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Viscoelastic relaxation in a heterogeneous Earth following the 2004 Sumatra–Andaman earthquake

Kelly Wiseman [a], Roland Bürgmann [a,*], Andrew M. Freed [b], Paramesh Banerjee [c]

[a] *Department of Earth and Planetary Science, University of California, Berkeley, CA, 94720-4767, USA*
[b] *Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN, 47907, USA*
[c] *Earth Observatory of Singapore, Nanyang Technological University, Singapore 639798, Singapore*

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ABSTRACT

Consideration of the three-dimensional heterogeneity of mantle rheology allows models of viscoelastic relaxation following the 2004 Sumatra–Andaman earthquake to simultaneously fit both the observed far-field and near-field postseismic deformation. We use horizontal and vertical campaign and continuous GPS observations from the Andaman, Nicobar, and Sumatran forearc islands, mainland Sumatra, Thailand, the Malay Peninsula, the Indian Ocean, and southern India, spanning the first five years of postseismic deformation. The postseismic relaxation models consider contributions from the 2004 M_W 9.2 Sumatra–Andaman, the 2005 M_W 8.7 Nias, and 2007 M_W 8.4 Bengkulu earthquakes. Far-field motions to the east of the ruptures are equally well fit by homogeneous or laterally variable earth models. However, only models with contrasting rheology across the subducting slab, a ten-times higher mantle viscosity under the Indian Ocean lithosphere than the backarc mantle, can also produce the observed enduring postseismic uplift along the forearc and lack of far-field transient displacements in southern India. While postseismic uplift of forearc stations can also be produced by rapid and enduring down-dip afterslip, the inferred rheology structure is consistent with the distribution of mantle temperature inferred from seismic tomography.

1. Introduction

Crustal deformation following megathrust earthquakes provides insight into the rheology of the subduction thrust fault and the relaxing mantle wedge and oceanic asthenosphere (Wang et al., 2012). Deep-seated postseismic relaxation can produce crustal deformation exceeding that from the earthquake itself in the intermediate-to-far field range. The 2004 M_W 9.2 Sumatra–Andaman earthquake (Shearer and Bürgmann, 2010), and subsequent 2005 M_W 8.6 Nias (Konca et al., 2007) and 2007 M_W 8.4 Bengkulu events (Konca et al., 2008) (Fig. 1), produced large stress changes in the lithosphere surrounding the ruptures, and in the upper mantle below the rupture zones. Postseismic deformation ensued during which various deformation processes relax the coseismic stress changes.

Investigations of postseismic deformation are often plagued by ambiguities between multiple processes that can be expected to contribute to the deformation field at different times and distances from the rupture, including viscous flow, localized afterslip, and poroelastic rebound (e.g., Bürgmann and Dresen, 2008). Previous studies of the postseismic transients following the 2004 Sumatra–Andaman earthquake have primarily focused on either the near-field or the far-field postseismic deformation field, and explained the motion with dominantly afterslip (e.g., Hashimoto et al., 2006; Paul et al., 2007; Chlieh et al., 2007; Gahalaut et al., 2008), poroelastic rebound in the crust or mantle (Hughes et al., 2010; Ogawa and Heki, 2007), or viscoelastic mantle relaxation (Pollitz et al., 2006; Panet et al., 2010; Broerse et al., 2015). Several studies argued for the importance of contributions from multiple mechanisms (e.g., Paul et al., 2012; Hoechner et al., 2011; Hu and Wang, 2012). Hoechner et al. (2011), Panet et al. (2010) and Broerse et al. (2015) find that no or modest afterslip are needed to explain GPS displacements and GRACE gravity-change measurements, if a rapidly relaxing Burgers viscoelastic rheology is considered. Here we consider both near-field and far-field measurements of five years of postseismic deformation since 2004 to explore the underlying relaxation processes.

Models of viscous relaxation in a vertically stratified earth without a strong subducting slab predict horizontal surface displacements towards the downdip end of the coseismic rupture plane (e.g., Pollitz et al., 2008). Postseismic subsidence from viscous

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* Corresponding author.
E-mail addresses: kellygwiseman@gmail.com (K. Wiseman), burgmann@berkeley.edu (R. Bürgmann), freed@purdue.edu (A.M. Freed), pbanerjee@ntu.edu.sg (P. Banerjee).

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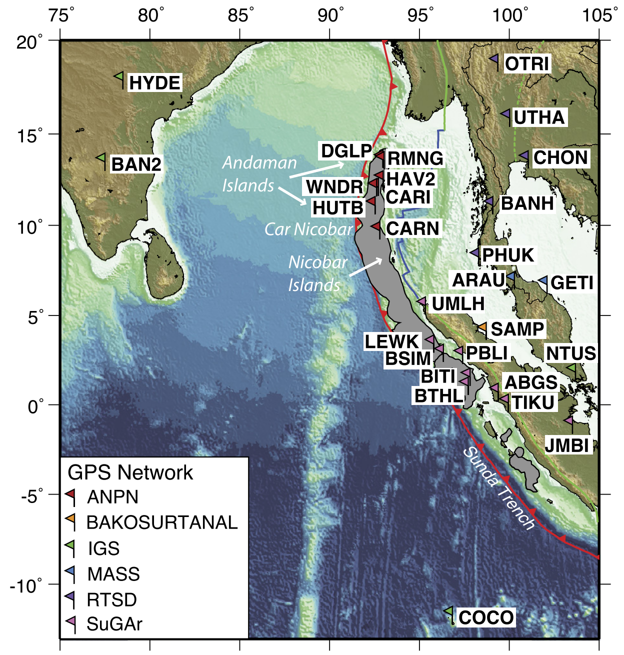

Fig. 1. Overview map showing the megathrust earthquake ruptures included in the viscoelastic modeling, shaded gray, and all the GPS stations used in the study. The geodetic data come from several GPS networks, including the Andaman and Nicobar Postseismic Network (ANPN), Badan Koordinasi Survei dan Pemetaan Nasional (BAKOSURTANAL), the International GPS Service (IGS), the Malaysia Active GPS System (MASS), the Royal Thai Survey Department (RTSD), and the Sumatran GPS Array (SuGAr).

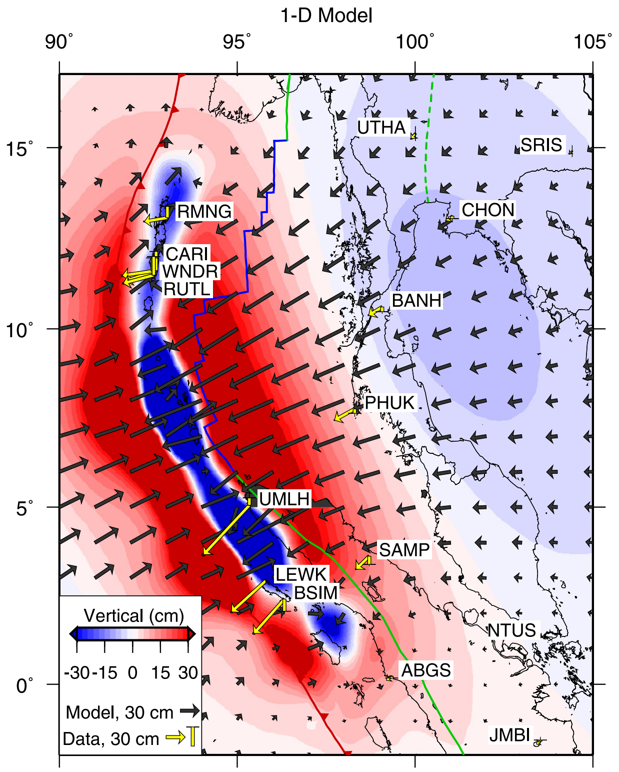

Fig. 2. Observed cumulative displacements from 2005 to 2010 associated with postseismic deformation from the 2004, 2005, and 2007 megathrust earthquakes. Yellow arrows and bars show observed horizontal and vertical 5-year displacements, respectively. Coseismic displacements from the megathrust earthquakes and interseismic rate estimates have been removed from the GPS data. Black arrows show horizontal model displacements, color contours indicate predicted vertical motions from a model of cumulative viscoelastic mantle relaxation following the three earthquakes using a 1-D layered earth model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

relaxation in such a layered earth model is concentrated along the zone above the rupture bottom, surrounded by a broad regional uplift which grades into a very modest zone of far-field subsidence (Fig. 2). The deformation magnitude and distribution are dependent on the earthquake source, mantle rheology, and the thickness of the elastic lithosphere. Such 1-D rheology models have been successful in matching far-field motions of GPS stations to the east of Sumatra (e.g., Pollitz et al., 2006; Panet et al., 2010; Hoechner et al., 2011; Broerse et al., 2015), but predict subsidence for near-field GPS stations on forearc islands along the Andaman–Sunda subduction zone, where observations indicate rapid postseismic uplift. Thus, when using layered earth models, either a rupture model with a shallower depth of peak coseismic slip (Hoechner et al., 2011) or rapid afterslip downdip of the rupture (e.g., Paul et al., 2012) are needed to allow for also fitting the near-field GPS data.

We can expect the rheology of the lithosphere and upper mantle in Southeast Asia to have significant 3-D heterogeneity based on geological and seismological considerations. The oceanic lithosphere thickness is dependent on the age of the oceanic crust, which varies by ∼70 Ma along the Andaman–Sunda Trench (Müller et al., 1997), but in general oceanic lithosphere is thinner than the continental lithosphere of the Sunda Plate interior. The Andaman Sea is an active back-arc basin (Curray, 2005), and low seismic velocities in this region imply a locally warmer, weaker mantle (Shapiro et al., 2008). Fig. 3 shows cross-sections of seismic shear-wave velocity and a map of mantle temperature at 50 km depth estimated from surface-wave tomography of the upper mantle surrounding the subduction zone (modified from Shapiro et al., 2008; Shapiro, pers. comm., 2013). The temperature estimate is based on Shapiro and Ritzwoller (2004), who describe the conversion from isotropic seismic velocities to temperature based on thermoelastic properties of mantle materials obtained in the laboratory. Assuming that the velocity changes are primarily due to temperature variations in the mantle, this indicates lateral temperature differences of as much as 500 °C from the cold sub-Indian Ocean lithosphere and subducting slab to the warm Sumatra–Andaman back-arc region. Variations of inferred temperature within the Indian Ocean plate are consistent with plate age increasing from the fossil Wharton Ridge and the effect of hot spot activity associated with the Ninety East Ridge (Shapiro et al., 2008). The importance of lateral variations of mantle temperature and rheology that can be inferred from seismic tomography has also been recognized in global models of post-glacial rebound (Paulson et al., 2005).

Pollitz et al. (2008) used an aspherical perturbation of a spherically stratified viscoelastic earth model to produce a first-order heterogeneous model that included a high-viscosity dipping slab and reduced asthenosphere viscosity in the mantle wedge. They find that while this model improved the fit to far-field vertical motions, it did not fit the near-field horizontal or vertical data. Hu and Wang (2012) present a spherical-Earth viscoelastic finite element model of the short-term postseismic deformation coming to similar conclusions, arguing for afterslip to improve the fit to the near-field motions. Here, we test a variety of earth structures, using a finite element model approach, ranging from a simple 1-D layered model to a 3-D model that includes an elastic subducting slab, contrasting mantle asthenosphere viscosities across the subduction zone, and a low-viscosity back-arc spreading center, to determine the effects on surface deformation in the near-to-far field range. We find that models with heterogeneous rheology informed by the tomographic model of Shapiro et al. (2008) appear to reconcile the displacements of near- and far-field GPS stations and suggest that viscoelastic relaxation dominates the postseismic deformation. The contribution of afterslip is likely to be localized in zones of low megathrust coupling near the recent ruptures (Avouac, 2015).