Stress changes along the Sunda trench following the 26 December 2004 Sumatra-Andaman and 28 March 2005 Nias earthquakes

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[1] The 26 December 2004 $M_w = 9.2$ and 28 March 2005 $M_w = 8.7$ earthquakes on the Sumatra megathrust altered the state of stress over a large region surrounding the earthquakes. We evaluate the stress changes associated with coseismic and postseismic deformation following these two large events, focusing on postseismic deformation that is driven by viscoelastic relaxation of a low-viscosity asthenosphere. Under Coulomb failure stress (CFS) theory, the December 2004 event increased CFS on the future hypocentral zone of the March 2005 event by about 0.25 bar, with little or no contribution from viscous relaxation. Coseismic stresses around the rupture zones of the 1797 and 1833 Sunda trench events are negligible, but postseismic stress perturbations since December 2004 are predicted to result in CFS increases of 0.1 to 0.2 bar around these rupture zones between 2 and 8 years after the December 2004 event. These are considerable stress perturbations given that the 1797 and 1833 rupture zones are likely approaching the end of a complete seismic cycle. **Citation:** Pollitz, F. F., P. Banerjee, R. Bürgmann, M. Hashimoto, and N. Choosakul (2006), Stress changes along the Sunda trench following the 26 December 2004 Sumatra-Andaman and 28 March 2005 Nias earthquakes, *Geophys. Res. Lett.*, *33*, L06309, doi:10.1029/2005GL024558.

1. Introduction

[2] The 26 December 2004 $M_w = 9.2$ Sumatra-Andaman earthquake ruptured about 1300 km of the Sumatra megathrust with more than 5 m average slip [*Banerjee et al.*, 2005]. Portions of the megathrust south of about 2.5°N latitude, the southern termination of this earthquake [*Lay et al.*, 2005], are similarly prone to large earthquakes, as witnessed by the occurrence of M 8 earthquakes in 1797, 1833, 1861, and the recent 28 March 2005 $M_w = 8.7$ Nias earthquake (Figure 1). These earthquakes released large amounts of accumulated strain on portions of the megathrust known to be highly locked based on coral morphology and geodetic data [*Simoes et al.*, 2004]. A recurrence interval of 230 years is estimated by *Sieh et al.* [2004] for the central Sunda trench. This suggests that the region south of the 28 March 2005 event is presently stressed highly enough to produce 1833-type events, and that the subduction interface may therefore be sensitive to small stress perturbations.

[3] Each earthquake alters the state of stress in its surroundings, and it is natural to investigate the stress changes associated with the 26 December 2004 and 28 March 2005 events in order to evaluate the potential for future earthquake triggering along the remaining Sumatra-Sunda megathrust [*McCloskey et al.*, 2005]. In the context of Coulomb failure stress theory [*Harris*, 1998; *Stein*, 1999], *Nalbant et al.* [2005] suggest that coseismic and postseismic stress changes from the 26 December 2004 event acted to trigger the 28 March 2005 event with an estimated Coulomb failure stress (CFS) change of $\sim$0.1 bar. *Nalbant et al.* [2005] note that the compounded stress changes from the 26 December 2004 and 28 March 2005 events should increase CFS along much of the Sunda trench south of the equator (roughly the southern termination of the March 2005 event). Here we investigate this issue in greater detail by employing fault models of the 26 December 2004 and 28 March 2005 events [*Banerjee et al.*, 2005; P. Banerjee et al., Coseismic slip distributions of the 26 December 2004 Sumatra-Andaman earthquake and 28 March 2005 Nias earthquake from GPS static offsets, submitted to *Bulletin of Seismological Society of America*, 2005, hereinafter referred to as Banerjee et al., submitted manuscript, 2005] derived from the final static displacement field, combined with postseismic relaxation of the asthenosphere on a self-gravitating, compressible Earth model (F. F. Pollitz et al., Postseismic relaxation following the great 2004 Sumatra-Andaman earthquake on a compressible self-gravitating Earth, submitted to *Geophysical Journal International*, 2005, hereinafter referred to as Pollitz et al., submitted manuscript, 2005). We find that predicted CFS from these perturbations will increase by >0.1 bar over much of the Sunda trench in the coming years, raising seismic hazards along certain portions which likely already have a substantial amount of accumulated stress.

2. Time-Dependent Coseismic and Postseismic Deformation

[4] The time-dependent perturbation to the regional displacement and stress fields depends on source models of the earthquakes and a rheological model of the regional crust and mantle. Slip models of the 26 December 2004 event based on seismic wave analysis at periods 2000 sec [*Ammon et al.*, 2005] underpredict observed static GPS offsets because they capture some, but not all, of the large slip known to have occurred on the Andaman segment [*Bilham et al.*, 2005; *Jade et al.*, 2005]. We use the slip

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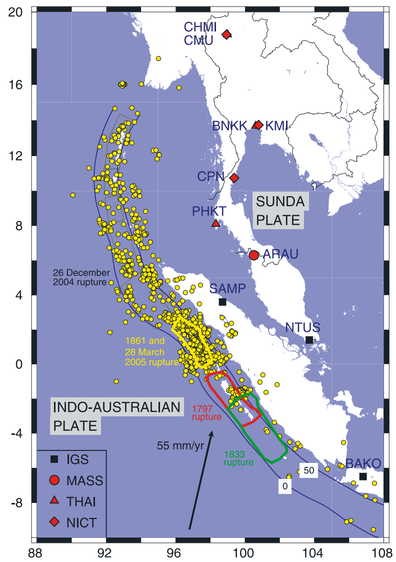

Figure 1. Rupture areas associated with known megathrust earthquakes along the Sumatra-Sunda trench. Gray planes are the coseismic rupture of the 26 December 2004 earthquake from Model M3 of *Banerjee et al.* [2005]. Indicated are the 0 and 50 km slab depth contours of *Gudmundsson and Sambridge* [1998]. Epicenters of M $\geq$ 4.0 earthquakes from 29 March 2005 to 1 August 2005 from the NEIC catalog are superimposed. Selected GPS sites from four regional networks are indicated.

model M3 of *Banerjee et al.* [2005] derived from the final static displacement field as measured by GPS; this model involves slip on each of 7 planes spanning the 1300-km-long rupture, with uniform slip on each plane. The 5-day postearthquake averages used in the analysis imply that the model captures all slippage out to ~2.5 days after the earthquake.

[5] For the 28 March 2005 Nias earthquake we use the source model derived by Banerjee et al. (submitted manuscript, 2005) using 32 regional GPS sites. The fit obtained by the simple 5-plane model is excellent (Figure S1 in the auxiliary material[1]). This model, obtained with a dip of 15°, corresponds to magnitude M_w = 8.66.

[6] We use the rheology model for oceanic lithosphere and mantle presented by *Pollitz et al.* [1998], with elastic structure modified to follow the isotropic elastic structure of PREM [*Dziewonski and Anderson*, 1981]. This spherically-layered rheology model (Figure S2 in the auxiliary material) has a low-viscosity asthenosphere of viscosity η_{asth} = 5×10^{17} Pa s, with a 62-km thick elastic lithosphere above it and higher-viscosity mantle ($\eta_{UM} = 10^{20}$ Pa s) below it. Coseismic stresses are calculated in a spherical geometry using the method of *Pollitz* [1996]. Time-dependent postseismic relaxation is realized on a self-gravitating compressible Earth model (Pollitz et al., submitted manuscript, 2005).

[7] GPS data from several regional continuous sites (Figure 1) were processed with the GAMIT/GLOBK software package developed at MIT to produce time series of station coordinates in the ITRF-2000 reference frame. Resulting time-dependent displacements are shown with predicted displacements in Figure 2 and auxiliary Figure S3. The simple low-viscosity asthenosphere model with Maxwell rheology satisfactorily predicts the postseismic movements between the December 2004 and March 2005 events and after the March 2005 event. This explanation, however, is not unique. Pollitz et al. (submitted manuscript, 2005) explore a transient asthenosphere rheology, and *Hashimoto et al.* [2006] and *Subarya et al.* [2006] explore afterslip models for explaining the continuous GPS measurements. In this paper we assume that the low-viscosity asthenosphere model with Maxwell rheology is sufficient to predict at least the longer-term future stress changes in the region. Since afterslip and viscoelastic models are designed to explain the early postseismic evolution (~first 3 months), they are expected to produce similar stress evolution at early times. At subsequent times, however, we expect that asthenosphere relaxation will dominate the stress evolution.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005gl024558.

3. Stress Changes

[8] We use a CFS function given by CFS = $\Delta\tau + \mu'\Delta\sigma_n$, which expresses CFS as a sum of the change in shear stress τ and the change in normal stress σ_n (here assumed positive tensile) weighted by an effective coefficient of friction μ'.

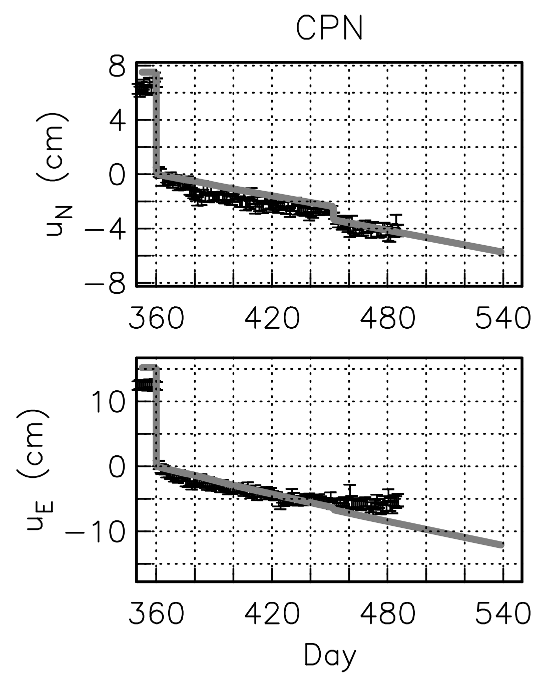

Figure 2. Observed GPS time series following the 26 December 2004 earthquake with 1-σ errors at continuous GPS site CPN (Figure 1). Additional time series are shown in Figure S3. u_E and u_N refer to east- and northward displacement, respectively. Day numbers refer to the year 2004. Superimposed are the predicted displacement curves that include the effects of coseismic and postseismic offsets due to the 26 December 2004 and 28 March 2005 Sumatra earthquakes.

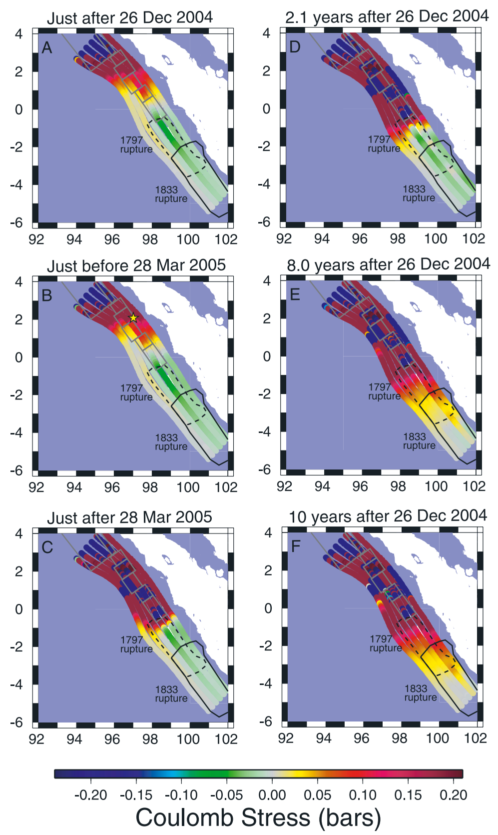

Figure 3. Snapshots of CFS changes from coseismic and postseismic deformation associated with the 26 December 2004 and 28 March 2005 earthquakes. Stresses are evaluated at positions which have been linearly interpolated between the 0 km and 50 km depth contours of *Gudmundsson and Sambridge* [1998]. The receiver fault geometry assumes pure reverse slip on the Sunda trench interface, which is locally approximated with 325°-striking, 15°-dipping planes. (a–c) Cumulative stress changes from just after the 26 December 2004 event to just after the 28 March 2005 event. (d–f) Cumulative stress changes from 2.1 years to 10 years after the 26 December 2004 event. Gray planes indicate the outlines of the fault planes of the 26 December 2004 and 28 March 2005 earthquakes. Yellow star is the epicenter of the 28 March 2005 earthquake.

Figure 3 shows snapshots of CFS on the Sunda trench interface assuming $\mu' = 0.4$. Results are similar for other values of μ' between 0 and 0.8. The receiver fault geometry is assumed to be 325°-striking, 15°-dipping planes with rake = 90°, i.e., pure reverse slip. Figures 3a and 3b show that coseismic deformation from the December 2004 event increased CFS by 0.25 bar near the nucleation zone of the March 2005 event at ~40 km depth (C. Ji, Updated result of the 05/03/28 (*Mw* 8.5) Sumatra earthquake, 2005, available at http://www.gps.caltech.edu/~jichen/Earthquake/2005/sumatra/sumatra.html) and downdip of the nucleation zone down to 50 km. CFS at the 28 March 2005 hypocenter by viscoelastic relaxation during the 0.25 years between the two events did not change (0.01 bar CFS change). The net 0.25 bar stress change at the 28 March 2005 hypocenter is similar to the 0.17 bar net stress change calculated by *Nalbant et al.* [2005], who noted the dependence of the coseismic stress change on the coseismic slip model being used.

[9] Figures 3d–3f shows that CFS continues to increase along the Sunda trench south of the equator for 10 years after the December 2004 event. At time 2.1 years (Figure 3d), postseismic CFS increases to ~0.1 bar around the shallow-depth, northern portion of the 1797 rupture zone. The locus of elevated postseismic CFS migrates southward with time, and by time 8.0 years most of the 1797 rupture zone has stress values of 0.05 to 0.20 bar, and much of the northern portion of the 1833 rupture zone has stress values between 0.05 and 0.10 bar. These values are of magnitude sufficient to potentially trigger large earthquakes in these regions based on stress to seismicity correlations obtained in many tectonic settings [*Stein*, 1999].

4. Discussion

[10] The stress patterns obtained are dependent on the assumption of lateral homogeneity of viscoelastic properties. This condition is not strictly satisfied given the large volume of downgoing slab beneath the Sunda plate which has an asymmetrical distribution around the plate boundary because of its shallow dip. The results obtained with the assumption of lateral homogeneity will be approximately valid if the downgoing slab were a passive feature that moves with the induced postseismic mantle flow. In more detailed studies of viscoelastic flow around a three-dimensional slab structure [e.g., *Cohen*, 1996; *Hu et al.*, 2004], the presence of an elastic slab can lead to substantial differences with a "slabless" viscoelastic structure.

[11] The effects of postseismic mantle flow on time-dependent stress on the slab interface are modest, but the induced stresses may help trigger aseismic slip, which would compound the stress increases from postseismic relaxation alone. Kinematic coupling along this and other subduction zones is commonly heterogeneous, and the stress changes from the viscous relaxation can change aseismic slip rates of the plate interface on "uncoupled" shallow segments, as well as on the sections below seismogenic depths. Aseismic slip on the slab interface downdip of major coseismic slip induced by the December 2004 rupture has been advanced by *Hashimoto et al.* [2006] and aseismic slip downdip of the coseismic rupture is likely the dominant mode of deformation after other recent subduction zone events [*Melbourne et al.*, 2002; *Yagi et al.*, 2003]. Aseismic slip may be plausibly induced not only along the downdip extension but also along the lateral extension of a megathrust event [*Miyazaki et al.*, 2004]. If applicable to the recent events on the Sumatra megathrust, the CFS patterns presented here could act to trigger aseismic slip within the 1797 and 1833 rupture zones. *Melbourne et al.* [2002] noted that at least deep aseismic slip following the M8.0 1995 Jalisco, Mexico (subduction) event could be sustained with a 0.2 bar stress increase. This is comparable with the ~0.1 to 0.2 bar net predicted stress increases 100s of km southeast of the December 2004 and March 2005 Sumatran events. Moreover, if the source regions of the 1797 and 1833 earthquakes were late in their respective seismic cycles, as suggested by the paleo-earthquake history of the region [*Sieh et al.*, 2004], then such a stress perturbation would represent a substantial

fraction of the stress necessary to return to the state(s) prior to the occurrence of these earthquakes.

[12] Another potentially important factor is dynamic triggering induced by the passage of seismic waves [*Freed*, 2005]. Its importance in the aftermath of the December 2004 and March 2005 events is suggested by the occurrence of numerous small events within the 1797 rupture zone within 3 months following the 28 March 2005 event (Figure 1). This region is not predicted to have had any substantial increase in CFS at such an early stage, but the effects of delayed dynamic triggering [*Parsons*, 2005] may play a role in generating this seismicity.

5. Conclusions

[13] Time-dependent stress along the Sunda trench interface is predicted to steadily increase over the next several years from the effects of the 26 December 2004 and 28 March 2005 earthquakes. Coseismic stress changes and postseismic stress changes driven by viscoelastic relaxation of the asthenosphere contribute to the stress changes. In the rupture areas of the 1797 and 1833 Sumatran earthquakes, coseismic stress changes are negligible, but postseismic stress changes amount to 0.1 to 0.2 bars within 8 years after December 2004. This perturbation may be substantial given that these rupture zones are likely late in their respective seismic cycles.

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