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A 15 year slow-slip event on the Sunda megathrust offshore Sumatra

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Abstract In the Banyak Islands of Sumatra, coral microatoll records reveal a 15 year-long reversal of interseismic vertical displacement from subsidence to uplift between 1966 and 1981. To explain these coral observations, we test four hypotheses, including regional sea level changes and various tectonic mechanisms. Our results show that the coral observations likely reflect a 15 year-long slow-slip event (SSE) on the Sunda megathrust. This long-duration SSE exceeds the duration of previously reported SSEs and demonstrates the importance of multidecade geodetic records in illuminating the full spectrum of megathrust slip behavior at subduction zones.

1. Introduction

“Silent earthquakes,” or slow-slip events (SSEs), release strain on tectonic faults at slip rates faster than plate rates but slowly enough that seismic shaking is not generated. They are manifested along subduction zone megathrusts either as preseismic slip prior to large earthquakes, afterslip following large earthquakes, or slip during the interseismic period of the earthquake cycle [Schwartz and Rokosky, 2007]. In this study, we use the term SSE to refer only to the last of these three manifestations.

SSEs are visible in geodetic time series as reversals of displacements associated with a locked fault interface. SSEs have been observed to typically last from a few days [e.g., Douglas et al., 2005] to a few months [e.g., Hirose et al., 1999], but longer-duration SSEs lasting several years have also been detected: ~2–3 years [Ohta et al., 2006], ~4 years [Fu and Freymueller, 2013], ~5 years [Miyazaki et al., 2006; Ochi and Kato, 2013; Ohta et al., 2004; Ozawa et al., 2002], and ~10 years [Li et al., 2014]. In order to detect SSEs of longer duration and thus illuminate the full temporal spectrum of megathrust slip behavior, multidecade geodetic records are required. However, existing geodetic networks have not been operating long enough to detect such events.

One way to extend our geodetic observations is to take advantage of paleogeodetic data preserved in the geological record. For example, coral microatolls along the Sumatran subduction zone provide high-resolution records of vertical deformation over the past several centuries [e.g., Zachariasen et al., 2000; Meltzner et al., 2010; Philibosian et al., 2014]. Using these data, Meltzner et al. [2015] reconstructed interseismic uplift and subsidence at multiple sites over the past three centuries. At one site on Bangkaru Island, in the Banyak Islands (site PBK, Figure 1), coral records show an abruptly reversed displacement trend from interseismic subsidence to interseismic uplift between 1966 and 1981 (Figures 1b–1d); an SSE on the underlying megathrust is a potential explanation.

In this paper we extend the work of Meltzner et al. [2015] to examine the potential physical processes that can explain the coral observations. We show that indeed, they likely reflect a very long duration SSE on the Sunda megathrust, where, to date, no SSEs other than afterslip following major earthquakes have been recorded. We include previously unpublished coral observations for the Simelue-Nias section of the megathrust, including additional sites in the Banyak Islands and neighboring islands of Simelue and Nias. These added observations allow us to model the possible locations and sizes of this SSE, both with improved constraints.
2. Displacement Rate Changes Recorded by Corals

We reconstructed interseismic uplift histories from coral microatolls at six sites along the Simeulue-Nias section of the Sunda megathrust (Figure 1). Microatolls are coral colonies that grow upward to a limit near mean low water springs, and their upper surfaces can track changes in relative sea level (RSL) over time [Scoffin et al., 1978; Taylor et al., 1987; Zachariasen et al., 2000; Meltzer et al., 2010]. Microatoll morphologies form because prolonged subaerial exposure at times of extreme low water limits the highest level to which the coral colonies can grow [Briggs et al., 2006; Meltzer et al., 2010; Meltzer and Woodroffe, 2015]. Flat-topped microatolls record RSL stability; colonies that rise radially outward toward their perimeter reflect rising RSL during their decades of growth, and colonies with progressively lower die-downs as they grow outward reflect gradually falling RSL.

Changes in RSL are themselves the combined effect of changes in land level and changes in local absolute sea level. As islands and their fringing reefs subside or rise in response to tectonic elastic strain accumulation and release, microatolls record changes in RSL. Because these corals’ skeletons have annual growth bands, we can precisely calculate rates of change in RSL, when those changes are gradual.

The coral microatolls were slabbed, X-rayed, and analyzed following the methods described by Meltzer et al., [2010, 2012] and Meltzer and Woodroffe [2015]. The interpreted coral cross sections and corresponding time series for the relevant corals are presented in Figures S1 – S6 and Table S1 in the supporting information. The displacement rates at each site (and their 2σ level of uncertainties) over various time periods are shown in Figures 1b – 1d. Three sites (PBK, PLM, and PUB) define a trench-normal transect through the Banyak Islands, and three additional sites are located near the southeastern tip of Simeulue (LBJ) and the northern tip of Nias (MZL and SBA).
The RSL history of site PBK is particularly well resolved as a result of various idiosyncrasies (as discussed by Meltzner et al. [2015]). Modern microatoll PBK-4 (Figure S1) started growing in the 1950s and first recorded a diedown in 1956. The first few diedowns were successively higher on the coral, but around 1966 there was an abrupt change, and for ~15 years successive diedowns were lower and lower. Around 1981, the trend reversed again, and successive diedowns were higher. After correcting for an assumed eustatic sea level rise of 2 mm/yr, Meltzner et al. [2015] estimated tectonic deformation rates at PBK-4 of $-2.7 \pm 3.4$ mm/yr (subsidence) from the beginning of the record in 1956 until 1966, +7.8 $\pm$ 2.1 mm/yr (uplift) from 1966 to 1981, and $-2.4 \pm 0.8$ mm/yr (subsidence) from 1981 until coseismic uplift in 2005 (Table S1). Although rates of sea level change are not well known in the eastern Indian Ocean in the decades prior to 1992, there is no compelling evidence that they differed markedly from the global average of $+2 \pm 1$ mm/yr. In this paper, we adopt the rates (and correction) of Meltzner et al. [2015], but we explore alternatives in the supporting information (Text S2).

The abruptness of each rate change at site PBK is well constrained. Meltzner et al. [2015] estimate that they can resolve the timing of rate changes at PBK-4 to within $\pm 2$ years of 1966 and 1981, respectively. Hence, these changes must have been rapid; each transition from the initial rate to the subsequent rate occurred over no more than 2 to 4 years, but it may have occurred over a period of a few months or even less.

Because of a combination of greater erosion and less frequent diedowns on all the other corals, the rates at the other sites are not as well constrained. However, they still provide useful information. At sites LBJ, MZL, and SBA on Simeulue and Nias, no rate change occurs between the beginning of the modern record (1945 at LBJ, 1970 at MZL, and 1962 at SBA) and 2005 (Figures S4–S6). At PLM and PUB in the Banyak Islands, however, the time series are more ambiguous; rate changes may occur at each site around 1966 and 1981, but the uncertainties in the various rates are large enough that the rates before and after each change are statistically indistinguishable from one another at $2\sigma$. At both PLM and PUB, we separately estimated rates for 1966–1981 and for 1981–2005 (Figures S2–S3), and we used those rates to constrain our models; we also estimated average rates over the duration of the modern coral record at each site.

3. Explaining the Coral Displacement Rate Changes

We identified and tested four scenarios that could explain the observed pattern of vertical displacement reversals recorded by the corals.

3.1. Scenario 1: Changes in Sea Level Due To Oceanographic Processes

Although evidence exists for global or ocean-basin-wide fluctuations in sea level on multidecadal timescales [e.g., Chambers et al., 2012; Woodworth et al., 2009], these cannot, by themselves, explain the changes in RSL observed in the Banyak Islands, because similar, contemporaneous changes would be expected at nearby sites on Simeulue and Nias but did not occur (details in Text S2).

If RSL varies significantly from site to site as a result of oceanographic processes, this could explain some and perhaps all of the observed site-to-site differences in the displacement rates. We therefore sought to quantify the magnitudes of spatial variations of sea level in this region and treated them as an independent error for the coral rate uncertainties. We added this error in quadrature to the $2\sigma$ coral rate uncertainties determined by the method of Meltzner et al. [2012] and then calculated the overall uncertainty associated with the displacement rate change at each site (details in Text S1). Our hypothesis is that if the summed uncertainties in the displacement rate changes at each site do not overlap at the $1\sigma$ confidence level, then the spatiotemporal changes in the coral displacement rates are unlikely due to oceanographic sea level changes and more likely consistent with tectonic changes on the underlying megathrust.

3.1.1. Scenario 1 Methods: Investigating Ocean Variability With Satellite Altimetry Data

We use satellite altimetry data from the past two decades as a proxy for the spatial variability of sea level over the twentieth century. The data, distributed by Aviso (Archiving, Validation, and Interpretation of Satellite Oceanographic data), span January 1993 to April 2014 and consist of daily sea level anomalies (SLA) estimated on a global grid, at a spatial resolution of 0.25° by 0.25° (more details in Text S1). Due to the spatial resolution of the data set, the data may not capture local coastal effects and related seasonal signals. Nevertheless, since regional tide gauge records are not yet available to provide better constraints on such local effects, analysis of satellite altimetry data is the best alternative.

We first extracted the time series of daily SLA at a set of grid points in the Simeulue-Nias region (Figure S8a) and estimated time series of 2 month mean SLA (Figure S8b). Second, we calculated the difference in the 2 month
mean SLA between each pair of grid points (Figure S8c). Third, we determined the 95th percentile of mean SLA differences between grid points (Figure S8d)—this represents the estimated maximum magnitude (at 2σ) of spatial variations in sea level in this region. Fourth, we calculated for each coral displacement rate an added amount of uncertainty, which is equal to the maximum magnitude of spatial variations in sea level divided by the length of time over which each displacement rate was determined. Finally, we ascertained whether any of the observed temporal rate changes overlapped between the sites, at the 1σ confidence level. Further details of this analysis method, as well as analysis of the time series of SLA rates, are provided in Text S1.

3.1.2. Scenario 1 Results: Uncertainty in Coral Displacement Rates Due To Spatial Variations of Sea Level
We estimated a mean SLA difference of 17.3 mm, at the 2σ confidence level (Figure S8d). The added uncertainty to each coral displacement rate, and the summed uncertainties, are detailed in Table S2 and discussed in Text S1. Our results suggest that the site-to-site and temporal variations in the coral displacement rates do not overlap at the 1σ uncertainties—that is, differences in sea level change across our small study area seem unlikely to contribute significantly to the observed rate changes.

3.2. Scenario 2: Triggered Postseismic Deformation From Regional Earthquakes
Since viscoelastic deformation has a larger spatial signature than elastic coseismic deformation, distant large-magnitude earthquakes have the potential to cause long-term changes in vertical displacement rates, without any discernable coseismic signals. An analogous example is the postseismic deformation recorded by the Sumatran GPS Array (SuGaR) following the 2012 Mw 8.6 Wharton Basin earthquake, in which most GPS stations experienced smaller coseismic than postseismic vertical displacements [Feng et al., 2015]. We tested the hypothesis that the 1966–1981 coral displacement rate changes are caused by viscoelastic deformation from a regional earthquake.

3.2.1. Scenario 2 Methods and Results
To support this hypothesis, we would first expect evidence of a large (M > 8) earthquake in the region, before the onset of the displacement reversal in 1966. However, we find no evidence of large, M > 8 earthquakes in the region from 1956 to 2004 (prior to the Mw 9.2 Sumatra-Andaman earthquake), from either instrumental, historical, or paleoseismic records [Newcomb and McCann, 1987] (Figure 1a and Text S3). Second, viscoelastic relaxation processes would need to be able to explain the 15 year-long linear uplift rate at site PBK. It is possible to observe an apparent linear uplift rate, if the mantle is sufficiently viscous (e.g., > 5 x 10^18 Pas) and our observation time window represents a short time snapshot of the total length of the viscoelastic signal. However, the abrupt reversal of displacements back to subsidence in 1981 is inconsistent with what is expected from viscoelastic processes. We therefore refute the hypothesis that the rate changes observed at site PBK are significantly influenced by viscoelastic processes.

3.3. Scenario 3: Temporal Changes in Fault Coupling Patterns and Downdip Limits of Locking
In the Sumatran subduction zone, temporal changes in long-term deformation rates have been reported to occur before or after major megathrust earthquakes [e.g., Prawirodirdjo et al., 2010; Philibosian et al., 2014; Meltzner et al., 2010, 2012, 2015]. Most of these rate changes maintained a sense of displacement consistent with locking on the underlying megathrust and have been modeled as spatiotemporal variations in interseismic coupling and/or downdip limits of locking.

The downdip limit of locking at subduction zones controls the location of the pivot line that separates regions of interseismic subsidence from interseismic uplift. If the pivot line shifts under a particular site, the sense of displacement at that site would reverse. To test whether spatial variations in coupling and downdip limits of locking could explain the 1966–1981 uplift rates in the Banyak Islands, we developed a suite of forward models of fault coupling. We hypothesize that if the displacement rate changes are due to temporal changes in coupling patterns, then tectonically feasible coupling parameters and downdip limits of locking should be able to explain the observations for each of the three periods (1956–1966, 1966–1981, and 1981–2005).

3.3.1. Scenario 3 Methods: Forward Models of Fault Coupling-Coupling Models
To model deformation from spatial variations in fault coupling, we assumed a plate subduction rate of 40 mm/yr [Simons et al., 2007; McNeill and Henstock, 2014] and calculated surface displacements with the Okada model of elastic dislocations [Okada, 1985], in a back slip framework [Savage, 1983] (other fault and model parameters are described in Text S4). In this framework, fully locked regions have a coupling ratio of 1, while parts of the fault that slip freely at the full plate subduction rate (40 mm/yr) have a coupling ratio of 0.

For all time periods, we assigned the coupling ratio along the shallowest 22 km of the fault to 0.4. Our rationale for including this partially coupled shallow region is discussed in Text S4. Its location is consistent with that of
the updip aseismic/seismic transition zone reported by Tilmann et al. [2010], though we note that the shallow region of the megathrust here may well be capable of rupturing seismically, as suggested by the M7.6 tsunami earthquake of 1907 [Kanamori et al., 2010].

In order to fit the subsidence rates in the Banyak Islands, we included in the models a region of partial coupling in the downdip portion of the fault (a downdip transition zone). We tested for its updip limit, downdip limit, and coupling ratio, with a range of values consistent with previous regional and global studies [McCaffrey et al., 2000; Tichelaar and Ruff, 1993] (Text S4).

In addition, we estimated separate downdip limits of full coupling under Simeulue and the Banyak Islands, respectively, because such along-strike variation was needed to substantially improve data-model fits at site LBJ (Figure S10 and Text S4).

In summary, we determined best fit models by varying the (a) downdip limit of the fully coupled zone under Simeulue and the Banyak Islands, (b) downdip limit of the downdip transition zone, and (c) coupling ratio of the downdip transition zone. We selected the best fit range of models based on the weighted mean of the sum of squared residuals (WMSSR), which is similar to a reduced chi-square value but uses the number of observations rather than the number of degrees of freedom in the model.

Although we incorporated constraints based on regional seismicity [Tilmann et al., 2010] and global studies of transition zone depths at subduction zones [McCaffrey et al., 2000; Tichelaar and Ruff, 1993], we are aware that the models are limited in resolution and include trade-offs between the fault geometry, downdip limits of locking, downdip transition zone location, and coupling ratios. The models therefore do not represent optimized or full-scale inversions of the data, but rather a range that fits the coral observations within their 2$\sigma$ uncertainties.

### 3.3.2. Scenario 3 Results: Coupling Models

Coupling models can explain the observed displacement rates during 1956–1966 and 1981–2005; Figures 2a and 2b show one such model. In this model, the portion of the fault under the Banyak Islands and northern Nias is locked to 30 km depth, while under southern Simeulue it is locked to 45 km depth. The downdip transition zone extends from depths of 30–60 km and 45–60 km under the Banyak Islands and southern Simeulue, respectively, and is coupled at 50% of the plate subduction rate. This model yields a WMSSR of 0.9. This represents our preferred coupling model, given the good data-model fits and comparisons with locking depth parameters determined from previous studies, although we note again that other models are possible given the limited model resolution (alternative models that fit the coral observations are listed in Table S3).

In contrast to models of deformation during periods of subsidence in the Banyak Islands, none of the tested coupling models do a good job of fitting the 1966–1981 displacement rates. Since the subsidence rates at sites on Simeulue and Nias remain unchanged between 1966 and 1981, we kept the same along-strike parameters under these sites (as shown in Figures 2a and 2b) and only varied parameters under the Banyak Islands in order to fit the uplift rates. To maximize uplift in the Banyak Islands, the underlying megathrust needs to be freely slipping at the full plate subduction rate (uncoupled). Thus, we included in the models a freely slipping patch under the Banyak Islands and consecutively tested for the updip, downdip, and along-strike limits of this patch.

Figure 2c shows our best attempt at such a model (additional models are described in Figure S12 and Table S4), which has a locking depth of 30 km along a 90 km section under the Banyak Islands, and creeps at the full plate subduction rate at depths greater than 30 km. This model yields a WMSSR of 2.5 and fails to explain the observed uplift rate at PBK. It is therefore difficult to explain the 1966–1981 uplift rates in the Banyak Islands with a model that only includes spatially variable coupling of the megathrust.

In addition, we performed an inversion of the data to ensure that we had not overlooked any distribution of coupling that could explain the 1966–1981 displacement rates. The results of the inversion are available in Text S5 and Figure S14. Due to the limited spatial coverage of the data, and therefore limited model resolution, we refrain from interpreting the details of the slip distribution suggested by the inverse models and prefer the relative simplicity of the forward models. However, on fault patches with reasonable model resolution, the first-order spatial patterns of the inverse models compare well with those of the forward models. Also, they show that while the 1981–2005 displacement rates are fit well (Figure S14a), there are large misfits to the 1966–1981 uplift rate at site PBK (Figure S14b). This supports our conclusion based on the forward models that changes in coupling on the megathrust cannot explain the 1966–1981 uplift rates in the Banyak Islands.
Figure 2. Preferred model of spatially variable coupling on the megathrust, during (a) 1956–1966 and (b) 1981–2005. In both periods, the fault is locked down to 30 km depth under the Banyak Islands and northern Nias, and 45 km depth under southern Simeulue. The downdip transition zone extends to a maximum depth of 60 km and is coupled at 50% of the subduction rate. Below 60 km, the fault is freely slipping at the full subduction rate. Everywhere along strike above 22 km depth, the fault is coupled at 40% of the subduction rate. (c) This model shows our best attempt to fit the 1966–1981 uplift rates with spatially variable coupling on the megathrust, but it nonetheless shows poor data-model fits at site PBK. (d) At least one model with a slow-slip event (slip rate exceeding the subduction rate) fits significantly better than any of our coupling models. Our preferred explanation for the 1966–1981 displacement rates includes a SSE localized along a 60 km section of the megathrust under the Banyak Islands, between 30 and 55 km depth.

3.4. Scenario 4: A Slow-Slip Event From 1966 to 1981
Since we could not explain the 1966–1981 displacement rates as spatially variable changes in coupling along the megathrust, we tested the hypothesis of an SSE on the underlying megathrust.

3.4.1. Scenario 4 Methods
We forward modeled the 1966–1981 displacement rates as a superposition of (a) back slip on the megathrust and (b) an SSE with thrust motion on the megathrust, with a slip rate greater than the plate subduction rate. For the back slip component, we assumed the spatial distribution of locking depths and transition zone parameters previously presented in our preferred model for the periods of subsidence (Figures 2a and 2b). This assumption leads to the desirable consequence that the only difference between our preferred model for 1956–1966 and 1981–2005, and our preferred model for 1966–1981 (as discussed in the following paragraphs), is the SSE itself.
We determined a range of best fit SSE models by testing for the best combination of the (a) upper and lower depth ranges of the SSE, (b) along-strike length and location of the SSE, and (c) SSE slip rates. For the depth ranges of the SSE, we tested upper and lower SSE depths ranging from 15 to 50 km and 25 to 65 km, respectively, at 5 km depth increments. Sites LBJ, MZL, and SBA allowed us to constrain the along-strike length and location of the SSE, to the nearest 10 km. We selected the range of SSE models that yield good fits between the data and model displacement rates. We again note that the models do not represent optimized inversions of the data, and the aim of our modeling approach was to explore whether an SSE could explain the 1966–1981 displacement rates within their 2σ uncertainties.

3.4.2. Scenario 4 Results: Our Slow-Slip Event Model
We found a range of SSE models that fit the 1966–1981 displacement rates (Table S5). Figure 2d shows our preferred SSE model, which yields the lowest WMSSR value. The results suggest that the SSE was localized along a 60 km section under the Banyak Islands, at depths of 30 to 55 km. The suite of best fit models (Table S5) suggests alternative downdip limits of the SSE ranging from 45 to 70 km and SSE slip rates ranging from 55 to 61 mm/yr (WMSSR values range from 1.2 to 1.3). Thus, the SSE likely occurred within the partially coupled downdip transition zone. Our preferred model suggests an SSE slip rate of 56 mm/yr, and an equivalent cumulative seismic moment of \(1.15 \times 10^{20}\) N m, corresponding to a moment magnitude of \(M_w\) 7.3 (assuming a rigidity of 30 GPa). The suite of best fit models (Table S5) suggests SSE moment magnitudes ranging from \(M_w\) 7.2 to 7.4.

The inversion results also support our hypothesis for an SSE on the megathrust (Text S5 and Figure S14). Although the inversion models are sensitive to slip constraints, the results show that data-model fits improve significantly when the fault is allowed to slip at rates greater than the plate subduction rate.

4. Discussion
Our results show that an SSE is the most likely explanation for the 15 year-long interseismic displacement reversal from 1966 to 1981 and that the event occurred on the Banyak Islands portion of the megathrust, at depths of 30 to 55 km. This depth range is consistent with the majority of SSE depth ranges found at other subduction zones, within the downdip zone of transitional friction properties from locked to creeping behavior [Schwartz and Rokosky, 2007].

The Banyak Islands portion of the megathrust appears to release its strain via a combination of several distinct slip phenomena. In addition to the SSE, this portion has ruptured in localized patches (e.g., the 2010 \(M_w\) 7.8 Banyak Islands earthquake (Figure 1)), participated in large coseismic ruptures (e.g., the 2005 \(M_w\) 8.6 Nias earthquake), and experienced afterslip following large earthquakes [e.g., Hsu et al., 2006]. This range of slip behavior may reflect distinctly different frictional properties on the Banyak Islands portion of the megathrust [Briggs et al., 2006]. Probing the physical processes and/or structures controlling these frictional properties remains a relevant topic for future work.

The SSE model suggests an equivalent cumulative seismic moment of \(1.15 \times 10^{20}\) N m, and corresponding moment magnitude of \(M_w\) 7.3, assuming a rigidity of 30 GPa. However, we note that equivalent seismic moment estimates are sensitive to modeling methods and assumed rigidities. For example, if we assume a higher rigidity of 75 GPa (representing the minimum rigidity estimate at > 30 km depths from the CRUST2.0 model in the Sumatran subduction zone), our SSE model yields an equivalent seismic moment of \(2.87 \times 10^{20}\) N m, corresponding to \(M_w\) 7.6. Figure 3 shows that our moment estimates for this SSE do not fall far from Ide et al. [2007]’s SSE moment-duration scaling relations. This result is reasonable, given that with our limited data set, moments cannot be estimated robustly.

There are a number of other studies reporting SSEs with durations longer than expected from current moment-duration relations, especially in Japan and Alaska. For example, Ochi and Kato [2013] obtained a revised equivalent moment magnitude of \(M_w\) 6.6 for the ~5 year-long Tokai SSE, corresponding to an equivalent seismic moment at least 16 times smaller than predicted by the lower limit envelope of Ide et al.’s [2007] moment-duration relations. As more long-duration SSEs are detected and studied, we speculate that we may gain new insights into the scaling relations of long-duration SSEs.

The Sumatran GPS Array (SuGAr) has been operating for 12 years, from 2002 to 2014. L. Feng et al. (manuscript in preparation, 2015) have carefully analyzed these 12 year-long time series and find no evidence for short-term SSEs. From the currently available data, it appears that the megathrust hosts long-duration SSEs.
Figure 3. SSE moment-duration scaling relations of Ide et al. [2007] (upper and lower limit envelopes shown by black lines) and SSEs at various subduction zones, compiled by Peng and Gomberg [2010] and Schwartz and Rokosky [2007] (events listed in Table 56). The lower and upper moment estimates of our SSE model assume rigidities of 30 and 75 GPa, respectively. The SSE does not fall far from the scaling relations of Ide et al. [2007]. SSEs with a range of reported moment estimates are shown by crosses on the circles, with connecting dashed lines.

5. Conclusions

Our results show that an SSE is the most likely explanation for a 15-year-long interseismic displacement reversal from 1966 to 1981, as recorded by coral data. The SSE occurred on the Banyak Islands portion of the megathrust, at 30 to 55 km depth, within the downdip transition zone. A range of slip behavior occurs on the portion of megathrust under the Banyak Islands, likely reflecting its different structural and frictional properties compared to adjacent parts of the Simeulue-Nias section of the megathrust.

References

[Long list of references cited in the text]

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