Coseismic Slip and Afterslip of the Great (Mw9.15) Sumatra-Andaman Earthquake of 2004.

Mohamed Chlieh1, Jean-Philippe Avouac1, Vala Hjorleifsdottir1, Teh-Ru Alex Song1, Chen Ji1,2, Kerry Sieh1, Anthony Sladen3, Helene Hebert3, Linette Prawirodirdjo4, Yehuda Bock4, and John Galetzka1

1.Tectonics Observatory, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA.
2.Laboratoire de Détection et de Geophysique, CEA, Bruyèe-leChatel, France
3.Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92093, USA.

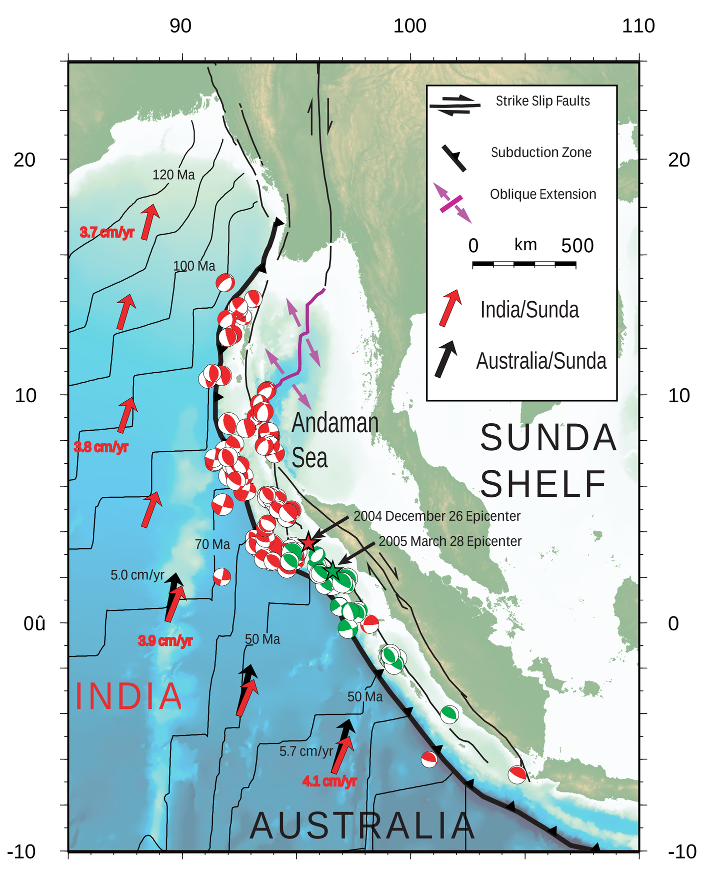
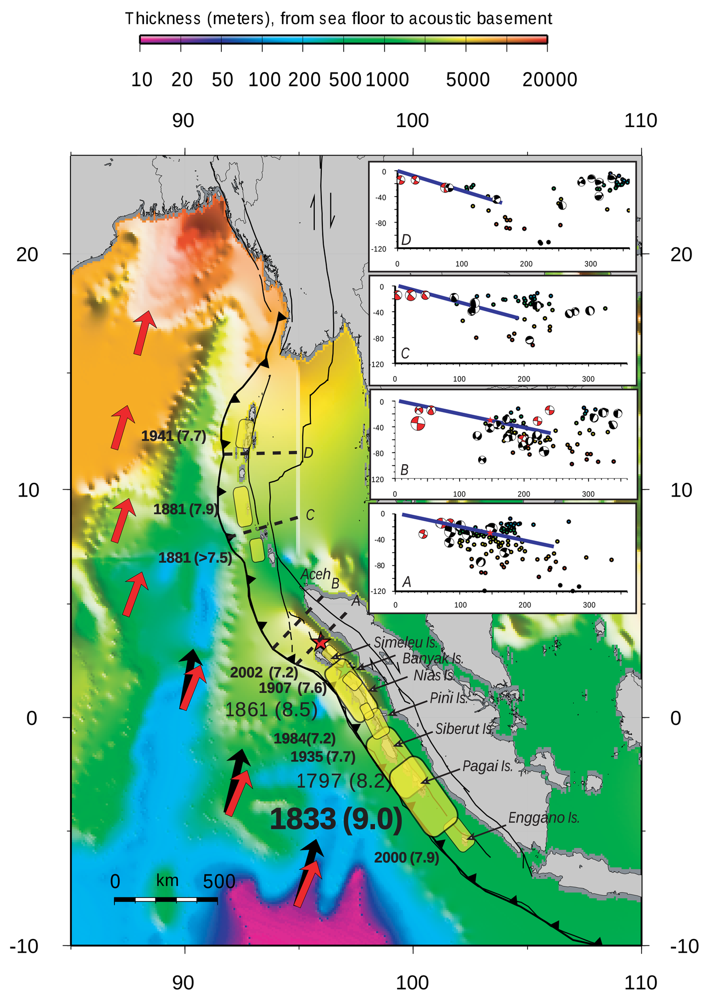


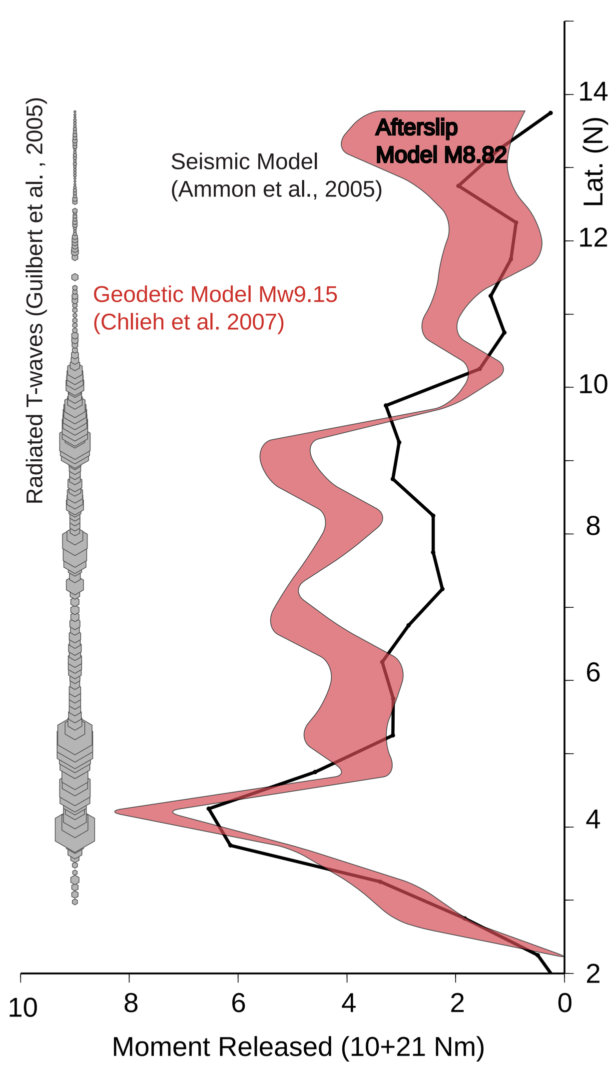
Figure 1: Neotectonic setting of the great Sumatra-Andaman earthquake. Plate velocities of Australia (~5.7cm/yr) and India (~3.8cm/yr) relative to Sunda were computed from the regional kinematic model of Bock et al. [2003] and Socquet et al. [2003]. Age of the sea floor [Cande and Kent 1995; Gradstein et al. 1994] increases northwards from about 50 Ma in the epicentral area to 90Ma near Andaman Islands. The red star indicates the epicenter of the 26 December, 2004 Sumatra-Andaman Mw9.15 earthquake and the green star the epicenter of the 28 March, 2005 Nias Mw8.7 earthquake. CMT associated to the aftershocks of the 2004 Sumatra-Andaman earthquake and in red and to the aftershocks of the 2005 Nias earthquake in green.

We determine coseismic and the first-month postseismic deformation associated with the Sumatra-Andaman earthquake of December 26, 2004 from near-field Global Positioning System (GPS) surveys in northwestern Sumatra and along the Nicobar-Andaman islands, continuous and campaign GPS measurements from Thailand and Malaysia, and in-situ and remotely sensed observations of the vertical motion of coral reefs. The coseismic model shows that the Sunda subduction megathrust ruptured over a distance of about 1500 km and a width of less than 150 km, releasing a total moment of 6.7-7.0 1022 Nm, equivalent to a magnitude Mw~9.15. The latitudinal distribution of released moment in our model has three distinct peaks around 4°N, 7° and 9°N, which compares well to the latitudinal variations seen in the seismic inversion and of the analysis of radiated T-waves. Our coseismic model is also consistent with interpretation of normal modes and with the amplitude of very long period surface waves. The tsunami predicted from this model fits relatively well the altimetric measurements made by the JASON and TOPEX satellites. Neither slow nor delayed slip is needed to explain the normal modes and the tsunami wave. The near-field geodetic data that encompass both coseismic deformation and up to 40 days of postseismic deformation require that slip must have continued on the plate interface after the 500s long seismic rupture. The postseismic geodetic moment of about 2.5 1022 Nm (Mw~8.8) is equal to about 30±5% of the coseismic moment release. Evolution of postseismic deformation is consistent with rate-strengthening frictional afterslip.

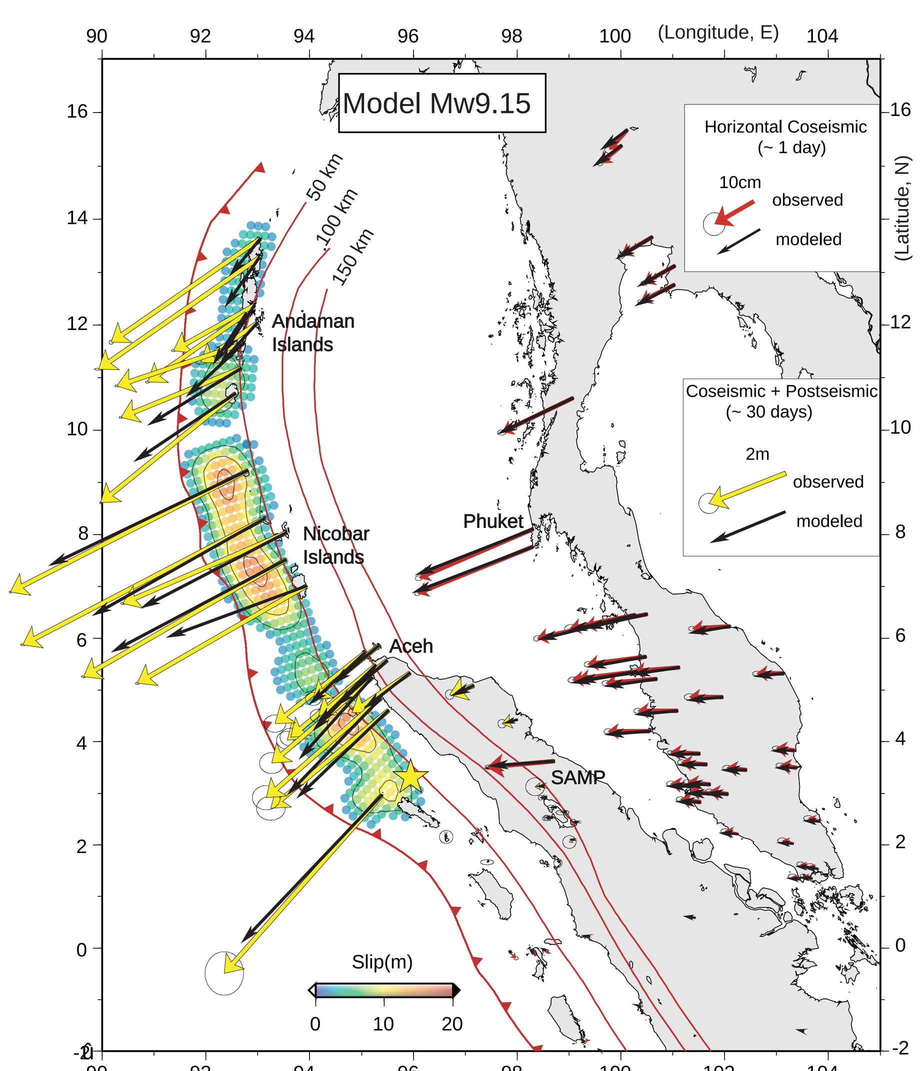


Estimated ruptured area of the major interplate earthquakes along the Sumatra subduction zone between 1833 and 2004 (Newcomb and McCann, 1987; Zachariasen et al, 1999; Natawidjaja et al, 2004). The background shows the sediments thickness from sea floor to accoustic basement. Insets show cross sections with Model's geometries, relocated seismicity and CMT solutions of aftershocks.

Coseismic Slip

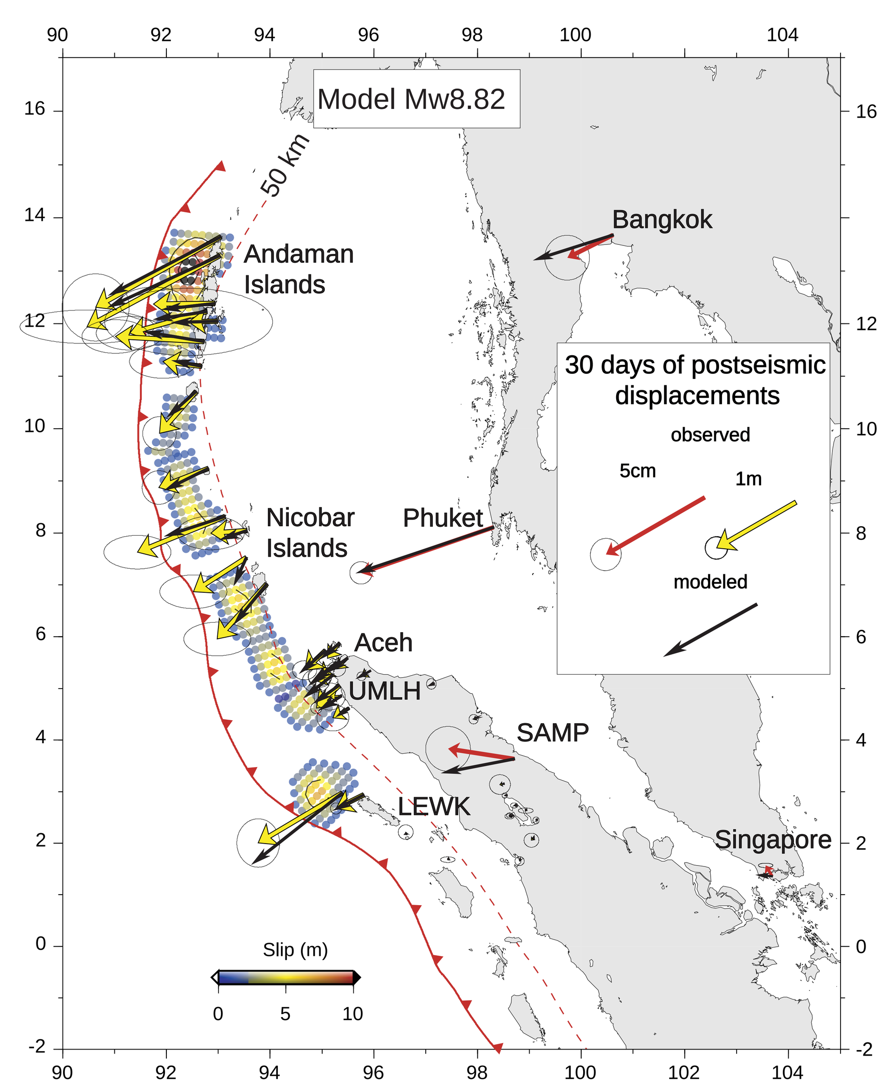


Latitudinal variations of scalar moments as determined from seismic model Ammon-III [Ammon et al. 2005] and from the geodetic coseismic slip model Mw9.15. Both our model and model derived from the latitudinal variation of radiated energy by T-waves [Guilbert et al. 2005] show three distinct regions of energy release. The size of hexagonale symbols corresponds to the relative amplitude released since the earthquake as recorded by hydrophone sensors at Diego Garcia islands.

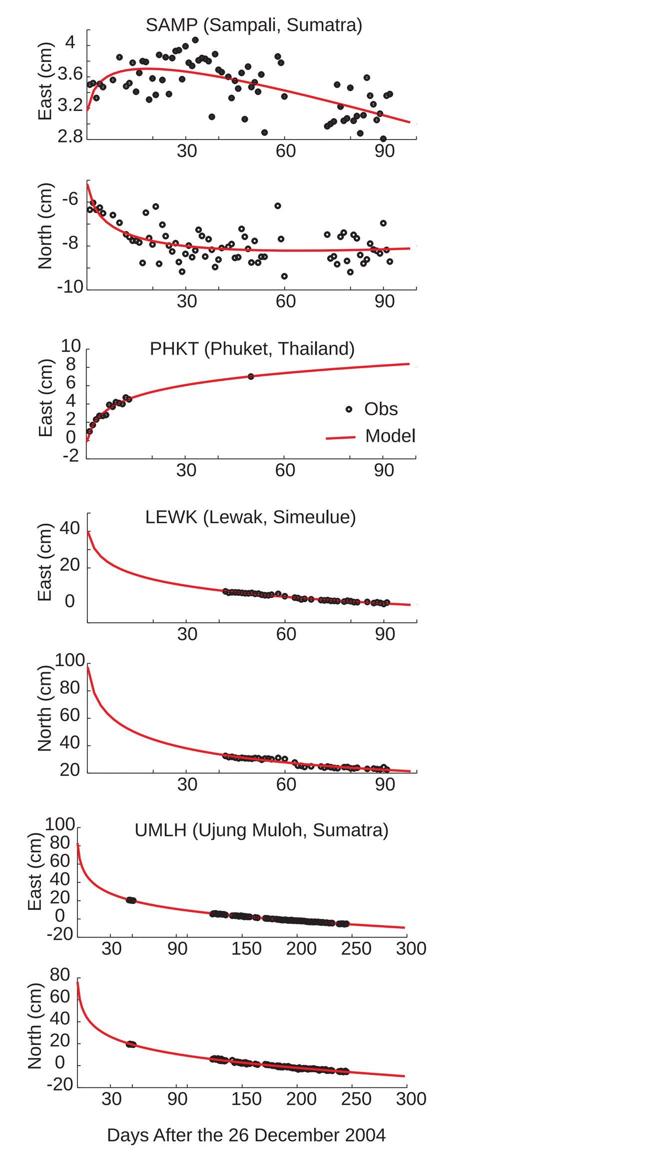


Slip distribution and predicted GPS displacements (black vectors) of the coseismic slip model (Mw9.15). Far-field coseismic displacements are representative to the displacements measured the day after the earthquake [Vigny et al. 2005]. Near-field displacements include coseismic and between 20 to 40 days of post-seismic deformation. Note the change of scale between arrows to the west (Andaman-Nicobar-Aceh) and arrows to the east (Thailand, Malaysia and SAMP).

Afterslip



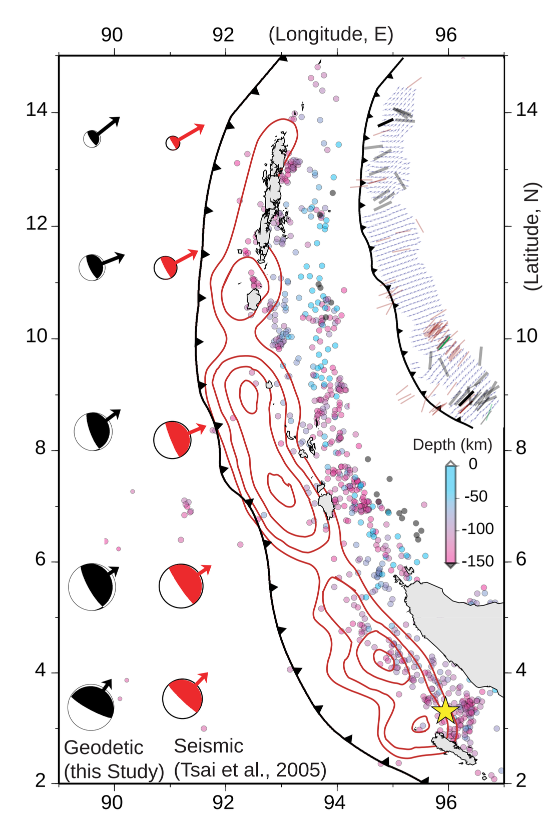
Postseismic slip distribution (slip contours are each 2-m)
Inversion of 1-month cumulative postseismic displacements recorded at permanent GPS stations of SAMP, UMLH, LEWK, Phuket, Bangkok and Singapore and the near-field residuals of the coseismic slip model M9w.15 covering 20 to 40 days of postseismic displacements (Model Mw~8.82).



Continuous GPS time series and best-fitting analytical function corresponding to frictional afterslip [Perfettini and Avouac 2004a]. The relaxation time was determined from the best fit to Sampali (SAMP) and Phuket (PHKT) time series and applied to fit the Ujung Muloh (UMLH) and Lewak (LEWK) time series.

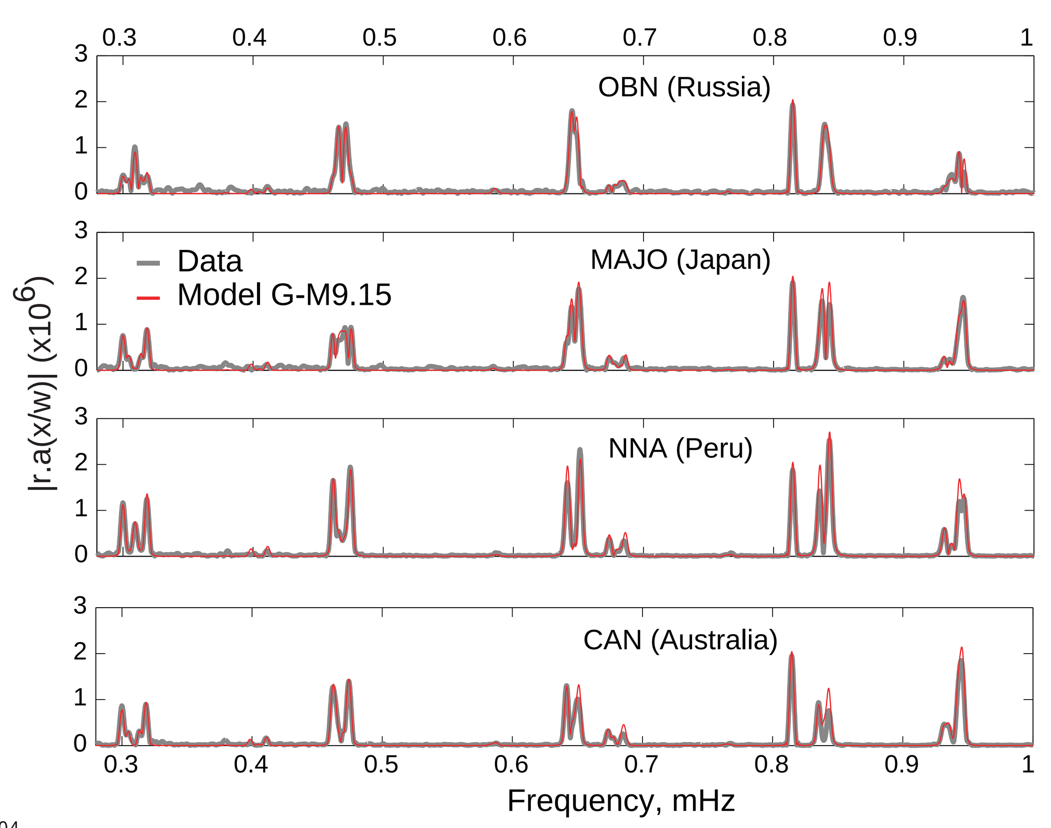
Consistencies of the Coseismic Slip model with:

CMT



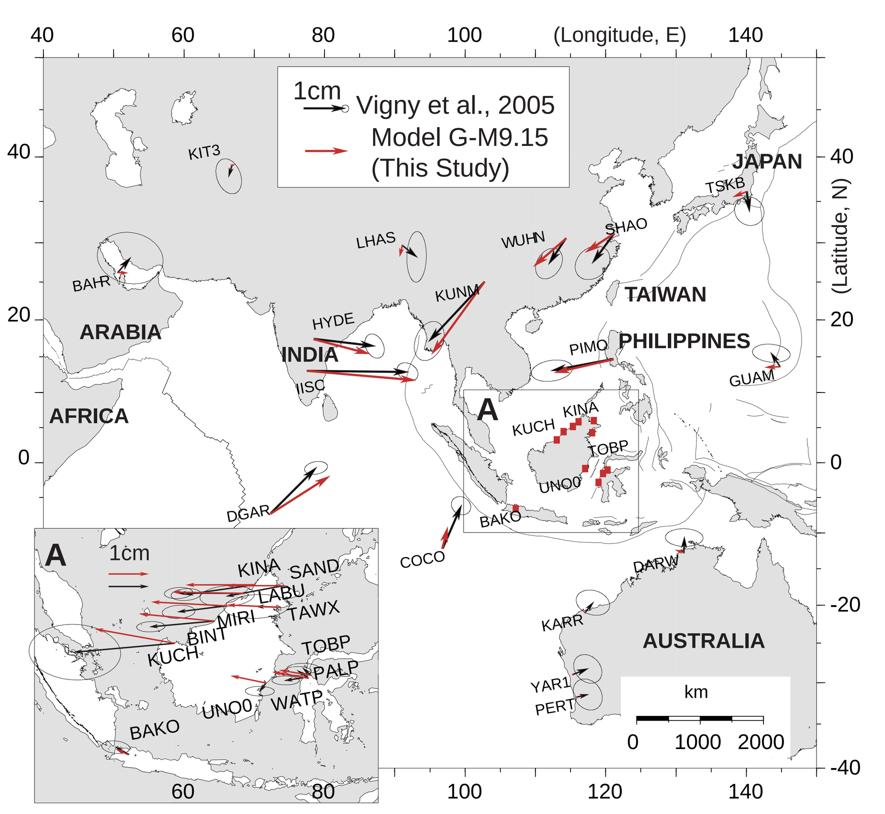
Summary of slip characteristics on the megathrust during the 2004 earthquake for the Coseismic Slip Model M9.15. Slip contours are each 5-m increments. Most of the 2004 coseismic slip occurred trenchward of prior seismicity (circles from [Engdhal et al. 1998]). Black beach balls are best-fitting double-couple mechanism for five regions of the rupture for the model. These are quite similar to the beach balls given by Tsai et al. [2005], based upon centroid-moment-tensor (CMT) analysis of the earthquake. The upper inset show the azimuth of slip on the megathrust (small arrows) which is primarily down dip south of 12N but strike-slip farther north. Bars are the slip vector azimuths of shallow dipping foreshocks and aftershocks from the Harvard CMT catalogue.

Normals Modes



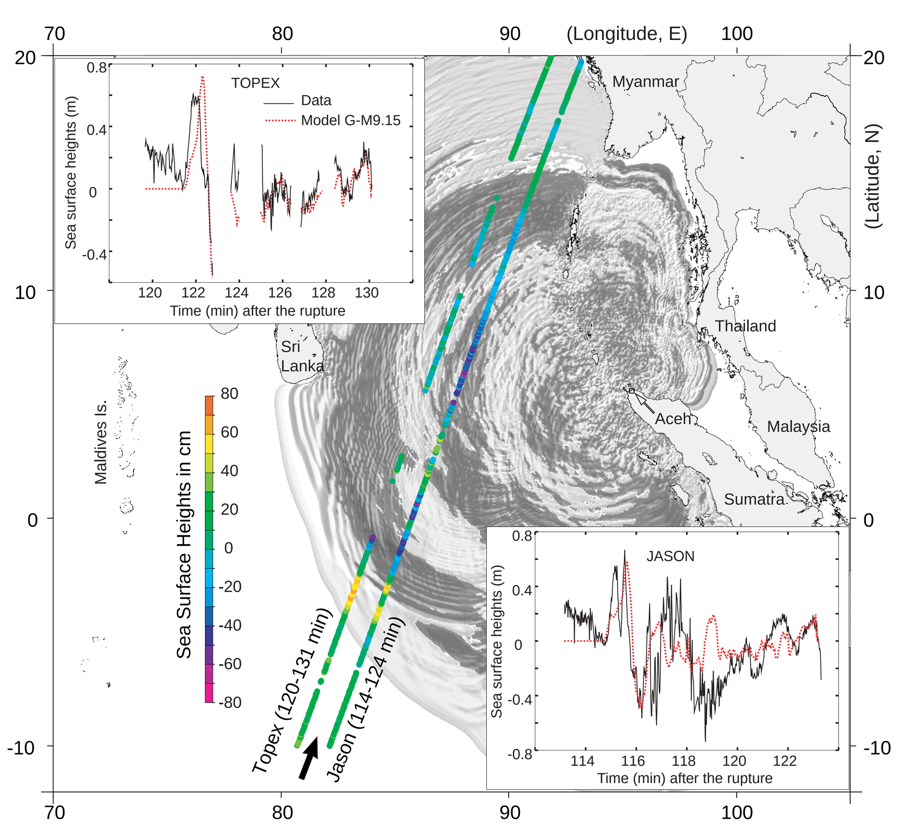
Comparison between normal modes data (thick line) and geodetic model M9.15 synthetics at four stations: OBN (Obninsk, Russia), MAJO (Matsushiro, Japan), NNA (Nana, Peru), CAN (Canberra, Australia).

Very Far-Field



Comparison of the very far-field GPS [Vigny et al. 2005] and predicted displacements of model M9.15 computed by SEM between 2000 and 4000 seconds. This model accounts for 3D structure (model Crust 2.0, [Bassin et al. 2000]), ellipticity, gravity, rotation, topography and ocean load.

Tsunami



Sea surface heights observed by the JASON and TOPEX-Poseidon satellites compared to numerical simulations of the tsunami based on the coseismic model M9.15 (dotted lines).

The model that fits best the geodetic measurements recorded within the first day of the 2004 earthquake is M9.15 . This model is consistent with seismological, tsunami and T-waves observations. We deduce that the seismic rupture must have propagated as far as 15ºN. The latitudinal distribution of moment in the model has three distinct peaks. This pattern is consistent with latitudinal variations in energy released by T-waves and high-frequency diffracted seismic waves . The general pattern in the model is a gradual northward decrease in slip. The fact that this mimics the northward decrease of the convergence rate across the plate boundary suggests that this pattern might be a characteristic feature of the large ruptures along this stretch of the megathrust.

Although our data place only low constraints on slip near the trench it seems that the coseismic rupture didn't reach to the trench everywhere. This inference is based on the slip distribution obtained from the inversion of the geodetic data and the consistency of that model with the amplitude of the deep-sea tsunami wave. Possibly that would reflect the effect of the poorly lithified sediments at the toe of the accretionary prism on the rheology of the plate interface, which would have inhibited the propagation of the seismic rupture due to a rate-strengthening friction mechanism [Byrne et al. 1988; Scholz 1998]. If this is so, one would expect afterslip on the megathrust proximal to the trench in response to stresses induced by the coseismic rupture [Marone et al. 1991].A model of frictional afterslip explains to first order the evolution of postseismic deformation. Within 60 days of the earthquake, post-seismic moment release equaled about 35% of the coseismic moment, the equivalent of an Mw 8.82 earthquake. The ratio of coseismic to postseismic slip is higher than this average north of 11ºN. In fact, afterslip in this portion of the megathrust in the month following the earthquake was larger than the coseismic slip . Perhaps this is evidence that the rheology of the megathrust there is strongly influenced by subduction of the exceptionally thick sedimentary sequence of the Bengal fan. Although its spatial distribution is poorly resolved, afterslip seems to have occurred over about the same width of the megathrust as coseismic slip.