Crustal Deformation at the Sumatran Subduction Zone Revealed by Coral Rings

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Abstract. Analyses of coral rings grown in the interval 1970-1997 reveal a geographically distinct pattern of interseismic uplift off Sumatra's western coast. At distances less than 110 km from the Sumatran trench, coral reefs are submerging as fast as 5 mm/y. At 130 and 180 km distance from the trench, they are emerging at similar rates. We suggest that a locked, or partially locked patch, located above 30 km depth on the upper surface of the subducting oceanic plate, generates this pattern.

1. Introduction

One concept of the earthquake cycle at subduction zones envisions a sinking slab whose upper surface exhibits dual behaviors. The shallow part of the surface remains locked or partially locked between earthquakes, whereas the deeper part slips more or less continuously. Seismic and interseismic phases of the earthquake cycle ascribe to rapid episodic displacements on the shallow surface and to slow continuous creep on the deeper part, respectively. Abundant seismological and geodetic data document the seismic phase of the cycle, but data relevant to the interseismic stage are sparse. Primarily, the disparate degrees of documentation arise from the different time scales for the two stages. Seismic deformations are sudden and are easy to spot. Interseismic deformations accumulate gradually over decades or centuries, and accurate, stable, and long-lived "tape recorders" of these signals have been difficult to identify.

Along some coastlines at least, one tool that is proving useful in illuminating interseismic deformations is coral microatolls. These coral forms do indeed fill the role of tectonic tape recorders by monitoring variations in relative sea level over decades with an accuracy of about one cm (*Zachariasen et al.*, 1999b). This paper employs 25-year average rates of uplift extracted from coral microatolls to examine previously invisible interseismic deformations along a transect perpendicular to the Sumatran subduction zone.

2. Paleogeodesy from Coral Microatolls

Certain head corals record vertical tectonic motions because their growth is restricted by occasional subaerial exposure (*Zachariasen et al.*, 1999b). In particular, these corals grow upward and outward until they reach a level close to the annual lowest low tide. From this point, they can only grow outward. The history of relative sea level at a site thus molds the shape of the corals growing there. Heads maturing on sta-

ble reefs develop nearly flat, pancake-like upper surfaces. Heads maturing on submerging coastlines develop a "teacup" appearance as their living perimeter grows to levels higher than older, dead interiors. On emerging reefs, corals evolve a conical top due to the progressive fall of the uppermost growth limit as the living perimeter expands outward.

In 1997 and 1998 we sampled and analyzed a suite of corals from 11 reefs above the Sumatra subduction zone near the Equator. Figure 1 locates the reef sites and their tectonic environment. The reefs lie 95 to 250 km from the active deformation front (Sumatran trench) and 20 to 100 km over the subducting plate. Typically, coral heads measure 1 to 2 meters in radius and stand 50 to 100 cm above the substrate. Coral sampling involves saw-cutting a vertical slice from the perimeter to the center of a head. The cut slabs measure several cm thick and about 50 cm high. On the surfaces of a slab, 1-cm spaced annual growth bands (resembling tree rings) of the coral skeleton are faintly visible with the naked eye. To enhance the visibility of the annual banding, a large circular saw, housed at a marble-fabrication facility, shaved 5 to 7-mm-thick "thin
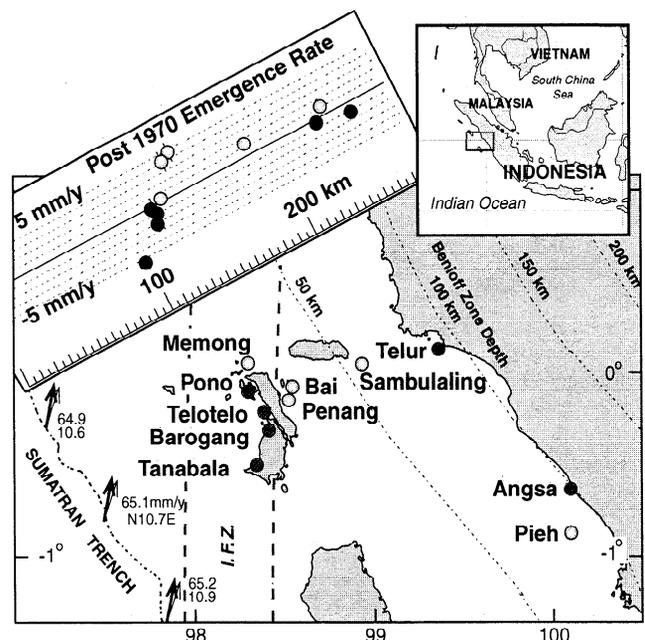
Figure 1. Location map for the study area and summary of post-1970 uplift rates projected on a section perpendicular to the Sumatran trench. Features of deformation include: relative subsidence trenchward, uplift over the islands, and a tapering to zero at the coast.
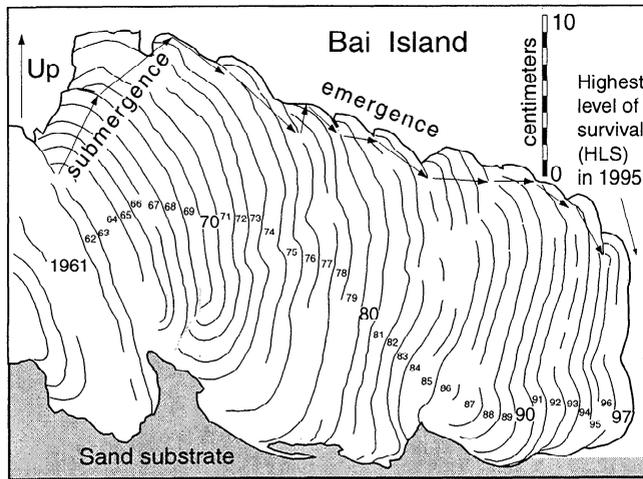
Figure 2. Cross section of a coral microatoll from Bai Island. The X-rayed thin slab reveals a clear record of annual growth bands expanding radially outward (from left to right) at about a cm/y. The Highest Level of Survival of the coral during the past 35 years is recorded in the topography of the coral's upper surface. The arrows track the rise of sea level in the 60s and its subsequent fall.

sections" from the slab. X-radiographed pictures of the thin section's annual growth rings comprise the raw material for interpretation (See Figure 2).

The tectonic tape recorder contained in these X-ray pictures works like this: In years when the annual lowest low tide is not unusually low, the corallites grow upward and outward unimpeded. In years with an unusually low tide, the uppermost part of the head dies from exposure, and the coral colony only grows outward. Early workers (*Scoffin and Stoddart*, 1978; *Taylor et al.*, 1987) termed this upper limit to growth the Highest Level of Survival (HLS). The changing elevation of the HLS along the radius of a coral section thus tracks the history of extreme low tide. On living corals, counting the rings backward from the year of sampling fixes the date of each HLS. For dead corals, spot U-Th dates help establish the age of selected rings. The cross-section in Figure 2 evidences a history of emergence since about 1974. The evidence is manifest in the progressive lowering of HLS with time (follow the arrow trail). Corals too, record submergence. A 1962 submergence episode appears as a spurt of upward growth at the left of the figure.

Of the many rapid and slow changes in HLS recorded in the corals, we concern ourselves here only with mean HLS change in the period 1970-1997. Figure 3 (middle right) displays the sea-level history obtained from the Bai Island slab in Figure 2. A least-square fit to the HLS elevations yields an average emergence rate of 4.8±0.6 mm/y for this time. Slabs from other sites yielded rates of emergence or submergence up to 5.5±0.4 mm/y. Note that the submergence rate at Tanabala (top left) stems from surrogate data (1900-1935) because we did not collect from a living, modern head there. Instead, a dead microatoll found in the intertidal zone spoke for the site. This coral was suddenly and fatally uplifted earlier in the century, most likely during a large earthquake on January 4, 1935 (U-Th analysis supports this proposal). Additionally, the rate at Pono Island (second row left) predicates on the removal of a sudden 100 mm uplift around 1984.

In overviewing the data in Figure 3, a geographically distinct pattern of interseismic uplift becomes apparent. At distances less than 120 km from the trench, the reefs are submerging. Between 120 and 220 km distance from the trench, they emerge with rates peaking near km #140. Below, we offer a possible mechanism for this uplift.

3. Deformation Modeling

Dislocations have had great success in interpreting coseismic deformation fields and in tying together seismic and geodetic observations. It is natural to attempt to extend this success to the interseismic stage as well. In this extension, we view dislocations causing interseismic deformation merely as slow versions of those that create coseismic fields. Figure 4 cartoons the concept. The vision involves a subducting slab of initial thickness T bounded by uniform slip rate (v_{plate}) dislocations forming its curved bottom surface and its upper surface beyond distance x_{slip} from the trench. The upper surface, from the trench to distance x_{lock}, coincides with a dislocation that is permitted to creep at rate v_{out} ("out" stands for outboard). The sense of v_{plate} and v_{out} are reckoned positive in the direction of subduction, as the figure indicates. Note that if $v_{out}=0$ and the thickness of the slab goes to zero, the dislocations on the top and bottom faces cancel, except for a piece of the interface between the trench and distance x_{slip} that suffers a negative slip rate, -v_{plate}. To this extent, the concept in Figure 4 represents a small, but geophysically meaningful, extension of the "backslip" model of interseismic deformation proposed by *Savage* (1983).

The shape of the subducting slab in the model follows the top of the Sumatran Benioff zone (See dashed contours, Figure 1). The slab, 15 km thick at the trench axis, thins to zero at a depth of 160 km. Although the concept visualized in Figure 4 could include along-strike variations in geometry, at this time, the narrow geographic and temporal extent of the coral data warrant only a two-dimensional, halfspace interpretation. Moreover, it seems appropriate in this application to fix v_{plate} from independent information. Both the NUVEL-1A Australia/Europe pole (15.2°N, 40.5°E, 0.69°/ma), and our GPS-
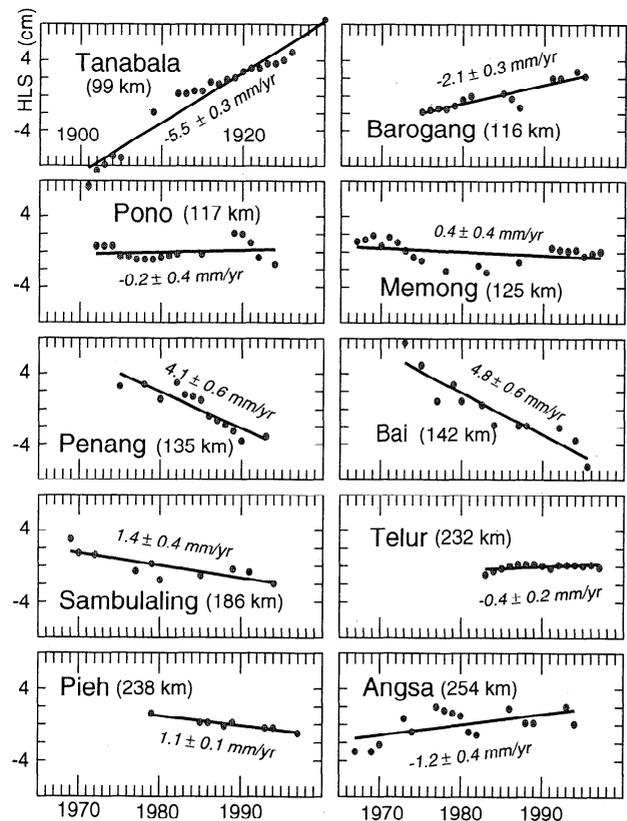
Figure 3. Representative coral HLS histories (in cm) with least-square linear fits. The HLS reference level is arbitrary. Note that the Tanabala record spans an earlier interval. The number in parentheses cites distance from the trench.
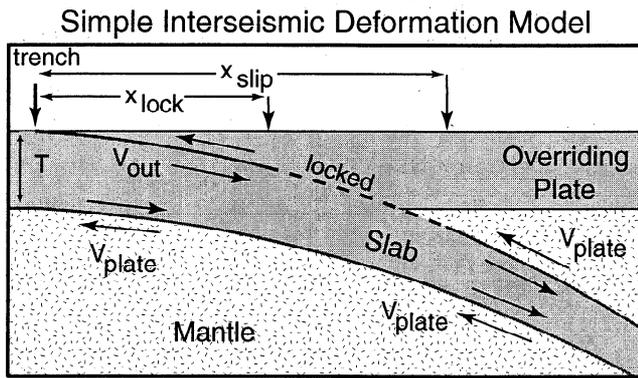
Simple Interseismic Deformation Model

Figure 4. Sketch showing the parameters of an idealized model of interseismic deformation at a subduction zone.

mismatch stems from an unmodeled, 3-D process. Relative to the geology toward the northwest or southeast, the Sumatran forearc structure under our transect is complex (*Sieh and Natawidjaja*, 1999). Also, just to the south, *Prawirodirdjo et al.* (1997) measure significantly higher convergence ($\approx$3 cm/y at 3-4^{0}S). Hydrous minerals rising from the slab and piped through the subducting Investigator Fracture Zone (IFZ, Figure 1) might be encouraging unusually strong aseismic slip (high v_{out}) in our field area.

4. Conclusions

Average offshore uplift in western equatorial Sumatra between 1970 and 1997 appears to be relatively well explained by a traditional concept of interseismic deformation at a sub-
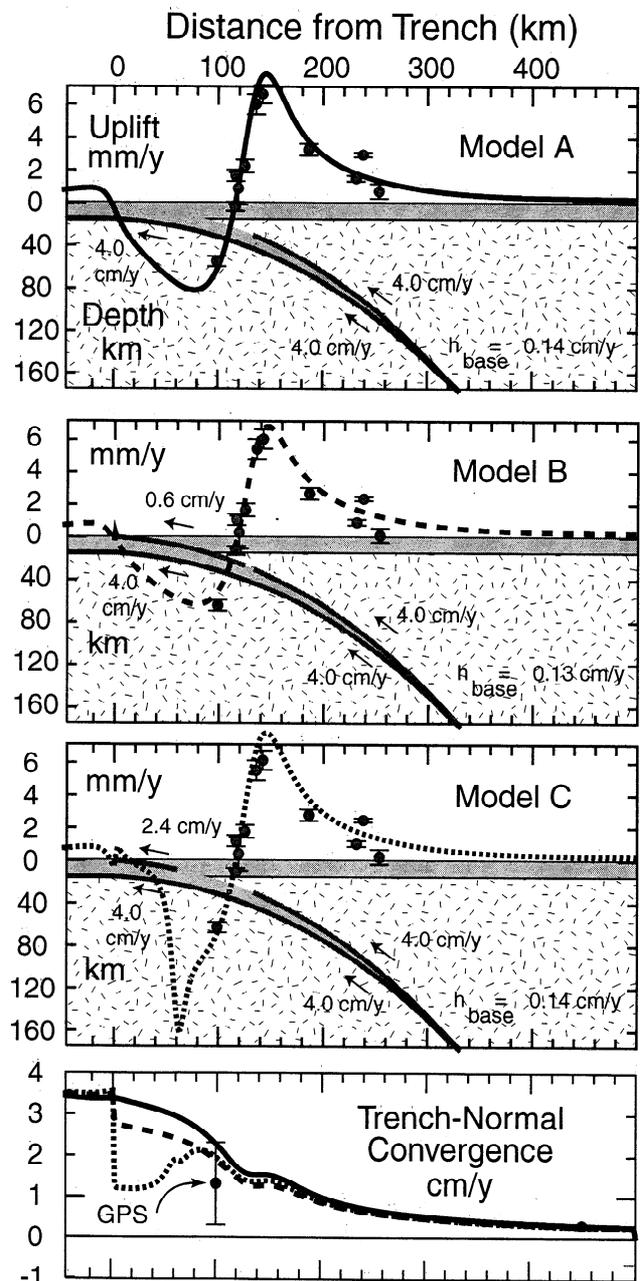
determined Australia/S.E. Asia pole (9.9^{0}N, 27.4^{0}E, 0.62^0/ma), predict 6.5 cm/y (N18^{0}E) and 6.5 cm/y (N11^{0}E) of oblique plate convergence across the field area (see Figure 1). Perpendicular to the trench, convergence amounts to 4.0 or 4.5 cm/y. Accordingly, in our inversions we set $v_{plate} = 4$ cm/y.

With the assumptions above, the number of free parameters falls to four: v_{out}, x_{slip}, x_{lock} and baseline correction h_{base}. The latter accounts for any post 1970 relative sea level changes caused by unmodeled processes. These include climatic and oceanographic sources or tectonic deformations on scales far larger than the dimension of the field region (e.g. postglacial rebound). Constraining the four model parameters are the eleven relative uplift data from Figure 1 and one summary GPS datum taken from *Prawirodirdjo et al.* (1997). They report that recent (1990-1995) shortening on lines between the outer islands and the Indonesian interior at the latitude of interest (0-1^{0}S) register only a small fraction of the convergence predicted by plate tectonics. The employed datum of 1.0±1.0 cm/y intends to summarize the GPS observations at several outer-arc sites.

The panels of Figure 5 portray a suite of models that fit the geodetic data equally well. Surprisingly, of the recovered parameters, x_{slip} (133 ± 3 km) is best determined. The upper terminus of the downdip dislocation always parks itself tightly under the peak of emergence at a depth of 30 km. Apparently, the 140 km seismogenic width (down-dip distance from the trench to the terminus at x_{slip}) of slab here compares closely to that 300 km to the southeast where a 175-km wide patch ruptured in the M9, 1833 earthquake (*Zachariasen et al.*, 1999a). The inversion also stably recovers parameter h_{base} at 1.3-1.4 mm/y; however, the correction correlates strongly with the assumed value of v_{plate}. A v_{plate} of 4.5 cm/y inflates h_{base} by 0.2 mm/y. In any case, our h_{base} offers no conflict with estimates of twentieth century global sea level rise that hover between 1.2 and 2.4 mm/y (*Gornitz et. al.* 1982; *Peltier and Tushingham*, 1989). The most poorly resolved model parameters are the size and strength of the outboard dislocation. Fully locked shallow slab surfaces (Model A: $x_{lock}= x_{slip}= 133$ km; $v_{out}=0$), fully creeping surfaces (Model B: $x_{lock}= x_{slip}= 133$ km, $v_{out}= 0.6$ cm/y) or partially locked and partially creeping surfaces (Model C: $x_{lock}= 63$ km; $x_{slip}= 133$ km, $v_{out}=2.4$ cm/y) all fit adequately. The large uncertainty of v_{out} reflects the fact that the contribution of the outboard dislocation to the deformation concentrates seaward of any coral data yet available. The least satisfactory behavior of the model suite is its misfit of the GPS datum. To reproduce the low trench-normal convergence rate, the outboard dislocation must creep more than 3 cm/y to about 15 km depth (x_{lock} ~90 km) (see Model C). Creep of this scale however, would submerge corals in the western edge of the field area far faster than we have yet observed. Perhaps the

Figure 5. Cross-sections, showing the coral uplift rates (dots), slab slip extent (red lines) and predicted uplift rates (curves) for three deformation models. (Bottom) GPS summary datum (dot) and the predicted rates of convergence (curves).

duction zone. The shallow face of the sinking slab, in this concept, is mostly locked to the overriding plate above 30 km depth, while the deeper face slips continuously. The upper slab interface may be creeping several cm/y, however current information poorly illuminates outboard behaviors.

By acting as tape recorders of relative sea level, corals stock a wealth of information on long and short-term tectonic and climatic processes. We continue to mine this wealth by densifying and expanding HLS maps, and by improving the tools of interpretation. Guided by initial models, future fieldwork will sample reefs both closer to the trench and further northward. HLS information from these sites should help to constrain v_{out} and expose the extent of along-strike two-dimensionality. Interpretations will concentrate on a finer dissection of temporal and spatial features of uplift. Particular targets are coseismic signals parented during huge subduction zone earthquakes. By patching histories from living and dead corals, we believe that these earthquakes can be detected and characterized back to the early part of the millennium.

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