Tectonics Observatory
California Institute of Technology

Heterogeneous coupling of the Sumatran megathrust constrained by geodetic and paleogeodetic measurements

Mohamed Chlieh*, Jean-Philippe Avouac, Kerry Sieh, Danny H. Natawidjaja, John Galetzka,

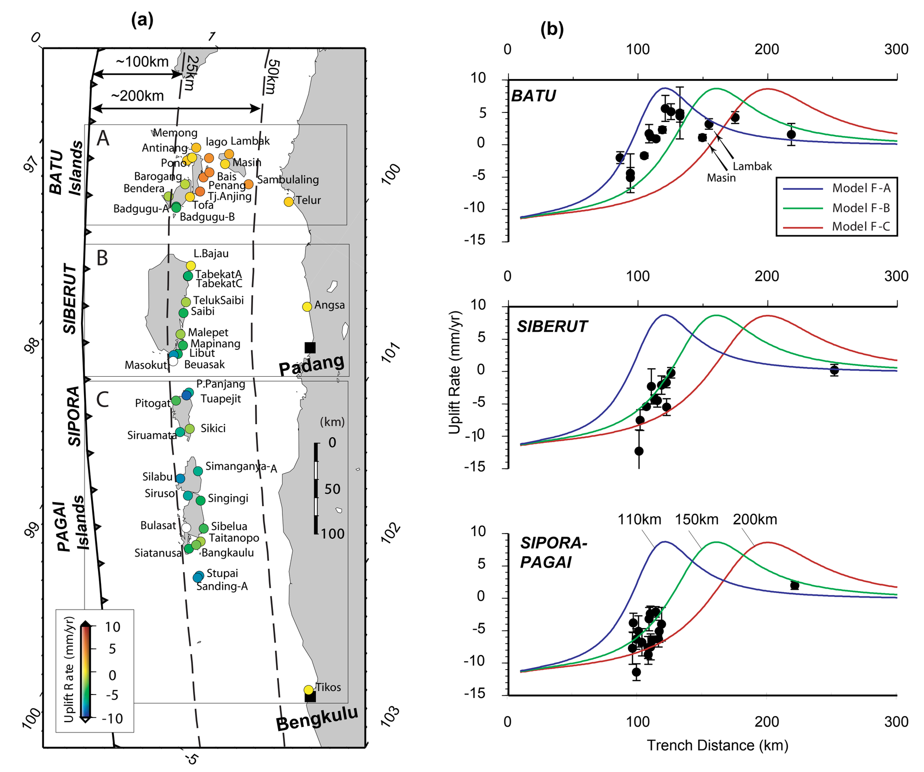
Tectonic Observatory, Caltech, Pasadena, CA

Research Center for Geotechnology, Bandung, Indonesia

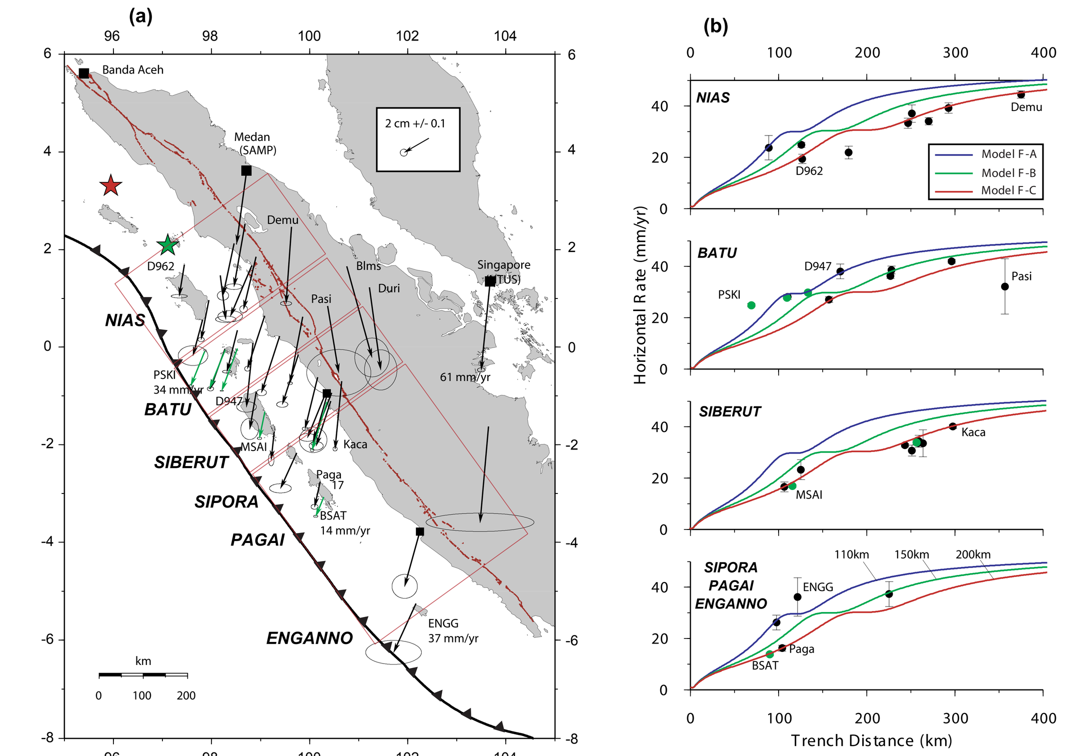
***Now at Institut de Recherche pour le developement, Geosciences Azur, Nice, France**

Geodetic and paleogeodetic measurements of interseismic strain above the Sumatran portion of the Sunda subduction zone reveal a heterogeneous pattern of coupling. Annual banding in corals provides vertical rates of deformation spanning the last half of the 20th century, and repeated GPS surveys between 1991 and 2001 and continuous measurements at GPS stations operated since 2002 provide horizontal velocities. Near the Equator, the megathrust is locked over a narrow width of only a few tens of kilometers. In contrast, the locked fault zone is up to about 175 km wide in areas where great interplate earthquakes have occurred in the past. Formal inversion of the data reveals these strongly coupled patches are roughly coincident with asperities that ruptured during these events. The correlation is most spectacular for rupture of the Mw 8.7 Nias-Simeulue earthquake of 2005, which released half of the moment deficit that had accumulated since its previous rupture in 1861, suggesting that this earthquake was overdue. Beneath the Mentawai islands, strong coupling is observed within the overlapping rupture areas of the great earthquakes of 1797 and 1833. The accumulated slip deficit since these events is slowly reaching the amount of slip that occurred during the 1833 earthquake but already exceeds the slip that occurred during the 1797 earthquake. Thus, re-rupture of part of the Mentawai patch in September 2007 was not a surprise. In contrast, coupling is low below the Batu islands near the Equator and around Enggano island at about 5S, where only moderate earthquakes (Mw<8.0) have occurred in the past two centuries. The correlation of large seismic asperities with patches that are locked during the interseismic period suggests that they are persistent features. This interpretation is reinforced by the fact that the large locked patches and great ruptures occur beneath persistent geomorphologic features -- the largest outer-arc islands. Depth- and convergence-rate dependent temperature might influence the pattern of coupling, through its effect on the rheology of the plate interface, but other influences are required to account for the observed along-strike heterogeneity of coupling. In particular, subduction of the Investigator Fracture Zone could be the cause for the low coupling near the Equator.

PALEOGEODETIC AND GEODETIC DATA

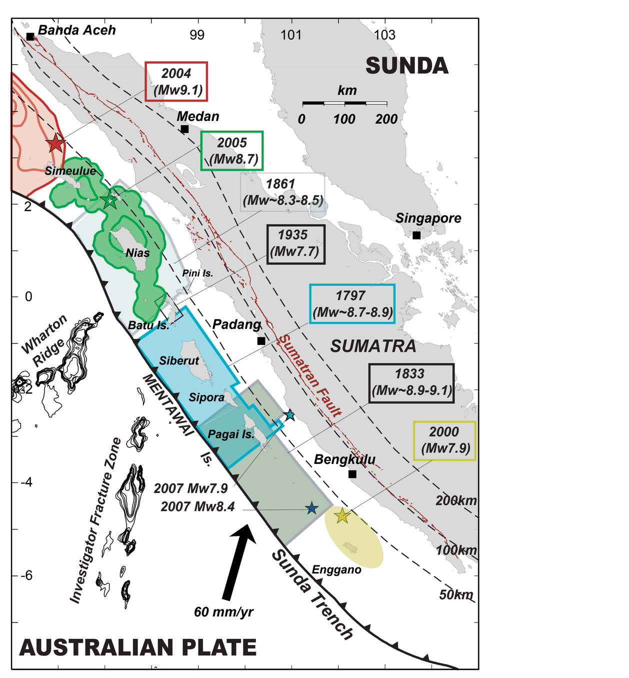


Vertical displacement rates determined from coral growth over the period 1962-2000 (Table 2) (a) in map view and (b) along sections normal to the trench [Natawidjaja, et al., 2007; Natawidjaja, et al., 2004]. Boxes (A, B and C) indicate the swath corresponding to each section. The origin of horizontal axis for each section is at the trench. Outer arc islands are subsiding, a pattern consistent with the interseismic locking of the shallow portion of the plate interface. Continuous lines in (b) show theoretical uplift rates predicted by assuming that the plate interface is fully locked from the trench down to a depth of either 30, 40, or 50 km, corresponding to a horizontal width of the locked fault zone of 110, 150 or 200km respectively. Subsidence rates increase southward along strike suggesting that the locked fault zone gets wider to the south.



Horizontal velocities relative to Australia (a) in map view and (b) along sections normal to the trench. Black arrows represent velocities determined from GPS campaign measurements [Bock, et al., 2003] and green arrows show velocities determined from continuous GPS measurements at stations of the Sumatra Geodetic Array, SuGAr (http://sopac.ucsd.edu/cgi-bin/sugarTimeSeries.cgi), prior to the occurrence of the Sumatra-Andaman earthquake of 2004. Ellipses show 1-Sigma uncertainties (Tables 3 and 4). Boxes in (a) show location of swath used to construct profiles in (b). Except at Enggano and Sipora horizontal velocities decrease noticeably trenchwards, as expected if the shallower portion of the megathrust is locked. The large velocities at Enggano and Sipora suggest little locking around these stations. Continuous lines show velocity profiles predicted from forward models F-a, F-b, and F-c. These models assume full locking of the megathrust from the trench to a horizontal distance of respectively 110, 150 and 200 km.

SEISMO-TECTONIC SETTINGS



Basic active structural elements and historical great earthquakes of the obliquely convergent Sumatran plate boundary. Green and red 5-m contour lines of slip for the 2004 Sumatra-Andaman and 2005 Nias-Simeulue earthquakes are respectively from Chlieh et al. [2007] and Briggs et al. [2006]. Outermost contours depict the limits of rupture. Approximate rupture area of the Mw~8.3-8.5 1861 earthquake is based on macroseismic effects [Newcomb and McCann, 1987]. Ruptures during the great 1797 and 1833 earthquakes are from elastic dislocation models based upon uplift of coral microatolls [Natawidjaja, et al., 2006]. The southern limit of the 1833 rupture is poorly constrained. The ellipse shows the approximate rupture of the 2000 earthquake and the relatively high seismic activity that occurred in this area in the last decade from Abercrombie et al. [2003]. Epicentres of the 2007 Mw 8.4 South Pagai and the Mw 7.9 Pagai-Sipora earthquakes are shown for reference (http://earthquake.usgs.gov/eqcenter/). Dashed lines parallel to the trench are the 50, 100 and 200 km depth of the megathrust [Gudmundsson and Sambridge, 1998].

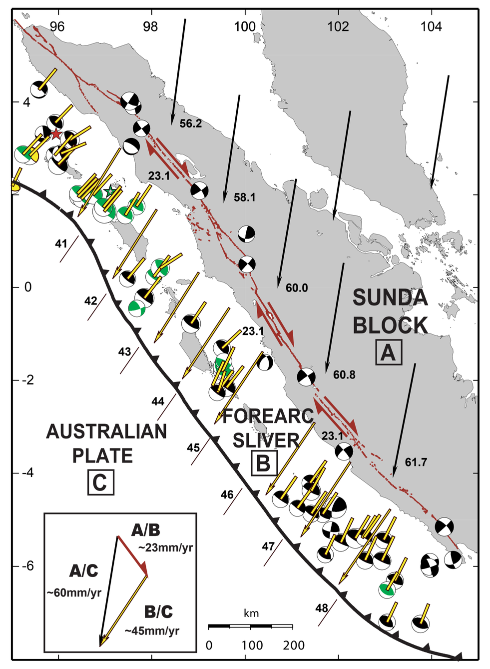
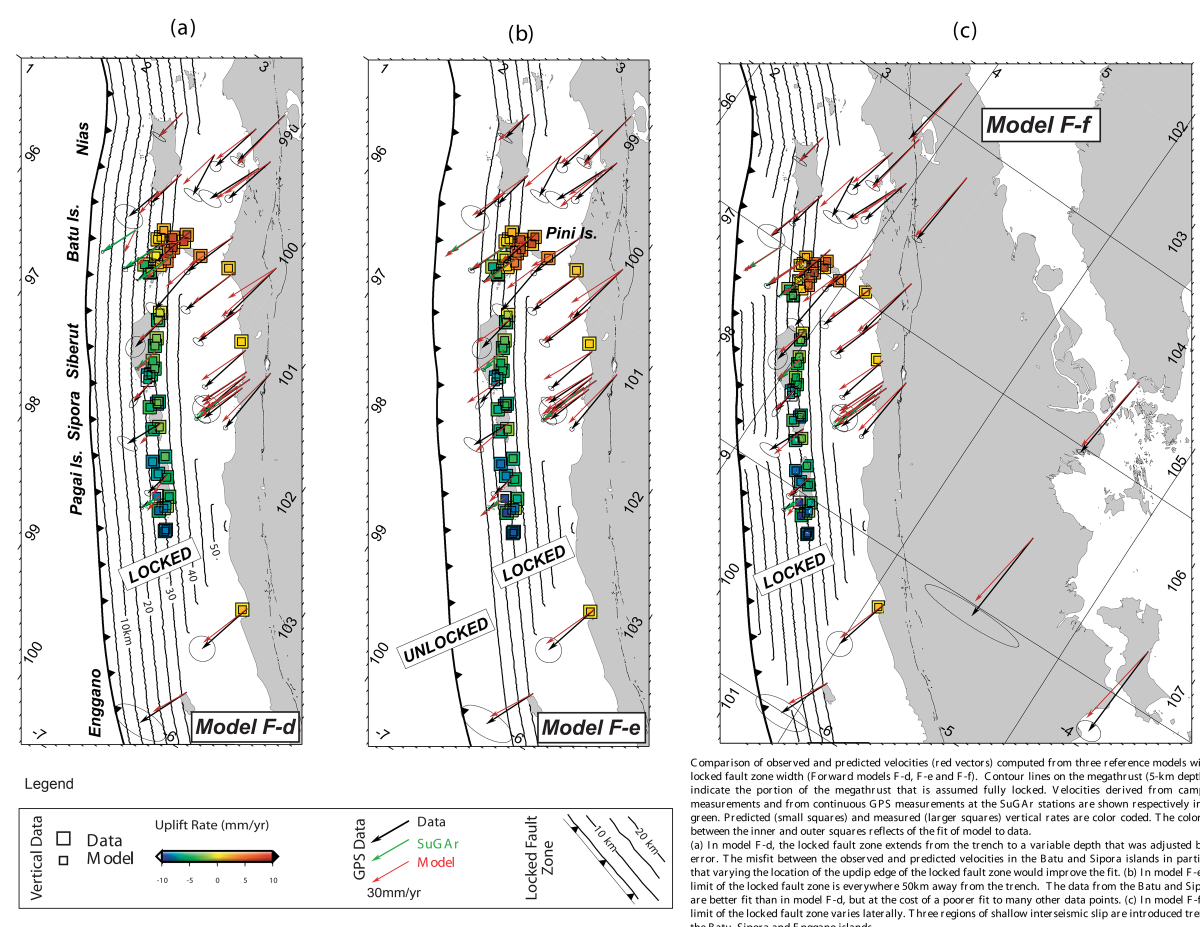


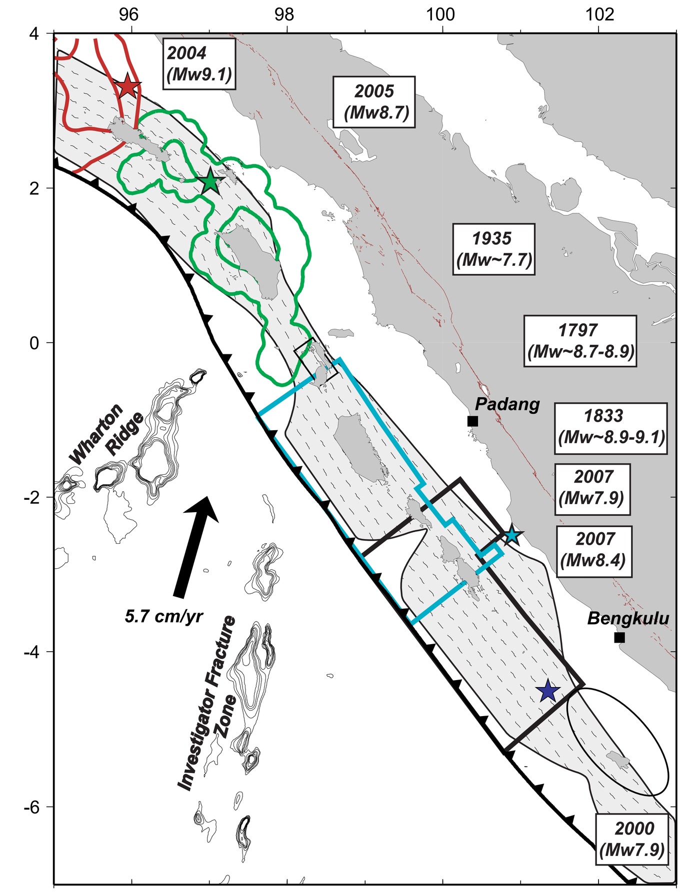
Plate tectonic setting of the study area. Secular motion of the Sunda block (A) and forearc sliver (B) relative to Australian plate (C), indicated by arrows with rates in mm/yr. Relative motion of Sunda block (A) relative to the Australian plate (C) is from Bock et al. [2003]. Plate motion of forearc-sliver was determined by assuming that its motion relative to Australian plate is parallel to slip vectors of moderate interplate earthquakes along the Sumatra megathrust. The forearc-sliver's motion relative to the Sunda block is parallel to the Sumatran fault and about 23 mm/yr. Resulting horizontal motion of the forearc-sliver relative to the Australian plate is about 45 mm/yr trenchward. Focal mechanisms are from the Harvard centroid moment tensor (CMT) catalogue for earthquakes with Mw > 6 between 1976 and June 2005 (http://www.seismology.harvard.edu/CMTsearch.html). Focal mechanisms of earthquakes posterior to the Mw 8.7 March 2005 Nias-Simeulue earthquake are shown in green.

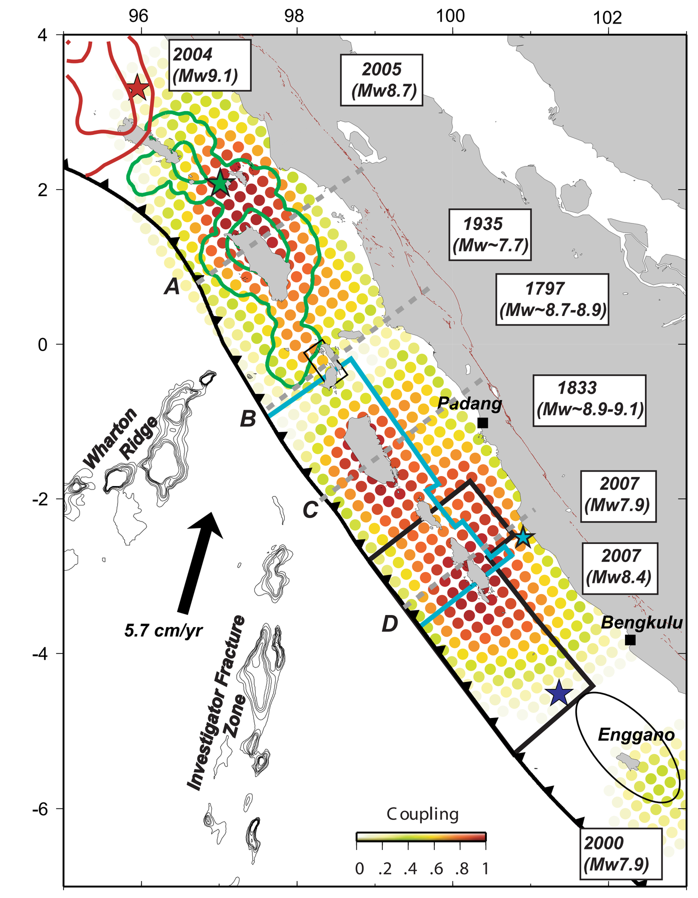
FORWARD MODELS



Comparison of observed and predicted velocities (red vectors) computed from three reference models with variable locked fault zone width (Forward models F-d, F-e and F-f). Contour lines on the megathrust (5-km depth intervals) indicate the portion of the megathrust that is assumed fully locked. Velocities derived from campaign GPS measurements and from continuous GPS measurements at the SuGAr stations are shown respectively in black and green. Predicted (small squares) and measured (larger squares) vertical rates are color coded. The color difference between the inner and outer squares reflects of the fit of model to data.
(a) In model F-d, the locked fault zone extends from the trench to a variable depth that was adjusted by trial and error. The misfit between the observed and predicted velocities in the Batu and Sipora islands in particular show that varying the location of the updip edge of the locked fault zone would improve the fit. (b) In model F-e, the updip limit of the locked fault zone is everywhere 50km away from the trench. The data from the Batu and Sipora islands are better fit than in model F-d, but at the cost of a poorer fit to many other data points. (c) In model F-f, the updip limit of the locked fault zone varies laterally. Three regions of shallow interseismic slip are introduced trenchward of the Batu, Sipora and Enggano islands.

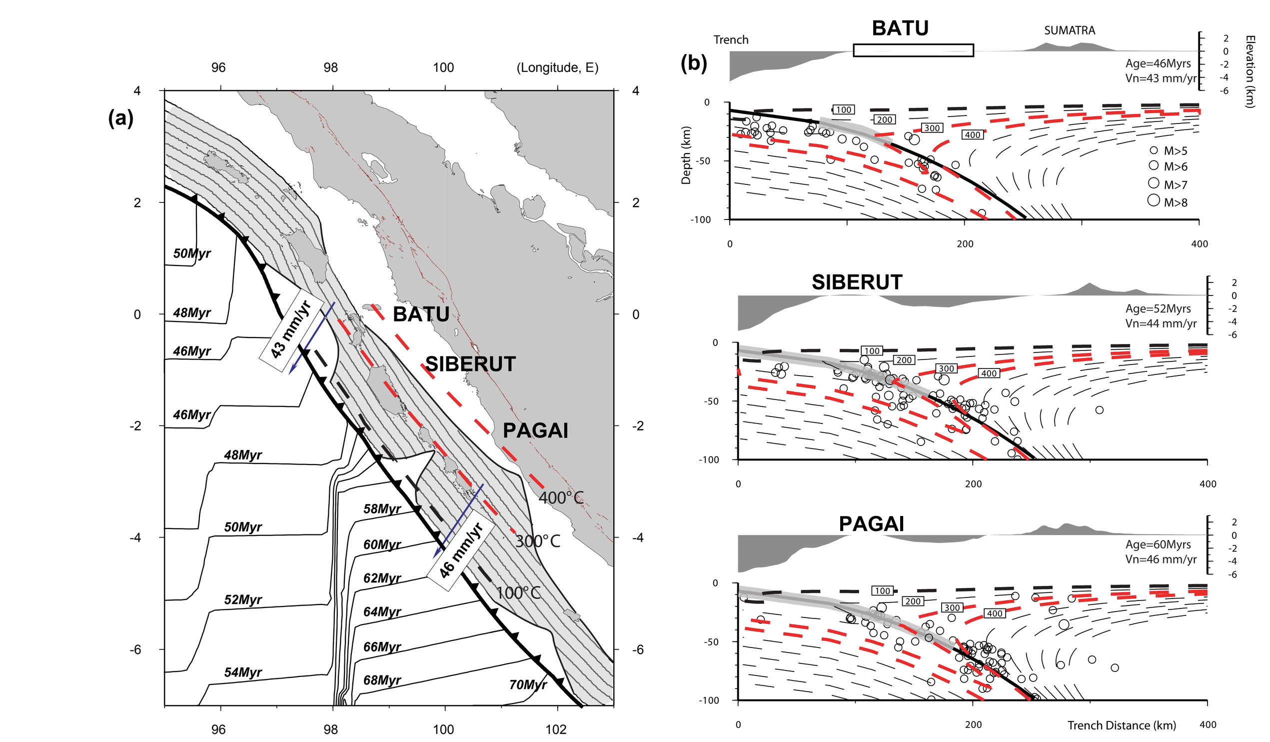
Locked Fault Zone vs earthquakes





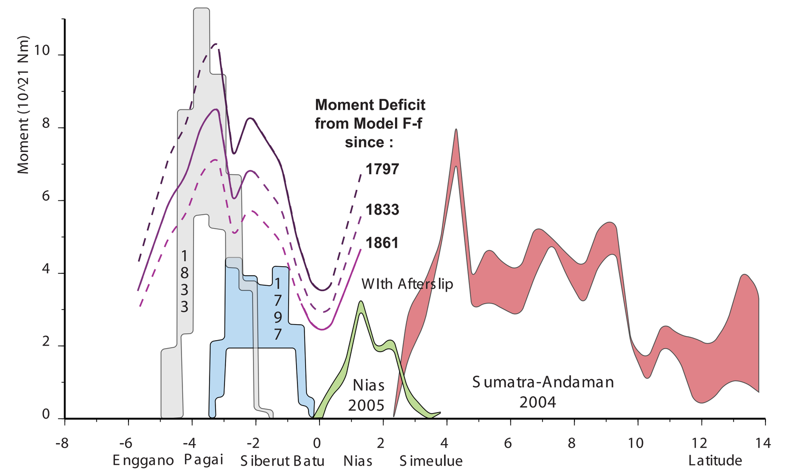
Comparison of interseismic coupling along the megathrust with the rupture areas of the giant 1797, 1833 and 2005 earthquakes. The southernmost rupture area of the 2004 Sumatra-Andaman earthquake lies north of our study area and is shown only for reference. Epicenters of the 2007 Mw 8.4 and Mw 7.9 earthquakes are also shown for reference.
(a) Geometry of the locked fault zone corresponding to forward model F-f (Figure 6c). Below the Batu Islands, where coupling occurs in a narrow band, the largest earthquake for the past 260 years has been a Mw 7.7 in 1935 [Natawidjaja, et al., 2004; Rivera, et al., 2002]. The wide zones of coupling, beneath Nias, Siberut and the Pagai islands coincide well with the source of

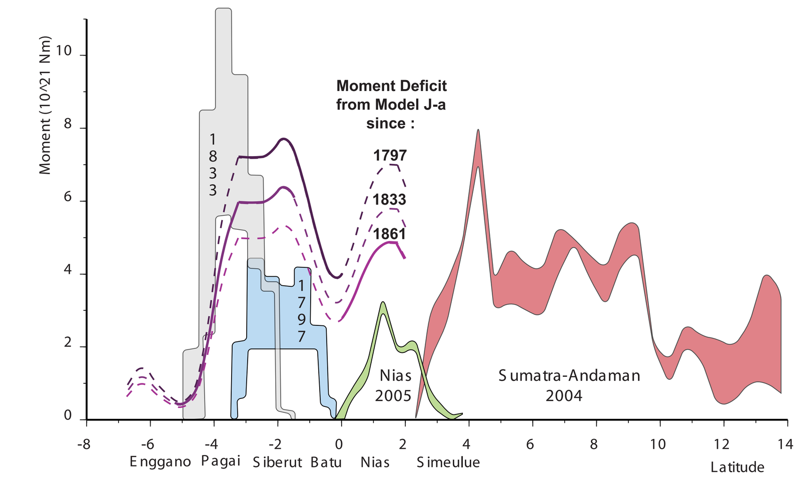
THERMAL MODELS



(a) Map view of the isotherms 100°C, 300°C and 400°C as deduced from the thermal modelling superposed on top of the LFZ of model F-F. The lateral variations of the age of the subducting oceanic plate are indicated in Myr [Cande and Kent 1995; Gradstein et al. 1994]. (b) Topographic and steady state thermal structure of the meagthrust interface for three trench-normal sections across the Batu, Siberut and Pagai islands. The slab interface is drawn using the background relocated seismicity catalogue of [Engdhal et al. 1998]. The LFZ of the meagthrust interface deduced from Model F-F are reported in grey. Isotherms are computed from analytical expression of the steady state thermal structure model proposed by [Royden, 1993]. The model accounts for conduction, advection, a shear heating of 40 mW/m2 and upper plate radiogenic heat production of 0.4 mW/m3. The two parameters varying between profiles are the age and the normal convergence velocity of the subducting plate. On each profile, the downdip end of the LFZ appears to be in the isotherms range of 300°C and 400°C (red dashed line).

Moment Released vs Accumulated Moment Deficit

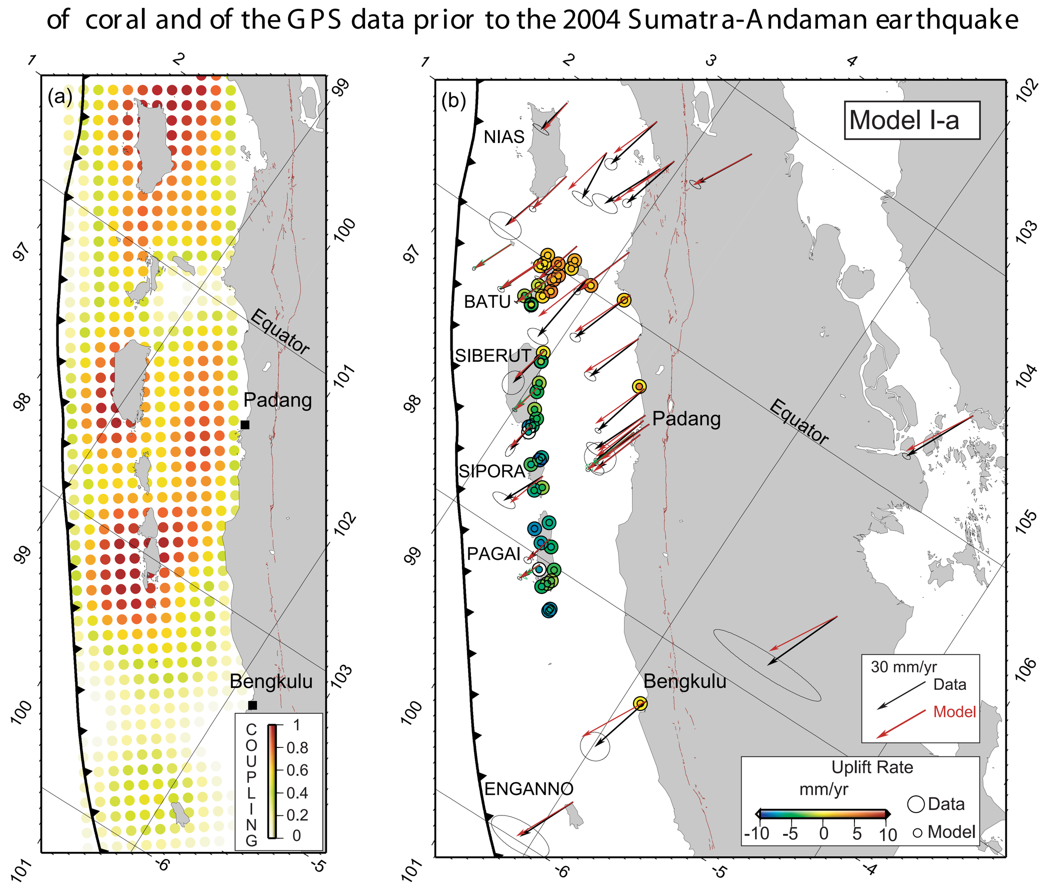




Latitudinal distributions of seismic moment released by great historical earthquakes and of accumulated deficit of moment due to interseismic locking of the plate interface. Values represent integrals over half a degree of latitude. Accumulated interseismic deficits since 1797, 1833 and 1861 based on (a) model F-f and (b) model J-a. Seismic moments for the 1797 and 1833 Mentawai earthquakes are estimated based on Natawidjaja et al. [2006], the 2005 Nias-Simeulue earthquake is taken from Konca et al. [2007] and the 2004 Sumatra-Andaman earthquake from Chlieh et al. [2007]. Postseismic moment released in the month that follows the 2004 earthquake and in the 11 months that follows the Nias-Simeulue 2005 earthquake are respectively shown is red and green respectively, based on Chlieh et al. [2007] and Hsu et al. [2006].

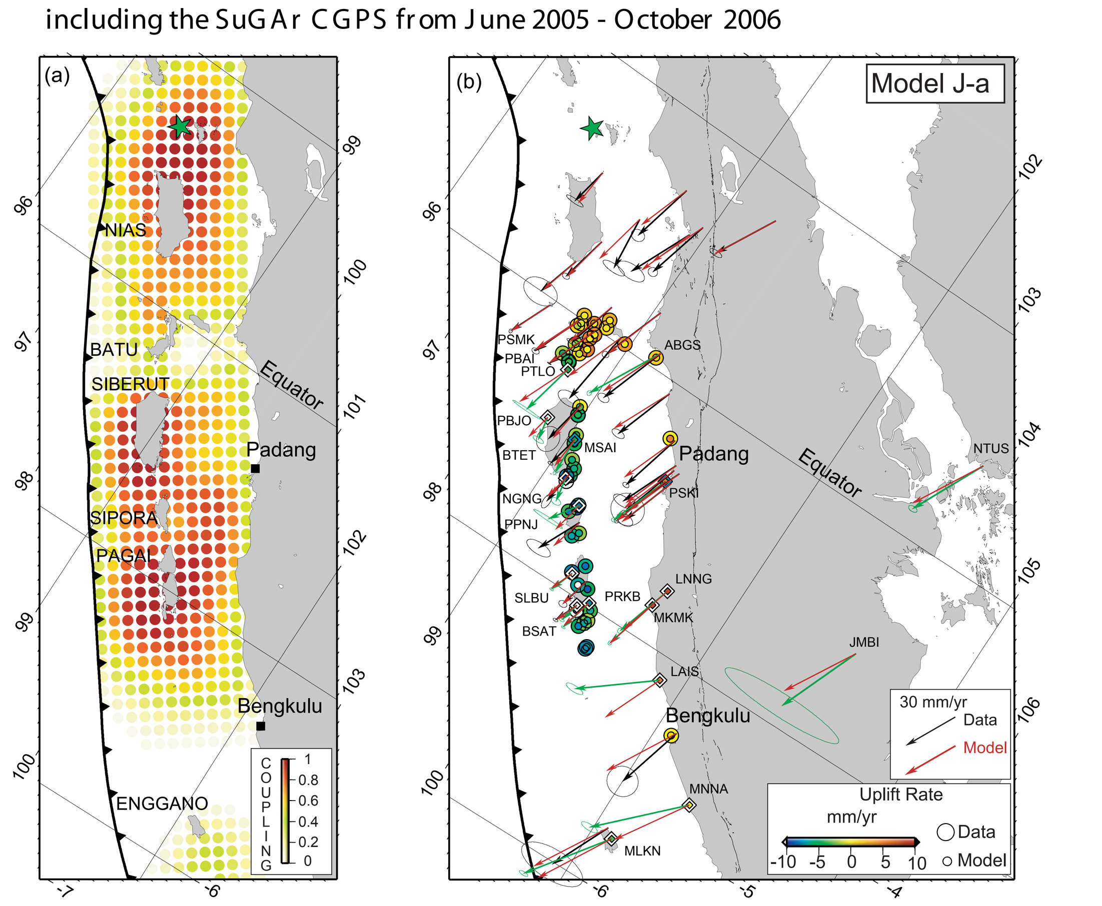
FORMAL INVERSIONS

of coral and of the GPS data prior to the 2004 Sumatra-Andaman earthquake



Distribution of coupling on the Sumatra megathrust derived from the formal inversion of the coral and of the GPS data prior to the 2004 Sumatra-Andaman earthquake (model I-a). (a) Distribution of coupling on the megathrust. Fully coupled areas are red and fully creeping areas are white. Three strongly coupled patches are revealed beneath Nias island, Siberut island and Pagai island. The annual moment deficit rate corresponding to that model is 4.0 x 1020 Nm/yr. (b) Observed and predicted horizontal velocities appear as black and red vectors respectively. Observed and predicted vertical displacements are shown by color-coded large and small circles respectively.

including the SuGAr CGPS from June 2005 - October 2006



Distribution of coupling on the Sumatra megathrust derived from the formal inversion of all the data (model J-a). (a) Distribution of coupling on the megathrust. Fully coupled areas are red and fully creeping areas are white. This model shows strong coupling beneath Nias island and beneath the Mentawai (Siberut, Sipora and Pagai) islands. The rate of accumulation of moment deficit is 4.5 x 10^20 Nm/yr. (b) Comparison of observed (black arrows for pre 2004 Sumatra-Andaman earthquake and green arrows for post 2005 Nias earthquake) and predicted velocities (in red). Observed and predicted vertical displacements are shown by color-coded large and small circles (for the corals) and large and small diamonds (for the CGPS) respectively.