Pore-fluid migration and the timing of the 2005 M8.7 Nias earthquake

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ABSTRACT

Two great earthquakes have occurred recently along the Sunda Trench, the 2004 M9.2 Sumatra-Andaman earthquake and the 2005 M8.7 Nias earthquake. These earthquakes ruptured over 1600 km of adjacent crust within 3 mo of each other. We quantitatively present poroelastic deformation analyses suggesting that postseismic fluid flow and recovery induced by the Sumatra-Andaman earthquake advanced the timing of the Nias earthquake. Simple back-slip simulations indicate that the megapascal (MPa)–scale pore-pressure recovery is equivalent to 7 yr of interseismic Coulomb stress accumulation near the Nias earthquake hypocenter, implying that pore-pressure recovery of the Sumatra-Andaman earthquake advanced the timing of the Nias earthquake by ~7 yr. That is, in the absence of postseismic pore-pressure recovery, we predict that the Nias earthquake would have occurred in 2011 instead of 2005.

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The M9.2 Sumatra-Andaman earthquake and subsequent great tsunami of 26 December 2004 ruptured over 1200 km of crust, lasted ~8 min, and killed over 250,000 people in 12 countries surrounding the Indian Ocean (Ammon et al., 2005; Bilek, 2007; Vigny et al., 2005). Three months later, on 28 March 2005, a M8.7 earthquake centered off the coast of Nias Island just west of northern Sumatra ruptured over 400 km of crust, killed over 1300 people, and caused a minor tsunami (Fig. 1) (Ammon et al., 2005; Banerjee et al., 2007). Here, we present poroelastic deformation analyses that suggest postseismic fluid flow and recovery induced by the Sumatra-Andaman earthquake advanced the timing of the later M8.7 Nias earthquake.

We constructed finite-element models (FEMs) to simulate the coseismic stress and pore (fluid) pressure fields of the Sumatra-Andaman

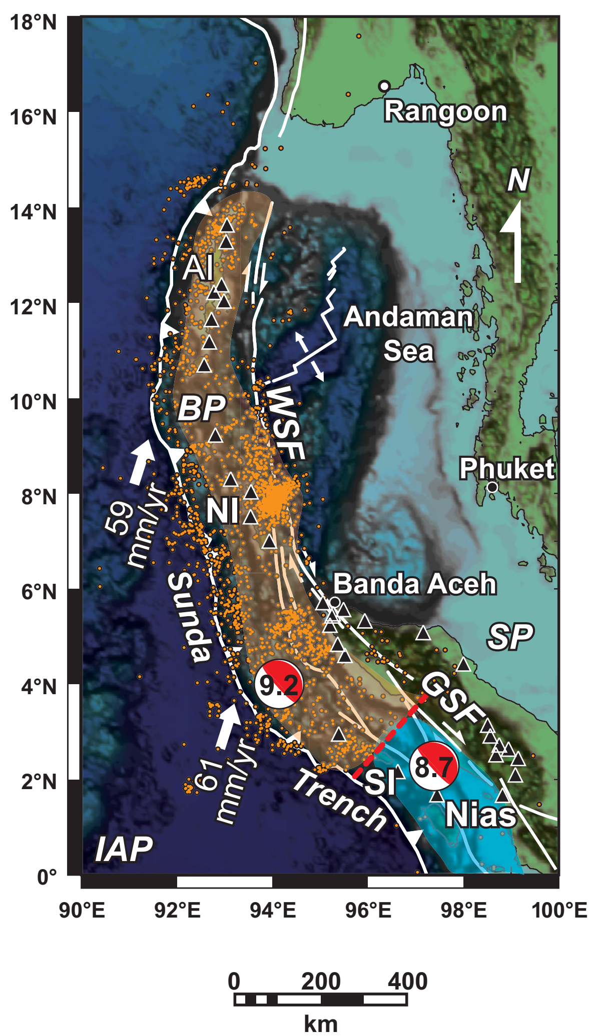

Figure 1. Seismotectonic setting of the Sumatra-Andaman subduction zone (adapted from Hughes et al., 2010). Harvard centroid moment tensor (CMT) focal mechanisms are given for the Sumatra-Andaman earthquake and Nias earthquake. Aftershock epicenters (orange dots), spanning 26 December 2004 through 28 March 2005 and transparent orange area, illuminate the surface projection of the Sumatra-Andaman earthquake rupture (http://neic.usgs.gov). The rupture initiated on the southeast portion of the fault and propagated ~1200 km northward. The blue transparent area represents the surface projection of the Nias earthquake rupture (http://neic.usgs.gov). The sharply truncated aftershock distribution, shown with a northeast-trending dashed line (red) that bisects Simeulue Island, marks the boundary between rupture of the Sumatra-Andaman earthquake and subsequent Nias earthquake and represents the seismic barrier between the two earthquakes. Black triangles are nearfield global positioning system sites (Gahalaut et al., 2006; Subarya et al., 2006). The tectonic configuration is modified from Bird (2003) and overlies a shaded relief image of global relief data (http://www.ngdc.noaa.gov). Abbreviations: AI—Andaman Islands, BP—Burma plate, IAP—Indo-Australian plate, NI—Nicobar Islands, SI—Simeulue Island, GSF—Great Sumatran fault, SP—Sunda plate, and WSF—West Sumatra fault.

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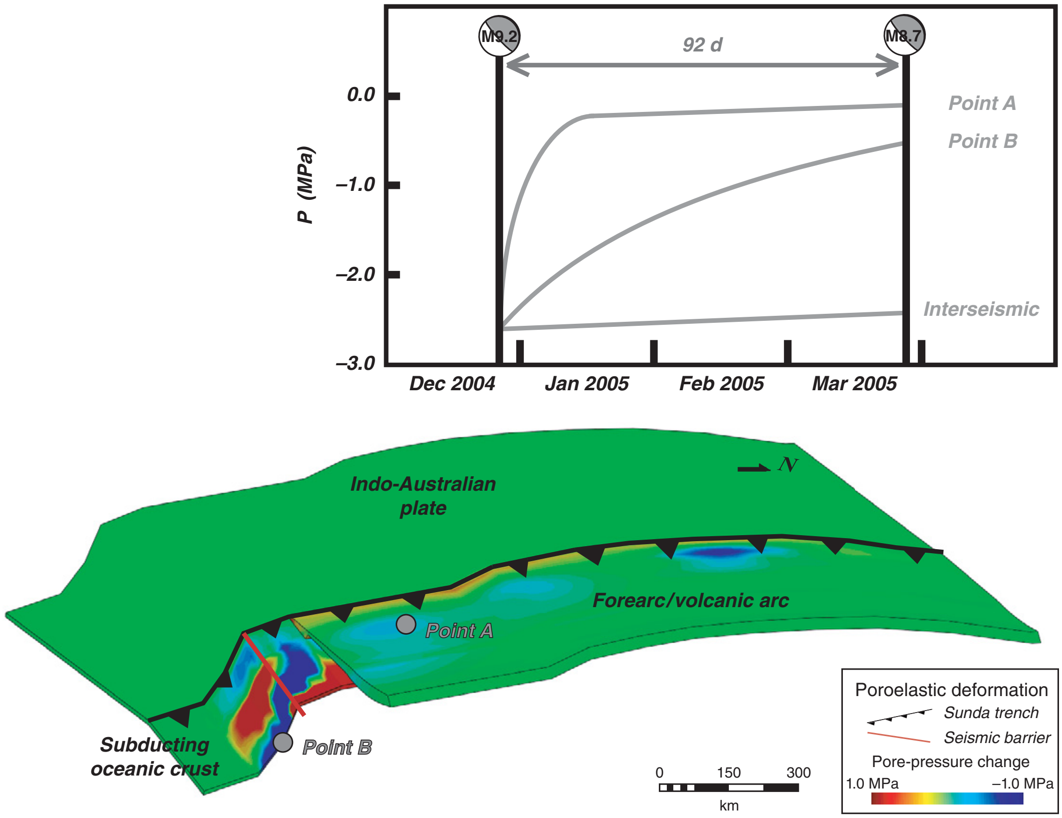

Figure 2. Graph shows change in pore pressure for point A (forearc), point B (near Nias earthquake hypocenter), and interseismic strain accumulation for the subduction zone. Map shows coseismic poroelastic deformation. Seismic barrier is red line between the Sumatra-Andaman earthquake (north) and Nias earthquake (south) ruptures. For point B, the upper forearc and volcanic arc have been cut away to view underlying subducting oceanic crust. For point A, the first few kilometers have been stripped off to see into the forearc.

earthquake, transient postseismic recovery of stress and pore pressure, and interseismic stress accumulation along the plate boundary (Hughes et al., 2010). FEMs are uniquely capable of simulating a subduction zone as a three-dimensional problem domain partitioned to represent poroelastic continental and oceanic crust and elastic mantle components.

The Sumatra-Andaman earthquake is still the largest earthquake for which coseismic deformation was recorded by global positioning system (GPS) data. We use the near-field GPS data, recorded for northern Sumatra and the Andaman and Nicobar Islands, to determine the slip distribution of the Sumatra-Andaman earthquake with FEM-generated Green's functions and linear inverse methods (Masterlark and Hughes, 2008; Hughes et al., 2010). It is the stress and pore-fluid pressure fields generated by this coseismic slip distribution that drive the postseismic poroelastic deformation as excess pore pressure recovers to equilibrium via Darcian flow. Changes in Coulomb stress—defined as $\Delta\sigma_c = \Delta\sigma_s + f(\Delta\sigma_n + \Delta P)$, where σ_c is Coulomb stress, σ_s is shear stress, f is friction, σ_n is normal stress, and P is pore pressure (Wang, 2000)—quantify the change in tendency for slip to occur along a fault. The Coulomb stress changes introduced by the Sumatra-Andaman earthquake, and thus the frictional stability of nearby faults, evolved in response to pore-pressure recovery.

The coseismic deformation due to the Sumatra-Andaman earthquake and the rheologic configuration of the three-dimensional FEM produce two transient flow regimes having two different time constants (Fig. 2). The first flow regime is shallow, within a few kilometers depth, and dissipates within 30 d of the Sumatra-Andaman earthquake. The second flow regime is deep, within the subducting oceanic crust of the downgoing slab, and it persists for several months after the Sumatra-Andaman earthquake (Fig. 2). The Sumatra-Andaman earthquake initially induced a negative megapascal (MPa)–scale pore-pressure change near the Nias earthquake hypocenter, which then increased (recovered) during the 3 mo time interval between the two earthquakes. This increase in pore pressure near the Nias earthquake hypocenter was due to pore fluids migrating both downdip and updip, as well as laterally along the strike of the slab within the oceanic crust due to coseismic pore-pressure gradients.

This 2.0 MPa pore-pressure recovery is two orders of magnitude greater than the Coulomb stress triggering threshold required for frictional slip, i.e., 10^4 Pa (Stein, 1999). Furthermore, these changes in Coulomb stress near the Nias earthquake hypocenter due to this pore-pressure recovery were significantly greater than changes attributed to either afterslip (McCloskey et al., 2005; Chlieh et al., 2007; Prawirodirdjo et al., 2010) or postseismic viscoelastic relaxation (Pollitz et al., 2006). Simple back-slip simulations (Savage, 1983) using the FEMs suggest that the 2.0 MPa pore-pressure recovery is equivalent to 7 yr of interseismic accumulation of Coulomb stress (0.22 MPa) near the Nias earthquake hypocenter—a result that suggests pore-pressure recovery of the Sumatra-Andaman earthquake advanced the timing of the Nias earthquake by ~7 yr. Therefore, instead of occurring in 2011, the Nias earthquake occurred in 2005 due to pore-pressure recovery. The results of this study indicate that the analysis of pore-pressure recovery is significant in addressing earthquake triggering at subduction zones worldwide.

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