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## An ancient shallow slip event on the Mentawai segment of the Sunda megathrust, Sumatra

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[1] The outer-arc islands of western Sumatra rise during great megathrust earthquakes, due to large slip on the underlying megathrust. In contrast, the islands subsided up to a few centimeters during the recent tsunamigenic earthquake of October 2010, due to slip far updip, near the trench. Coral microatolls on one of the islands recorded a much larger subsidence, at least 35 cm, during an event in approximately A.D. 1314. We calculate a suite of slip models, slightly deeper and/or larger than the 2010 event, that are consistent with this large amount of subsidence. Sea level records from older coral microatolls suggest that these events occur at least once every millennium, but likely far less frequently than their great downdip neighbors. The revelation that shallow slip events are important contributors to the seismic cycle of the Mentawai segment further complicates our understanding of this subduction megathrust and our assessment of the region's exposure to seismic and tsunami hazards.

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### 1. Introduction

[2] The identification of historical seismic gaps along subduction megathrusts has long been the principal basis for anticipating which section of these great faults are most likely to rupture next [e.g., *Imamura*, 1928; *Kelleher et al.*, 1973]. Nonetheless, it has been known for several decades that this method sometimes fails to identify significant seismic sources. For example, great fault ruptures sometimes overlap patches that have already ruptured during other recent large earthquakes, such as the 2004 Aceh-Andaman earthquake [*Bilham et al.*, 2005] and the 2011 Tohoku-Oki earthquake [*Simons et al.*, 2011]. Moreover, great ruptures do not always involve failure of the entire seismic width of a megathrust. Models for coseismic slip during the great

Nias-Simeulue earthquake of 2005, for example, do not infer rupture of a wide band of the megathrust between the outer-arc islands and the trench [*Briggs et al.*, 2006] and afterslip on that updip section does not appear to be accumulating fast enough to recoup potential slip accumulating at the rate of plate convergence [*Hsu et al.*, 2006]. The tsunamigenic 1907 Nias-Simeulue earthquake may have been produced by a major shallow megathrust rupture which filled in this gap [*Kanamori et al.*, 2010].

[3] It used to be thought that such shallow, near-trench sections of subduction megathrusts failed only aseismically and thus posed no seismic or tsunami threat [e.g., *Byrne et al.*, 1988; *Scholz*, 1998]. The insensitivity of land-based geodetic measurements to strain accumulation near the trench falsely reinforced this notion [*Avouac*, 2011]. Several recent large, near-trench earthquakes have shown that shallow sections of megathrusts may commonly slip seismically. Modeling of surface deformation and seismic data suggests that the 2004 Aceh-Andaman rupture extended all the way up to the trench along much of its length [e.g., *Subarya et al.*, 2006], the tsunamigenic 2006 Java earthquake was caused by failure of a section of the Sunda megathrust very close to the trench [*Ammon et al.*, 2006; *Fujii and Satake*, 2006], and much of the moment of the 2011 Tohoku-Oki earthquake resulted from failure updip from previous magnitude 7–8 earthquakes, possibly within a few tens of kilometers of the trench [e.g., *Lay et al.*, 2011]. As such shallow ruptures often produce disproportionately devastating tsunamis [*Polet and Kanamori*, 2000], it is of significant humanitarian (as well as scientific) interest to investigate the recurrence of shallow megathrust ruptures.

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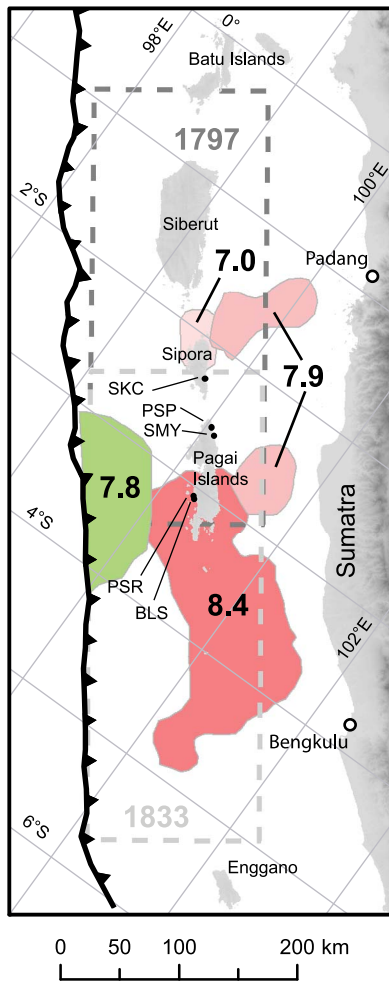
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**Figure 1.** Recent and ancient ruptures along the Mentawai section of the Sunda megathrust. Colored patches are surface projections of 1-m slip contours of the deep megathrust ruptures on 12–13 September 2007 (pink to red) and the shallow rupture on 25 October 2010 (green). Dashed rectangles indicate roughly the sections that ruptured in 1797 and 1833. Ancient ruptures are adapted from *Natawidjaja et al.* [2006] and recent ones come from *Konca et al.* [2008] and Hill et al. (submitted manuscript, 2012). Labeled points indicate coral study sites Sikici (SKC), Pasapat (PSP), Simanganya (SMY), Pulau Pasir (PSR), and Bulasat (BLS).

[4] An example of particular importance to this study is the  $M_w$  7.8 Pagai Islands earthquake of October 2010 (Figure 1). It and its lethal tsunami were caused by rupture of a section of the megathrust within just a few tens of kilometers of the trench and updip from the ruptures of the  $M_w$  8.4 and 7.9 earthquakes of 2007 (E. M. Hill et al., The 2010  $M_w$  7.8 Mentawai earthquake: Very shallow source of a rare tsunami earthquake determined from tsunami field survey and near-field GPS, submitted to *Journal of Geophysical Research*, 2012). In this paper we present and analyze data from one coral microatoll that implies a large seismic rupture of the megathrust (at intermediate depths between the 2007 and 2010 earthquake source regions) occurred about 700 years ago.

[5] The tops of annually banded coral microatolls, which track relative sea level as they grow near the base of the intertidal zone, record tectonic vertical deformation [*Zachariassen et al.*, 1999, 2000; *Natawidjaja et al.*, 2004] and can be dated precisely using uranium-thorium disequilibrium techniques [*Edwards et al.*, 1988; *Shen et al.*, 2002, 2008, 2010]. Almost without exception the microatolls of the Sumatran outer-arc islands display a sawtooth pattern of gradual interseismic subsidence that is interrupted and restored by sudden coseismic uplifts. This is evidence of interseismic strain accumulation across the megathrust and subsequent rupture. A coral record from Pulau Pasir, an islet off the west coast of South Pagai Island (Figure 1), provides the first evidence of an ancient coseismic subsidence in this region, potentially linked to rupture of the megathrust updip of the “conventional” seismogenic zone.

## 2. Pulau Pasir Coral Record

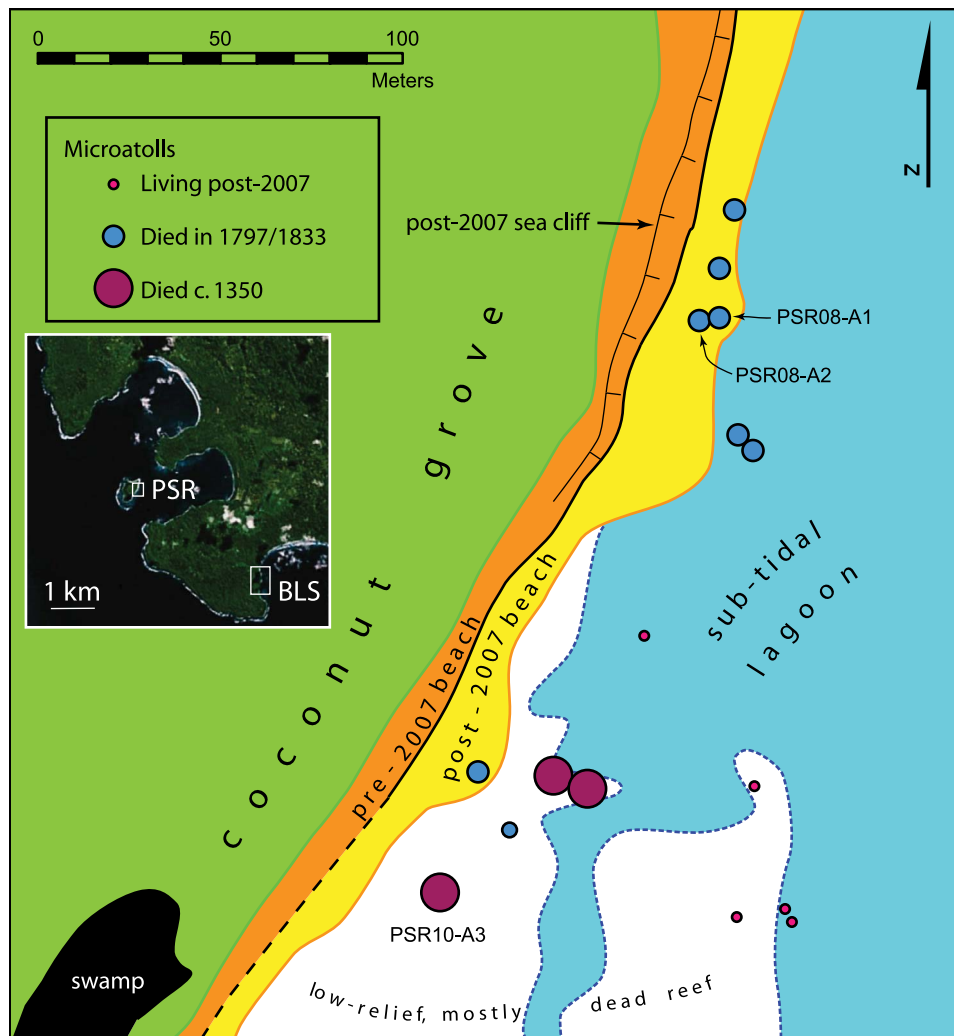
[6] The ancient microatoll that displays a striking exception to the sawtooth pattern sits on the fringing reef of Pulau Pasir (“Sand Island,” alternatively called Pulau Kasi on some charts), a small island at 100.25°E, 3.07°S, off the southwest coast of South Pagai Island (Figure 2). Like numerous other sites on South Pagai [*Natawidjaja et al.*, 2006], this locality contains a population of coral microatolls that are known, from U-Th disequilibrium dating, to have died due to uplifts during great earthquakes in 1797 and 1833 (Figure S1 in Text S1 of the auxiliary material).<sup>1</sup> Pulau Pasir also contains a population of microatolls that died c. A.D. 1350. Microatoll populations of similar age at several neighboring sites on South Pagai suggest that these corals were also killed by uplift due to megathrust rupture [*Sieh et al.*, 2008].

[7] One of the 14th-century coral microatolls at Pulau Pasir is unusual in that it contains a record of sea level that spans 150 years prior to its death (most coral colonies live less than 100 years). This specimen is particularly accessible to sampling, because its raised outer rim has fallen radially outward in pieces, exposing its interior and making it amenable to sampling by chainsaw (Figure 3). We determined its growth history by reconstructing the original morphology from three different slices, each representing a partial radius that overlaps with its neighbor. Figure 4 displays the reconstructed cross-section and the derived sea level time series. The cross section is a cartoon of the perimeter of the radial slice and the form of its annual growth bands. The reconstruction is apparent in the overlap of the three slabs, each represented on the sea level graph by a different color of symbol.

### 2.1. Interseismic Subsidence and Climatic Die-Downs

[8] The cross section shows that the overall trend of growth of the microatoll was upward and outward through its two-hundred year history. Hence, during most of the life of the coral, the island was dropping relative to the sea surface. The brief primer that follows on the interaction of coral with sea level is necessary to understand how one can read this from the cross section.

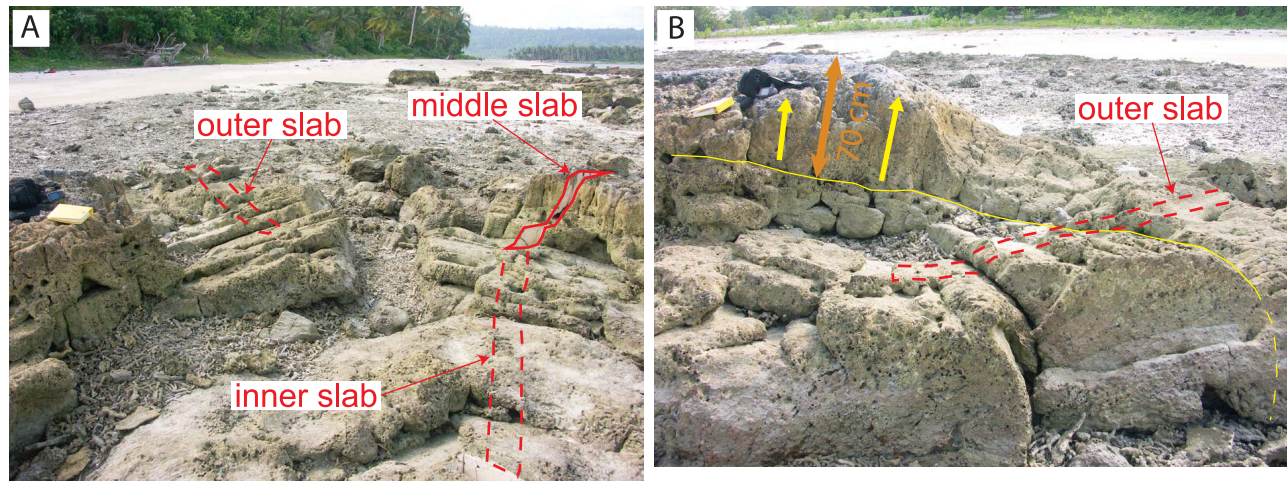
<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2011JB009075.



**Figure 2.** Map of living and fossil microatolls at the Pulau Pasir site. One family of microatolls died in the historical great earthquakes of 1797 and 1833 and another died in about A.D. 1350. The site rose tectonically  $\sim 50$  cm during the 2007 Mw 8.4 earthquake, causing many of the modern coral microatolls to die and the beach to re-establish itself farther seaward. Microatoll PSR10-A3 contains a very long record of interseismic subsidence and a sudden subsidence of  $\geq 35$  cm in  $\sim$ A.D. 1314. (inset) Satellite image of the southwest coast of South Pagai Island showing locations of Pulau Pasir (PSR) and Bulasat (BLS) sites.

[9] Coral growth in any one year is limited by its growth rate and the level of that year's extreme low water (ELW) [Taylor *et al.*, 1987]. Initially, a coral head grows radially upward and outward, limited only by its growth rate; its elevation in each year can be termed its highest level of growth (HLG). When an upward-growing hemispherical coral colony first reaches the upward limit at which it can survive, termed its highest level of survival (HLS), the top surface dies while its outer perimeter continues to grow radially outward below the HLS. The HLS for *Porites lutea* and *lobata* in this region is  $\sim 20$  cm above ELW [Meltzner *et al.*, 2010], so HLS is a proxy for ELW plus about 20 cm. After first reaching HLS, due to short-term oceanographic sea level fluctuations, corals are typically growth-limited for periods of several years between subsequent HLS "hits" which again kill the uppermost surface.

[10] Figure 4 shows that the coral head was growing radially upward and outward through the latter decades of the 12th century. (Note: all calendar years mentioned in the following discussion are based on the weighted average of U-Th subsample ages and band counting, which for this coral record produce an absolute age uncertainty of  $\pm 19$  years. The relative timing of events recorded by coral morphology is dependent only on band counting and is therefore far more precisely known, generally within a few years.) About A.D. 1208 the upper part of the colony died, due to a relative drop of sea level. Until about 1220 the remaining, living perimeter of the head experienced another period of unfettered upward growth. Erosion obscures the details of sea level between 1220 and about 1235, but it appears that sea level did not change much during that period. A  $\sim 50$ -cm drop in the coral's HLS occurred in about 1237.



**Figure 3.** Field photographs of coral microatoll PSR10-A3 show that its raised outer annulus has fallen away in sections, revealing the older core of the colony. Yellow notebook is  $16 \times 20$  cm in dimension, and lies in the same place in both photographs. (a) View from the center of the head shows fallen and broken sections of outer rim and locations of collected slabs. (b) Cross-sectional view of a piece of the outer rim shows unfettered columnar overgrowth (yellow arrows) above the c. A.D. 1314 isochron surface (yellow line). Vertical overgrowth has eroded or broken from the part of the head from which the slab was taken, but is clearly contemporaneous with the post-1314 eroded section of the outer slab. The highest preserved point on the columnar overgrowth extends 70 cm above the 1314 surface (orange arrow).

Because the outer annulus of the coral head later broke away from the central disc at this growth discontinuity (after the death of the colony), there is some uncertainty in the original elevation of the outer annulus. The reconstruction shows the minimum original elevation; the true elevation may have been higher. However, regardless of its original elevation, for the next 80 years after  $\sim 1237$ , the coral records a more-or-less steady rise in HLS of about 1 cm/yr, broken by only a few small drops in HLS. This 80-year subsidence rate is similar to long-term interseismic subsidence rates recorded over the past 7 centuries in corals at the nearby Bulasat site [Sieh *et al.*, 2008], as well as to the pre-2007 rate recorded in the past decade by the continuous Global Positioning System (cGPS) station there [Natawidjaja *et al.*, 2007]. It is most reasonable to attribute this long-term, interseismic strain accumulation to locking of the subjacent megathrust [Chlieh *et al.*, 2008].

[11] The “die-downs” recorded in the coral bands, during which the HLS dropped below its long-term trend, have several plausible causes. Although tidal harmonic ELW in a given location varies only a few centimeters from year to

year, non-harmonic oceanographic phenomena such as the Indian Ocean Dipole (IOD) can temporarily change local sea level by tens of centimeters [Webster *et al.*, 1999]. Consequently, the coral die-down events in this record may be either climatic (due to a temporary ocean lowering) or tectonic (due to uplift of the ground). Examination of coral morphology may allow discrimination between these causes: after a climatic temporary lowering in sea level, the coral will grow back upward until reaching an HLS that is in line with its previous trend. In contrast, after a tectonically induced die-down, the coral will resume growing radially outward and upward, but the trend after it reaches HLS will not align with the previous trend due to the ground level change. The morphology of this microatoll suggests that the first two die-downs (about 1208 and 1237) were tectonic, involving uplift of the island, whereas the other, smaller die-downs were climatic.

## 2.2. Sudden Subsidence Event

[12] About 35 years prior to the final death of the microatoll in about A.D. 1350, an abrupt, major change in the

**Figure 4.** A sea level record spanning  $\sim$ A.D. 1200 to 1350 reveals two small uplifts in about 1208 and 1237, followed by a sustained interseismic subsidence at about 9.5 mm/yr. Sudden subsidence occurred in about 1314, and death due to uplift occurred in about 1350. (top) Cross section of PSR10-A3 reconstructed from three slabs and corrected for post-mortem tilting. Some preserved columnar growth can be seen on the middle slab. The outer slab originally had similar growth but this has been eroded away in the immediate vicinity of the slab cut. The approximate original extent of the columnar growth is shown based on the less eroded area adjacent to the outer slab (see Figure 3). Heavy orange line shows the outer surface of middle slab which died at the same time columnar growth initiated on the top surface. (bottom) HLS/HLG history of PSR10-A3. Vertical lines highlight timing of climatic and tectonic morphology changes. Green arrows show inferred post-1314 relative sea level history: 35 cm coseismic subsidence, followed by 35 cm interseismic subsidence (at the same rate as before), and finally  $>1$  m of uplift which killed the coral colony. The continued upward growth of the coral during this period is evidenced by the thick section of columnar growth shown in Figure 3b, which our slabs do not transect but clearly grew at the same time as the post-1314 section of the outer slab.

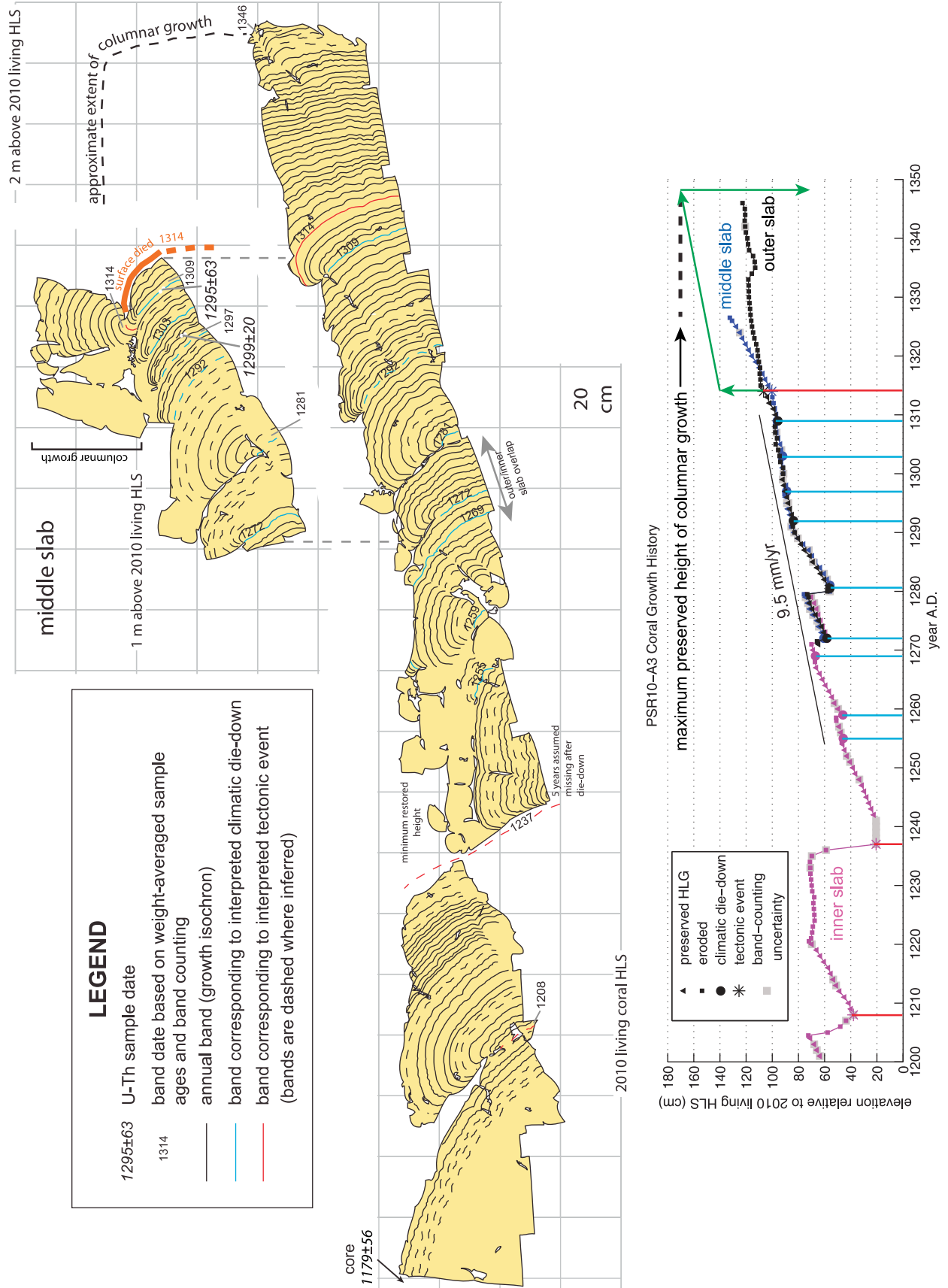
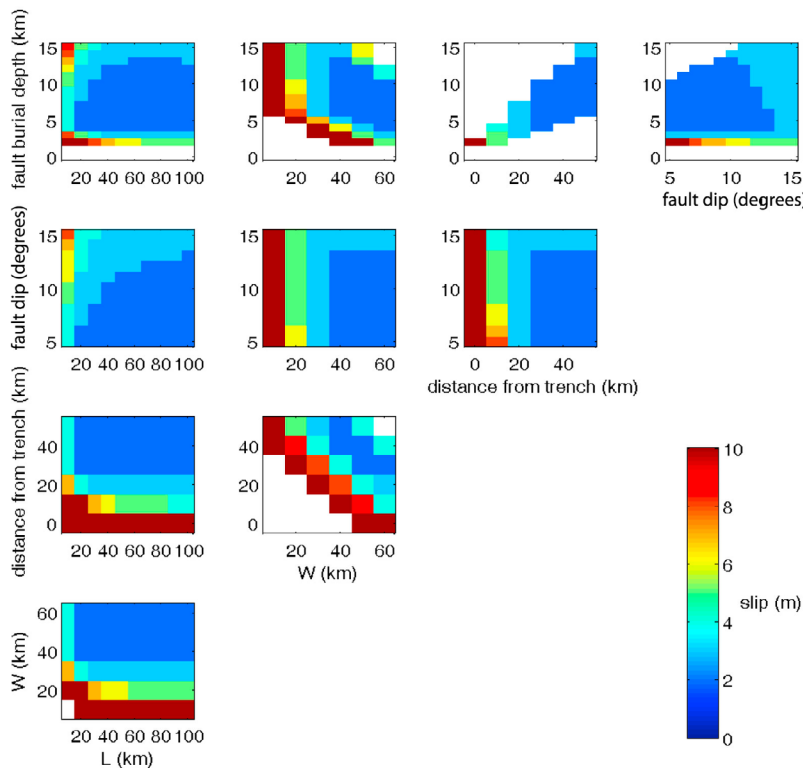


Figure 4



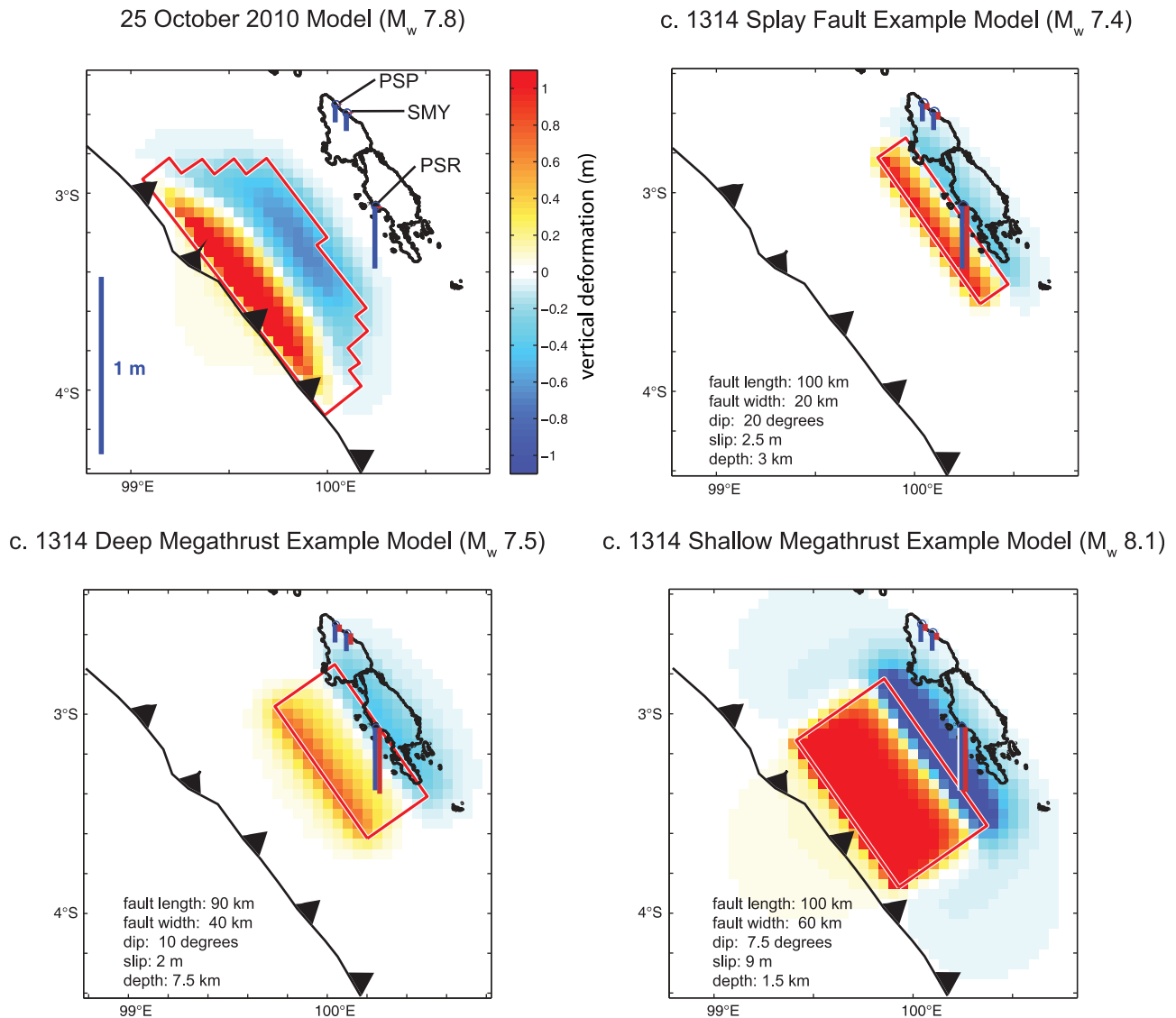
**Figure 5.** A grid search for fault parameters that would reproduce a sudden subsidence c. 1314. Each plot displays two model parameters on the x and y axes, whereas color indicates the minimum amount of fault slip required to produce 35 cm of subsidence at the Pulau Pasir site for each parameter pairing. Areas colored brown require very large slip (between 10 and 50 m). White parameter space either requires unreasonably large (>50 m) slip or was eliminated by other constraints such as the deformation limits at PSP and SMY. All scenarios require at least 2 m of slip.

morphology of the microatoll records a sudden submergence of at least 35 cm. The large subsidence event is most obvious in the middle slab, where one can clearly see that the growth morphology of the microatoll abruptly changed about A.D. 1314 from occasional small HLS impingements to unfettered, columnar upward growth, completely devoid of die-downs (Figure 4). The columnar growth has broken or eroded off the outer slab, but it can be seen adjacent to the slab's location in Figure 3. This style of growth continued for the remainder of the lifetime of the coral colony, a span of at least 31 years (a few annual bands have likely been eroded off the outer surface). The upper surface of this columnar growth has been eroded, with its highest preserved point 70 cm above the c. 1314 HLS. This indicates that a minimum of 70 cm of subsidence occurred in the last ~35 years of the colony's lifetime, equivalent to an average rate  $\geq 2$  cm/yr, double the rate observed during the first ~115 years of growth. While this could have been accomplished simply by a change in interseismic subsidence rate, the death of some sections of the colony's outer surface (such as that shown the middle slab, Figure 4) coincident with the change in morphology suggests that at least some of the subsidence occurred suddenly rather than gradually. The outer surface along the portion of the perimeter cut by the middle slab must have died due to some very local disturbance to the microatoll in ~1314, since the outer

perimeter cut by the outer slab continued to grow without incident until ~1346 (Figure 4). Sedimentation caused by seismic shaking or a tsunami could be responsible for killing part of the outer surface. Assuming that the site continued to subside at only 1 cm/yr for 35 years, at least 35 cm of subsidence must have occurred suddenly. We can obtain some idea of the post-1314 interseismic subsidence rate from BLS02-A3, a microatoll that died c. 1350 at the nearby Bulasat site [Sieh *et al.*, 2008]. Its short history suggests a subsidence rate of ~1.5 cm/yr during ~1335–1350. If the subsidence rate at P. Pasir was truly that high, a greater proportion of the 70 cm total subsidence would be allocated to interseismic rather than coseismic deformation. However, due to the sporadic nature and varying magnitude of climatic die-downs, a 15-year coral HLS record is insufficient to constrain the rate precisely, and a rate of only 1 cm/yr is still plausible given the data.

### 3. Forward Modeling of Possible Rupture Models

[13] A seismic rupture of the megathrust (or a splay fault in the accretionary prism) trenchward of Pulau Pasir is the most plausible explanation for the sudden subsidence, since the downdip limit of slip must have been below or southwest of the islands in order to produce such subsidence. Unfortunately, other data that might constrain the size and extent of the rupture are scarce. We have not found any other coral



**Figure 6.** Comparison of the modeled 25 October 2010 fault rupture (Hill et al., submitted manuscript, 2012) with selected fault slip models for the c. 1314 event. Slip in 1314 must have been either larger than in 2010 or closer to the islands. Red outlines indicate areas of fault slip. Colored areas show uplift and subsidence generated by each model fault, saturated at 1 m to more clearly show areas of lesser displacement. Vertical blue bars at Pasapuat (PSP) and Simanganya (SMY) represent the maximum permitted subsidence of 10 cm, whereas the blue bar at Pulau Pasir (PSR) represents the minimum required subsidence of 35 cm. Red bars show subsidence produced by each model rupture at each site. Models generated using the Coulomb 3.2 software [Lin and Stein, 2004; Toda et al., 2005].

microatolls in the region that were living and recording HLS through the early decades of the 14th century. The microatoll BLS02-A3 at Bulasat began growing after 1314 [Sieh et al., 2008] and thus cannot directly constrain the subsidence event. Microatolls at Simanganya and Sikici [Sieh et al., 2008] and Pasapuat (Figure S2 in Text S1) started growing before 1314 and hit HLS shortly thereafter, suggesting that any coseismic subsidence that occurred there cannot have been large. However, dating uncertainties of the coral samples at these sites preclude precise constraints. With so few constraints, it is not reasonable to attempt to invert for or otherwise speculate about a single “best-fit”

earthquake rupture model. However, it is instructive to identify the range of possible models that fit the data.

[14] To characterize the range of fault ruptures that could have produced the observed subsidence at Pulau Pasir, we employed a grid-search technique to select plausible models from a suite of forward models. Our models are based on the analytical solution of Okada [1985] for surface displacement due to slip on a dislocation embedded in an elastic half-space. Each model imposed uniform dip slip (between 1 and 50 m) on a single rectangular fault plane with a strike corresponding to the trench orientation ( $325^\circ$ ), centered southwest of Pulau Pasir. The parameter space comprised



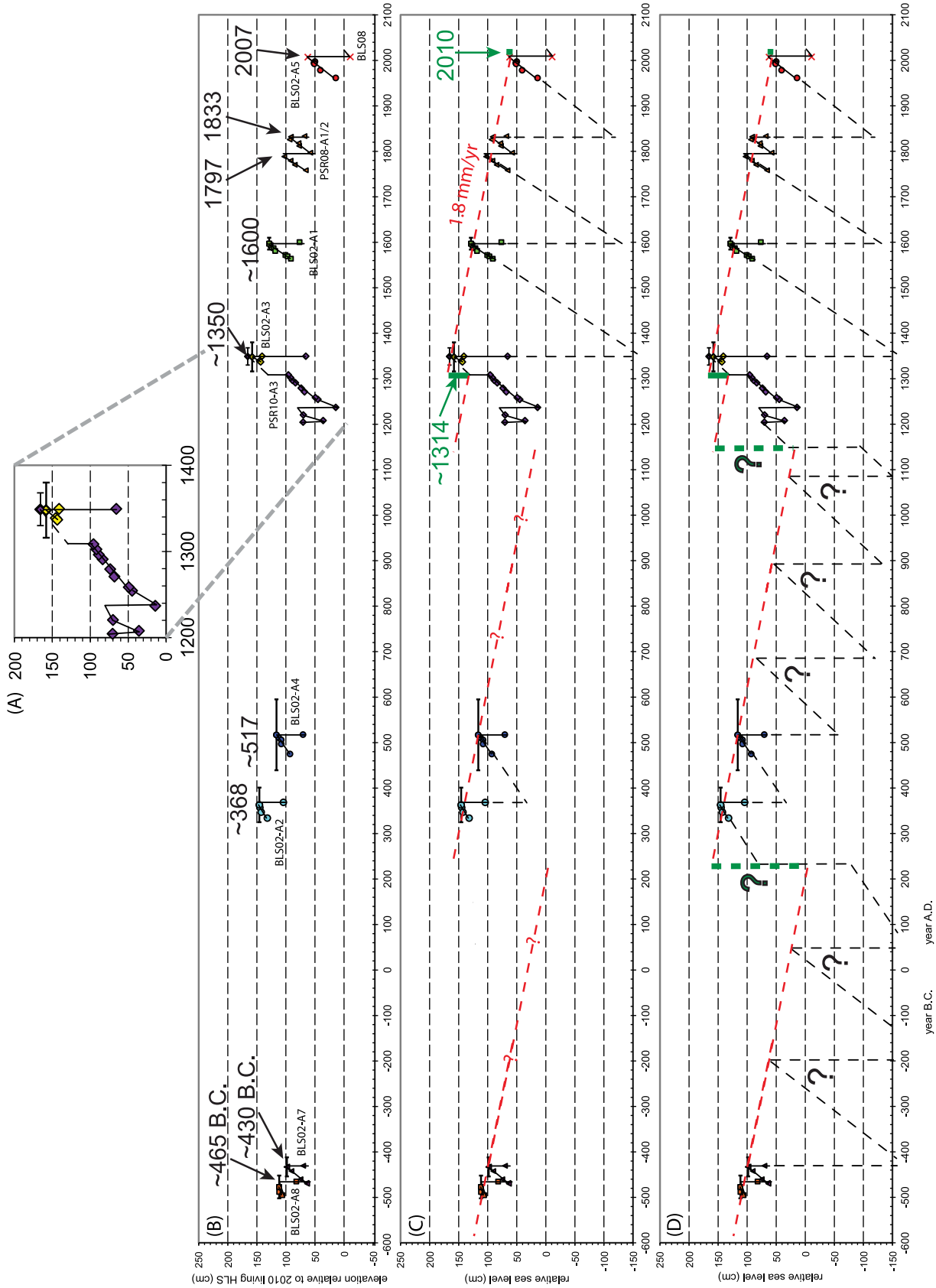


Figure 7

fault planes 20 to 100 km long, 10 to 60 km wide, dipping between  $5^\circ$  and  $15^\circ$ , with updip edges located between 0 and 50 km from the trench and 1.5–15 km burial depth. Note that our model does not account for the  $\sim 6$  km of topography between the trench and the islands, instead placing our “zero datum” flat free surface at the level of the seafloor at the trench. This simplification means that we may slightly underestimate the fault slip required to reproduce the observed deformation. However, the effects of topography on vertical elastic deformation are likely no more than a few percent [Hsu *et al.*, 2011].

[15] While the precise geometry of the shallow megathrust trenchward of the Mentawai islands is not well constrained, seismic reflection studies [Singh *et al.*, 2011] and Wadati-Benioff zone earthquake distributions [Engdahl *et al.*, 2007] suggest that the megathrust dip between the trench and the outer arc high falls within our  $5^\circ$ – $15^\circ$  range, and that the megathrust interface is buried below  $\sim 1.5$  km of sediment at the trench [Singh *et al.*, 2011]. The dip of each model fault plane is required to be consistent with a concave-down fault geometry (e.g., if the position of the model fault plane would require an average  $10^\circ$  dip to outcrop at the trench, the model fault plane cannot have a dip shallower than  $10^\circ$ ).

[16] Figure 5 shows pairwise parameter plots of the minimum fault slip required to produce 35 cm of subsidence at Pulau Pasir. We excluded models that produced more than 10 cm of subsidence at Simanganya, Pasapat, or Sikici. Our results indicate that at least 2 m of slip is required to produce 35 cm of subsidence at the Pulau Pasir site, regardless of the other model parameters. With that limitation, a wide variety of megathrust rupture scenarios fit the data, ranging in moment magnitude between 7.4 and 8.6 (based on a constant rigidity of 33 GPa).

[17] Two representative megathrust slip models selected to match the fault geometry revealed by a nearby seismic reflection study [Singh *et al.*, 2011] are shown in Figure 6. The c. 1314 subsidence data can be reproduced by large slip on the shallowest part of the megathrust, or by smaller slip on a deeper patch. Figure 6 also shows one model with slip on a splay fault. This hypothetical fault outcrops on the ocean floor a few kilometers southwest of the islands. Although this is not specifically known to be the location of

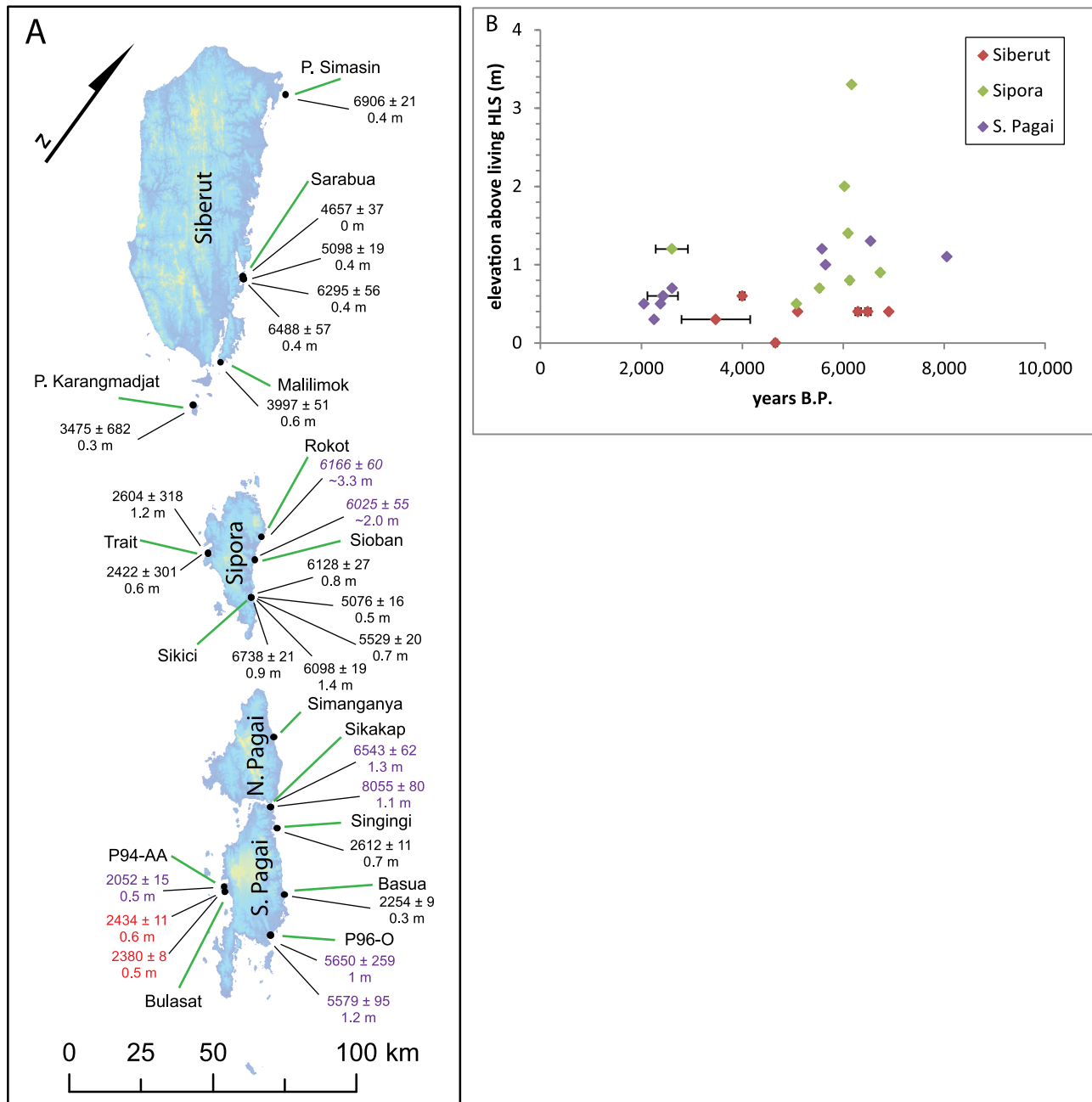
a splay fault, nearby seismic reflection data show faults in the accretionary prism at a similar distance from the trench [Singh *et al.*, 2011].

#### 4. Recurrence Constraints From Bulasat Record and Mid-Holocene Age Corals

[18] The sudden subsidence event of about A.D. 1314 recorded at Pulau Pasir is the only known direct evidence of an ancient shallow megathrust rupture along the Mentawai island chain. However, there are clear, indirect indications of at least two earlier subsidence events. Figure 7 displays a combined record of coral HLS levels from Pulau Pasir and the nearby Bulasat site (see Figure 2 inset for location). The younger records from corals BLS02-A1, 3, and 5 were presented in detail by Sieh *et al.* [2008], whereas the older Bulasat coral records appear in the supplementary materials of this paper. Ages for the Bulasat corals are from Shen *et al.* [2008]. Our reconstruction places the pre-1350 elevation of PSR10-A3 only about 10 cm higher than the contemporaneous BLS02-A3 (Figure 7a), suggesting that the minimum-elevation restoration of the outer annulus is correct (restoring the outer annulus higher would require excessively disparate tectonic behavior for sites only 3 km apart).

[19] As noted by Sieh *et al.* [2008], a long-term uplift rate of about 1.8 mm/yr appears to be superimposed on the seismic cycle sawtooth curve for the past 700 years (Figure 7c), resulting in the elevation of PSR10-A3 and BLS02-A3 about 1 m above their modern (pre-2007 earthquake) counterparts. However, this long-term uplift cannot be extrapolated farther into the past, since microatolls dating to the first millennia A.D. and B.C. are no higher in elevation than the 14th-century microatolls. Thus, the 1.8 mm/yr uplift over the past 700 years cannot represent permanent inelastic deformation, but must be balanced by subsidence. The relative elevations of older corals are consistent with similar long-term uplift rates in the past, provided that large subsidence events occurred to recover this uplift. The  $\sim 35$  cm of subsidence that occurred c. 1314 is actually insufficient to recover the  $\sim 150$  cm of uplift that we infer to have accumulated during the previous thousand years. Therefore, if our interpretation is correct, a second, larger

**Figure 7.** The combined relative sea level record from Pulau Pasir (PSR) and nearby Bulasat (BLS) site implies that sudden subsidence events relieve residual uplifts accumulated over the centuries at a rate of about 1.8 mm/yr. (a) Relative sea level history of PSR10-A3 (purple symbols), simplified from Figure 4b. Yellow symbols show the much shorter BLS02-A3 record, which is at a comparable elevation. (b) Compilation of coral microatoll records that constrain relative sea level over the past 2500 years, with dates (A.D.) of uplifts interpreted as downdip (“conventional”) megathrust ruptures. Horizontal error bars indicate uncertainty in U-Th age for each microatoll. (c) The relative sea level sawtooth curve is interpolated between downdip ruptures by extending the measured late-cycle interseismic rates over entire interseismic periods (dashed black line). A longer-term uplift rate of 1.8 mm/yr appears to be superimposed on the last 700 years of cycles (red dashed line), but projecting this trend farther into the past is inconsistent with the height of older microatolls unless the uplift is periodically balanced by subsidence. The c. 1314 subsidence helps to complete the cycle, but is not large enough to span the vertical offset between the projected 1.8 mm/yr trends. The 2010 subsidence has barely any effect. (d) Dashed green bars show hypothetical sudden subsidence events that could have balanced the accumulated uplift. We assume that there are many “conventional” seismic cycles missing from our record (black question marks); this may be because the corals growing during these times were at lower elevations and thus subject to greater wave erosion after the land level dropped. In our interpretation, the red/green sawtooth curve represents strain accumulation and release on the shallow megathrust updip of the islands, a cycle which is superimposed on the higher-frequency downdip seismic cycle to form the complete relative sea level history (black sawtooth curve). If uplift accumulated since 1314 were relieved soon, about 1.25 m of subsidence would occur. This would reflect far larger slip on the megathrust than in either 1314 or 2010.



**Figure 8.** Many fossil microatolls more than 2,000 years old still lie within the modern intertidal zone throughout the Mentawai Islands, which indicates that little or no permanent uplift has occurred since these corals were alive. This implies that very long-term residual rates of emergence seen throughout the islands are due to tectonic strain accumulation that is relieved by slip on the megathrust between the islands and the trench. (a) Map of microatoll locations with dates in years B.P. (before 1950) and heights in meters above modern living coral HLS. Ages in purple are from Zachariassen [1998], in red from Shen *et al.* [2008], and black from this study (see Table S2 in Text S1). Radiocarbon ages appear in italics; all others are U-Th ages. (b) Plot of elevation versus age reveals no obvious trend, suggesting that seismic cycle deformation swamps any long-term vertical deformation. Permanent uplift rates greater than ~0.2 mm/yr are unlikely given these data. (Note: age error bars on most data points are smaller than the symbols.)

subsidence event occurred prior to the one recorded in 1314. Similarly, one or more subsidence events must have occurred between ~430 B.C. and ~A.D. 350 (Figure 7d). The most plausible explanation for this cycle, opposite in

sign to the deformation cycle produced by strain accumulation and release on that portion of the megathrust below the island chain, is a similar seismic cycle on the shallow megathrust updip and seaward of the island chain. (The lack

of appreciable permanent deformation is evidence against the splay fault model.) These coral records suggest that shallow megathrust ruptures have a much longer recurrence interval than conventional megathrust ruptures, about 1000 years. The magnitude of residual strain accumulated at  $\sim 1.8$  mm/yr since the most recent such event,  $\sim$ A.D. 1314, is about 1.25 m. An equivalent amount of subsidence would require fault slip of at least 5.5 m on a patch immediately updip of the islands, comparable to the average slip magnitude during the 2010 event (Hill et al., submitted manuscript, 2012); such a rupture seems entirely plausible.

[20] A direct calculation of potential slip on the trenchward section of the megathrust would be 32 m (4.6 cm/yr times 700 years), three times the maximum slip in 2010. The recent Tohoku earthquake has illustrated that even larger near-trench slip is possible [e.g., Lay et al., 2011]. However, it is unlikely that a narrow-width rupture could produce slip so large, and a Tohoku-type earthquake would involve rupture of the 2007 patch as well as the 2010 patch, likely producing uplift rather than subsidence of the islands. While not impossible, there is no evidence that Tohoku-type (full width) ruptures have occurred on the Mentawai segment, and it is not unlikely that a significant portion of the interplate motion on the shallow megathrust is accommodated aseismically.

[21] An obvious remaining question is whether the shallow megathrust ruptures seismically along its entire length, or whether such events only occur in a limited area southwest of the Pagai Islands. While the Simanganya and Sikici sites do not seem to have experienced significant subsidence during the 1314 event, both sites exhibit long-term uplift trends over the past 700 years similar to Bulasat [Sieh et al., 2008]. The presence of mid-Holocene age microatolls in the modern intertidal zone throughout the Mentawai Islands (Figure 8) indicates that, similarly to Bulasat, this uplift cannot reflect inelastic, permanent deformation. Sea levels between 7000 and 2000 yr B.P. (before A.D. 1950) are not well constrained in this region, but probably were no lower than present levels [e.g., Horton et al., 2005]. Thus, if the observed 1–2 mm/yr uplift rate had been sustained over thousands of years, corals of that age would be expected to be meters higher than their modern counterparts. These data rule out permanent uplift rates greater than about 0.2 mm/yr, suggesting even lower inelastic deformation rates than those observed on Nias Island [Briggs et al., 2008]. While we have no direct evidence for subsidence events at sites other than Pulau Pasir, the data from other sites are generally consistent with strain buildup and release on the shallow megathrust along the entire Mentawai segment (though it will not necessarily all rupture in a single earthquake).

## 5. Conclusions

[22] The coral record at Pulau Pasir implies that a large rupture of the megathrust between the trench and the islands occurred c. A.D. 1314. This rupture must have been larger and/or deeper than the 25 October 2010 rupture. The elevations of four older microatolls at Bulasat suggest that at least two other shallow megathrust ruptures occurred during the 1500 years before the A.D. 1314 event. The existence of numerous mid-Holocene microatolls in the intertidal zone throughout the Mentawai island chain

precludes any large permanent uplift for the last  $\sim 7000$  years, and implies that the long-term trend of emergence observed at Bulasat and other sites (1–2 mm/yr) is due to tectonic strain accumulation across the megathrust between the trench and the islands.

[23] The amount of uplift accumulated at Bulasat since 1314 is about 1.3 m, whereas only  $\sim 4$  cm of subsidence occurred coseismically in 2010 (Hill et al., submitted manuscript, 2012). It is important to note that post-seismic subsidence recorded by the Bulasat cGPS station is already more than double the October 2010 coseismic subsidence [Feng et al., 2011], but nevertheless the total subsidence is still only  $\sim 10\%$  of the accumulated uplift. Therefore, it is possible that an additional shallow megathrust event larger than the October 2010 rupture will occur in the near future. (The recent post-seismic behavior also suggests that a significant portion of the c. 1314 subsidence may have been post-seismic as well, but there is no way to determine this from the coral record). Regardless of the exact characteristics of the ancient and modern shallow megathrust slip events, it is clear that such ruptures play an important part in the seismic cycle of the Sumatran subduction zone. Geoscientists and policymakers alike should be aware that shallow tsunamigenic earthquakes similar to (or perhaps larger than) the 25 October 2010 event may occur in the future on adjacent parts of the Sunda megathrust, and should be included in scenario-based forecasts for the region.

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