dating can be used on corals, potentially yielding ages with uncertainties of less than a decade. Furthermore, the relative timing of events (annual precision) within a given coral record is not affected by absolute dating uncertainties.

Coral microatolls are sampled by cutting a radial slice, obtaining an X-ray image of the slice to reveal the annual bands, and measuring the growth height of each band (Fig. 1). Large, sudden height changes can be interpreted as earthquakes, whereas gradual trends in growth height over time record interseismic behavior. However,

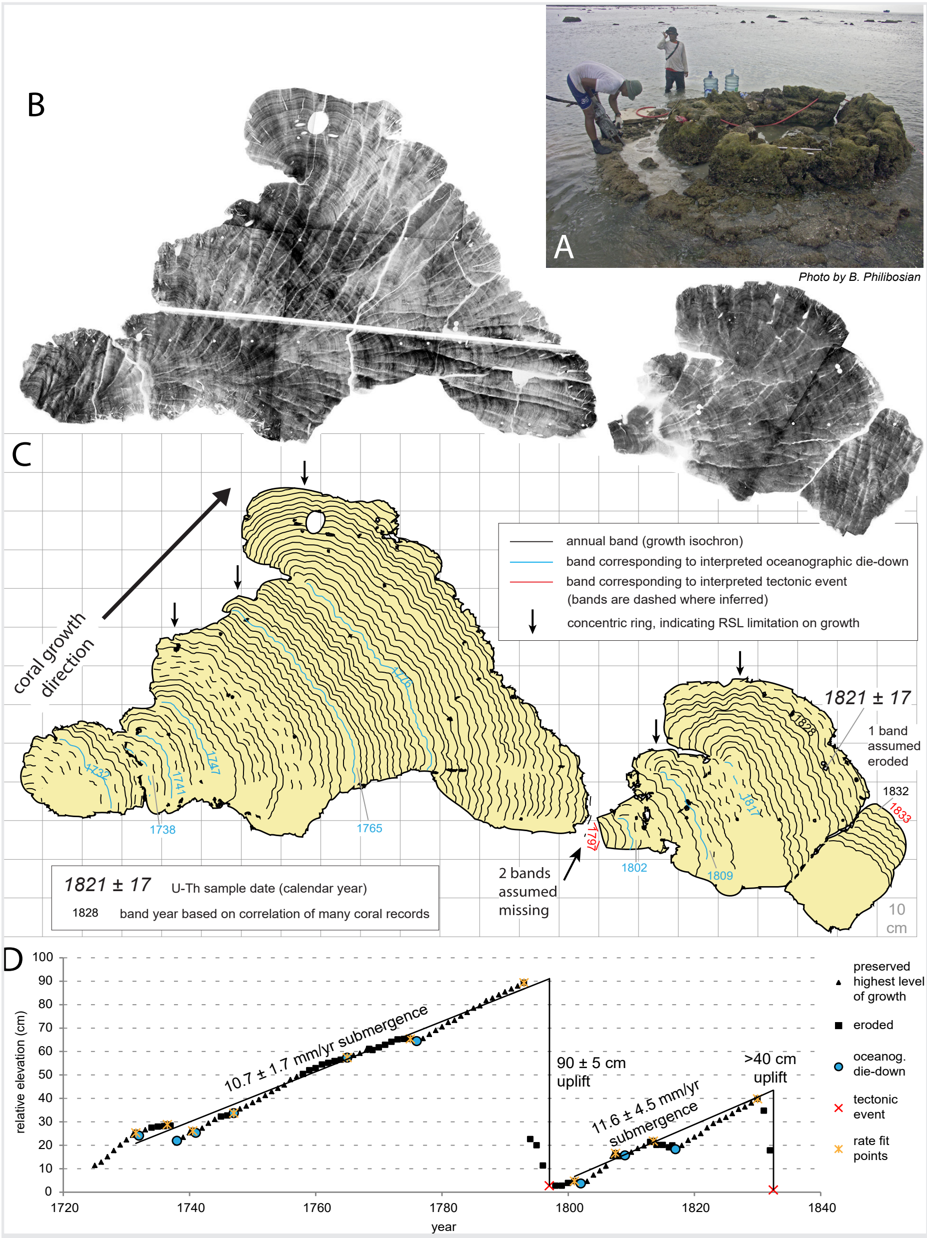

Figure 1: Example microatoll interpretation (modified from Philibosian et al. 2014; Philibosian 2024). **(A)** A microatoll from which a radial slice is being cut with a hydraulic chainsaw. **(B)** X-ray image of the collected slice showing annual banding. **(C)** Interpreted microatoll cross-section. **(D)** Plot of annual coral growth height with measured uplifts and submergence rates estimated by linear fits to points preceding die-downs. This microatoll recorded two earthquakes 36 years apart; others have similarly recorded doublets separated by as little as four years (e.g. Philibosian et al. 2017).

there are several interpretive steps between coral growth height and tectonic uplift or subsidence. The relationship between coral upward growth and RSL change is asymmetric, as a drop in sea level will cause the upper part of the coral to die within days, but a rise in sea level will usually leave an intertidal coral within its depth range, simply providing space for the coral to grow. This response takes years to be recorded (Fig. 2). In combination with the noise generated by interannual oceanographic fluctuations in sea level (such as those associated with the El Niño – Southern Oscillation), this means that gradual changes in RSL derived from microatoll records are often inaccurate unless averaged over a decade or more (as in Fig. 1d).

Finally, to isolate tectonic uplift or subsidence, all other signals (most significantly eustatic sea-level change) must be removed from the RSL record (see Philibosian 2024). For sudden uplift or subsidence events (as often occur during earthquakes), the nontectonic contributions are generally negligible, but their impact can be more significant on estimates of gradual interseismic motion. Fortunately, most of the other potential signals affect large regions equally, such that any differences in RSL trend between nearby sites (up to a few hundred kilometers apart) can confidently be attributed to active tectonics.

In regions where coral microatolls are plentiful, numerous study sites can be fairly easily established over a broad area (Philibosian 2024). Whereas the specialized equipment and logistics for sampling microatolls are expensive, there are significant economies of scale that many other paleoseismic techniques (such as trenching) do not have.

Past and current applications

The coral-microatoll technique has long been used in paleoclimate studies (beginning with Scoffin and Stoddart 1978), and has since been applied and further tailored to earthquake research beginning with Taylor et al. (1987), but primarily in the 21st century. Thus far, the most extensive and successful use in an active tectonic context has been to establish the history of uplift and subsidence during and between earthquakes along the Sumatran Sunda Megathrust. The majority of the now-known best practices were established over the course of the Sumatran tectonic studies (see Meltzner and Woodroffe (2015) and Philibosian (2024) for details). These microatoll studies enabled multiple cycles of paleoearthquakes to be examined in unprecedented detail, including disambiguating individual events that occurred only a few years apart, and estimating rupture extent and slip magnitude for each event.

The Sumatran microatoll records have illuminated many hitherto underappreciated aspects of fault behavior, such as persistent rupture segmentation (e.g. Meltzner et al. 2012), complex earthquake recurrence cycles (Philibosian et al. 2012; Philibosian et al. 2017; Sieh et al. 2008), years-long

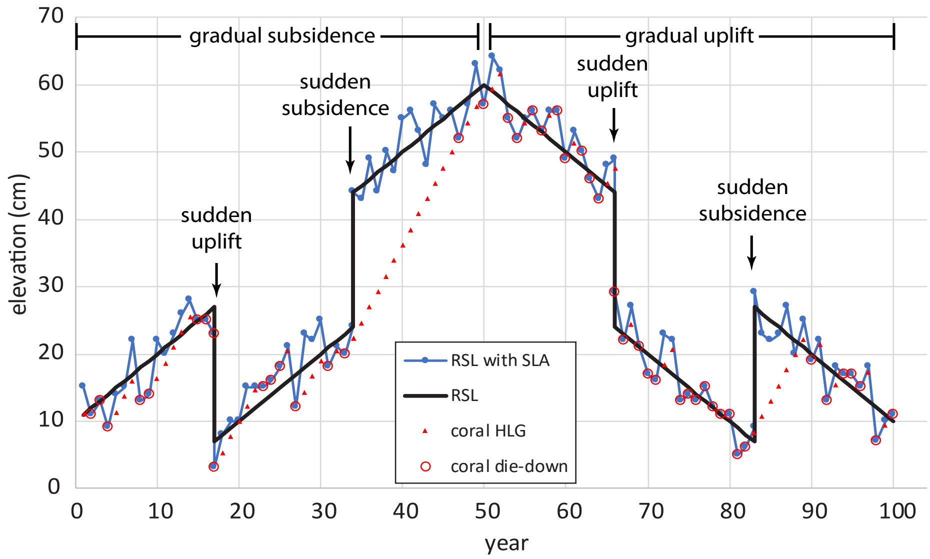

Figure 2: Synthetic illustrative RSL history and resultant microatoll growth record (modified from Philibosian 2024). Black line shows RSL history with steady 1 cm/yr submergence over the first 50 years and equivalent emergence over the second 50 years, with sudden 20-cm emergence and submergence events during each period. Blue line with markers shows the same RSL curve with random ±5 cm interannual sea-level anomaly (SLA) fluctuation added. Red markers show response of a coral with 2.3 cm/yr upward growth rate; triangles indicate years in which height is limited by growth rate (highest level of growth, HLG) and circles show years when it is limited by sea level (die-downs).

slow-slip events (Tsang et al. 2015b), and variable strain accumulation over time (e.g. Meltzner et al. 2015; Philibosian et al. 2014; Tsang et al. 2015a).

The microatoll technique is gradually spreading to other tropical active-tectonic study areas, having been applied with varying degrees of success to subduction paleoseismology and paleogeodesy along the northernmost Sunda (Arakan) margin, the Solomon Islands, the Lesser Antilles, and the Ryukyu Arc, with nascent application in the Philippines. Microatolls have also served as vital recorders of uplift and subsidence during recent subduction earthquakes in Vanuatu and the Solomon Islands, as well as those along the Sumatran Sunda Megathrust. They have additionally been applied in an oblique strike-slip environment to measure vertical motion during the 2010 Haiti earthquake. Philibosian (2024) includes a complete current list of publications that have used coral microatolls in active tectonic studies.

Successful coral-microatoll studies ultimately provide maps of tectonic vertical motion with annual precision. This precision allows individual earthquakes that occurred only a few years apart to be distinguished in the geologic record, and demonstrates that no earthquakes producing significant uplift or subsidence occurred during parts of the record that lack sudden RSL changes. For each individual earthquake rupture, the distribution of uplift and subsidence can be modeled to obtain the rupture extent and fault-slip distribution, using the same procedures as would be done for any other type of surface-deformation measurement. Similarly, gradual interseismic vertical motion can be modeled to estimate the distribution of fault coupling and concomitant strain accumulation.

Obtaining such precise characteristics of individual paleoearthquakes is vital for assessing fault behavior, including the persistence of rupture segmentation, recurrence patterns, and similarity of successive events; key issues in both fault mechanics and hazard assessment. The coral-microatoll technique may be a useful component for any study involving active tectonic uplift or subsidence along coastlines where corals grow.

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