Improved Characterization of Megathrust Supercycles, Mentawai Islands, Sumatra

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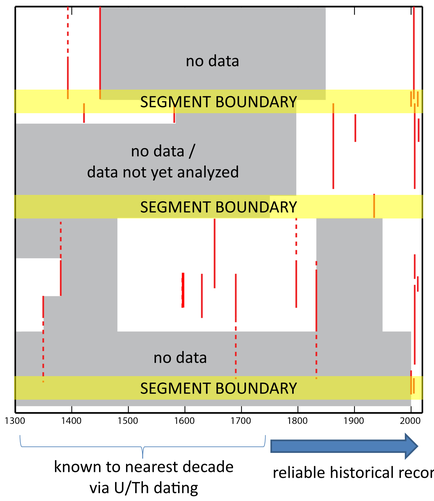
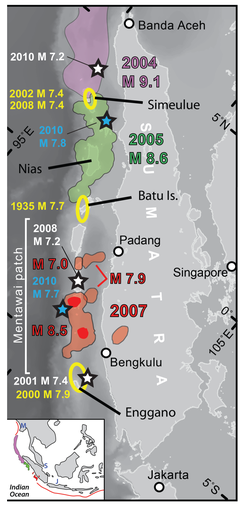
Abstract

Large sections of the Sunda megathrust have failed progressively over the past decade in an extraordinary earthquake sequence. One question of great humanitarian and scientific importance is how the remaining un-ruptured and under-ruptured patches might fail in coming decades. We use annually banded coral microatolls, which preserve precise information about past relative sea levels, to deduce tectonic histories centuries into the past. Observations over multiple seismic cycles illuminate diverse types of fault rupture behavior.

Megathrust Rupture History Overview

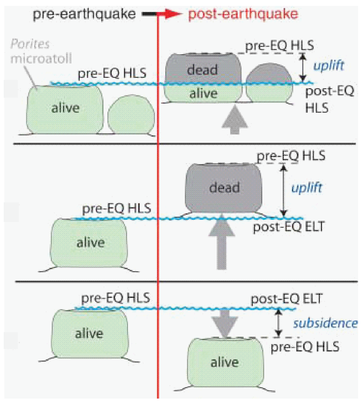


Space-time diagram of rupture history for the past 700 years compiled from our research. While Simeulue, the Batu Islands, and Enggano appear to lie above permanent barriers to throughgoing fault fupture, the Mentawai patch is characterized by temporary barriers to rupture. As a result, it breaks in sequences of earthquakes rather than single end-to-end ruptures.



Map of recent seismic ruptures of the Sunda megathrust. (Inset) M, S, and J are Myanmar, Singapore and Java.

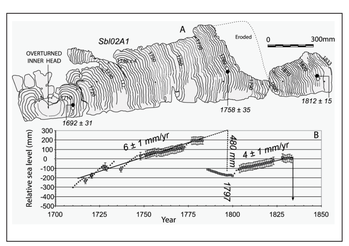
Paleogeodesy and Paleoseismology Techniques



HLS = Highest Level of Survival
ELT = Extreme Low Tide

Techniques for measuring recent coseismic or postseismic vertical deformation. We measure net uplift by comparing pre- and post-earthquake HLS (top), and net subsidence by comparing pre-earthquake HLS to the extreme low tide (bottom). Adapted from Briggs et al. (2006).

Example of a radial coral slab cut.



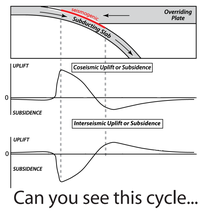
Example of a slab cross-section, showing the annual band growth history and the corresponding relative sea level over time. This coral demonstrates slow interseismic subsidence before and after a coseismic uplift event. From Natawidjaja et al. (2006).

Four Differing Seismic Supercycles

(right) Four emergence episodes of the past seven centuries. Each episode consists of more than one major event, and each rupture sequence has unique features. Updated from Sieh et al. (2008).

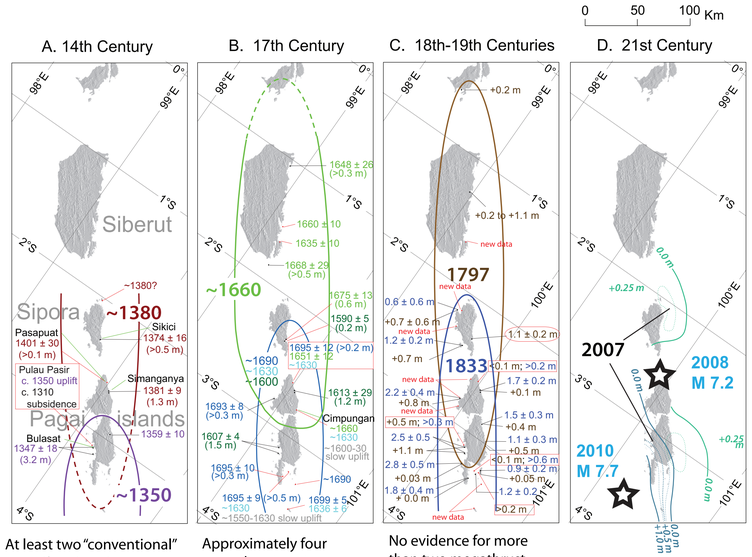
(below) Idealized interseismic and coseismic vertical deformation in a purely elastic subduction zone.

(below right) A newly uplifted coral reef, showing the seismic cycle. The dead tree snags represent jungle trees that had grown when their roots were above the sea. Slow subsidence above the locked Mentawai patch lowered them into the sea. Just before the September 2007 earthquakes the shoreline was to their left, at the sandy beach, and their substrate was below lowest tide. Uplift during the earthquake raised their bases once again well above low tide.



Can you see this cycle...

...in this photo?



At least two "conventional" megathrust ruptures, preceded by a shallow rupture.

Approximately four megathrust ruptures, with some slow slip between seismic events. Data are possibly sufficient for a time-series model (see future work).

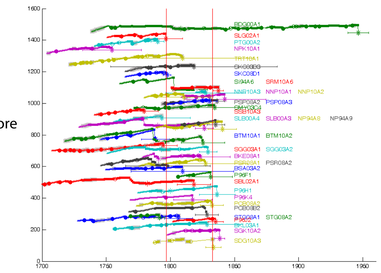
No evidence for more than two megathrust ruptures or for significant slow slip. Time-series modeling of interseismic and coseismic slip before and between the ruptures will illuminate spatial and temporal variations in fault coupling (see below).

Four "conventional" M>7 megathrust ruptures so far, with some slow slip between seismic events. At least one more M>8 rupture is expected. October 2010 shallow rupture is likely the first of its kind since the early 1300s.

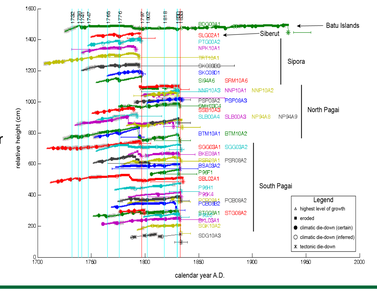
Correlating Coral Time Series

In preparation for modeling, we correlate coral records using temporary oceanographic lowerings in sea level (blue vertical lines) that, like tectonic uplifts, kill the top of the coral. This provides more precise correlation than radiometric dating uncertainties allow.

Before



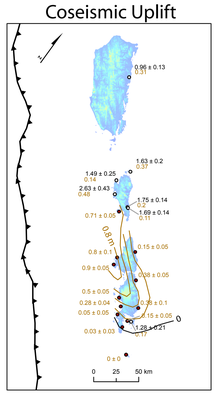
After



Detailed Analysis of the Historical Supercycle

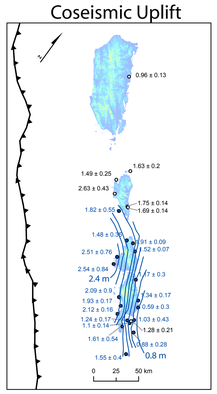
While northern reefs died completely in the 1797 uplift and no corals survived the 1833 uplift, the total uplift can be inferred in those cases by projecting modern interseismic rates backward in time (right). Observations at ~30 "fossil coral" sites and ~30 modern coral sites illuminate interseismic and coseismic vertical deformation patterns (below). Time-series modeling using PCAIM will allow more quantitative analysis of temporal and spatial changes in coupling patterns (below right).

1797 Coseismic Uplift



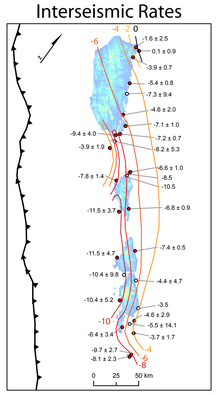
Brown numbers with uncertainty are totals in meters whereas those without are minima. Black numbers indicate total uplift to be apportioned between both ruptures. Contour interval is 20 cm. The tapering southern end of the uplift pattern is well resolved.

1833 Coseismic Uplift

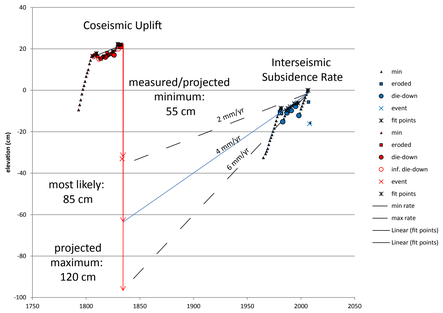


Blue numbers are totals whereas black numbers indicate total uplift to be apportioned between both ruptures. Contour interval is 20 cm. The northern end of the uplift likely tapered off over Sipora, though it is as yet unclear how far it extended.

20th-Century Interseismic Rates

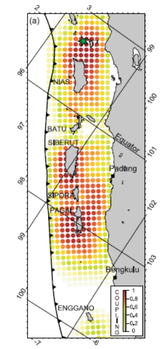


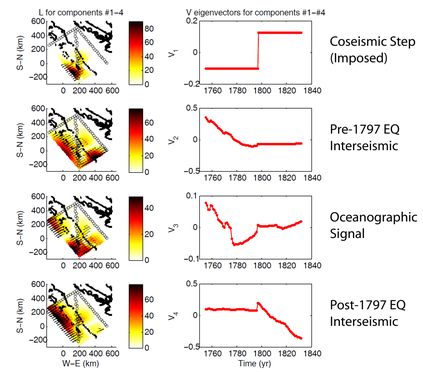
Subsidence rates (in mm/yr) measured over the mid to late 20th century suggest a peak of about 10 mm/yr trending along the southwest edge of the islands. This pattern is directly responsible for the derived pattern of 1833 uplift.



Example determination of coseismic uplift from interseismic subsidence rate (vertical scale is in terms of relative sea level, inverted vertical motion.)

Modern interseismic coupling pattern based on coral and GPS data, from Chlieh et al. (2008). Time-series modeling will permit the study of coupling evolution before and during supercycle rupture sequences, an improvement upon static-rate coupling studies.





A preliminary PCAIM model demonstrates how the different signal sources may be decomposed into spatial and temporal component pairs.

Future Work

These datasets are sufficient to compare interseismic rates and coseismic uplift patterns over three seismic supercycles, providing unprecedented insights into the variability of fault behavior and its implications for stress transfer. After completion of the historical supercycle modeling project, we will apply the same techniques to the 16th- and 17th-century coral records. This will allow us to compare the behavior of the megathrust during that period to its behavior in the past 5 years, hopeful that the events of the 17th century will yield insights into megathrust behavior during the next few decades.