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Short-term pre-2004 seismic subsidence near South Andaman: Is this a precursor slow slip prior to a megathrust earthquake?

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ABSTRACT

We report here on the campaign GPS data from the Andaman Islands just previous to the great 2004 Sumatra–Andaman earthquake. The campaign-mode acquisitions at Port Blair showed that the site started to subside between 2003 and 2004. In addition, during this period, the horizontal displacement of Port Blair with respect to Indian plate, deduced from 1996 to 2000 GPS data, changed its orientation to that obtained during the 26th Dec 2004 co-seismic. This short-term subsidence can be modeled as slip in the up-dip portion of the fault, a slip that is equivalent to an earthquake with moment magnitude of 6.3. Previously, slow slip was thought to appear at intermediate depths roughly 35–55 km but simple models of the deformation at this single site suggest slow slip at much shallower depth than this. This observation of subsidence obtained by GPS methods is in rough agreement with subsidence observed from tide gauge data. Campaign-mode GPS data between 1996 and 2000 suggest uplift for Port Blair during the inter-seismic period and so does the reported field observations of interseismic micro-atoll emergence. Lack of exposed land with GPS stations along the southern part of the thrust fault deprive of arriving at any indication of this preseismic subsidence in those areas. Although GPS data is lacking the geological indices reported from some sites on the Alaskan Coast, for example, imply short-term subsidence just previous to the great 1964 earthquake. The pre-earthquake subsidence recorded in Port Blair, therefore, may have global implications as a precursor signal of great earthquakes at least along some of the subduction zones.

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1. Introduction

Stress builds up between plates until it reaches a critical strain, and the accumulated potential energy is released as the earthquake. The discovery of slow slip, which is thought to be tectonic fault slip many orders of magnitude slower, and generally just a bit deeper, has added a new dimension to this picture. This resulted in monitoring of aseismic slip at plate boundaries for understanding the processes that occur before and after major earthquakes. Laboratory experiments and numerical simulations of earthquakes using laws of friction suggest the occurrence of premonitory and postseismic slip transients. Some of these studies indicate a nucleation process that initially involves stable, slow rupture growth within a confined zone on a fault, just before unstable, high-speed rupture (Dieterich, 1978; Lapusta et al., 2000; Ohnaka, 1992; Shibazaki and Matsu'ura, 1992). Other studies predict longer precursory slip accelerations that may extend for a considerable fraction of the earthquake cycle (Hori and Miyazaki, 2011; Yoshida and Kato, 2003). Dieterich (1978) proposed that pre-seismic fault creep may be the underlying process responsible for observations of earthquake precursors supported by evidence from at least some earthquakes and by analogy with detailed laboratory observations. However, precursory slip before a large earthquake is not commonly observed (Roeloffs, 2006). Whether this is due to the small amount of slip and difficulty in observation or because the phenomena are not generally active on natural faults is under discussion.

Shennan and Hamilton (2006) quantified uplift and subsidence along the Alaskan Coast during one earthquake cycle. Inter-seismic uplift and short pre-seismic subsidence were observed. Hawkes et al. (2005) suggested that megathrust earthquakes in Alaska and western North America (Oregon Coast) may be preceded by a precursor phase (1–3 years) of subsidence prior to megathrust earthquakes. Sediment cores from coastal marshes showed that the foraminifera and the camoebian assemblages reflected a change from forest phase to a mildly brackish stage under the tsunami deposition suggesting a subsidence phase immediately prior

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to the 1964 megathrust earthquake. Further, they observed that the paleo-event dated at 1800 yr B.P. identified in the Alaskan Coast was also associated with a similar depositional stage, indicating a small subsidence prior to the megathrust earthquake. Such precursor stage is also found in the sediment cores from the Oregon Coast before the geologically inferred ancient earthquakes/tsunamis (Hawkes et al., 2005).

Postseismic slip, however, is more widely observed for many earthquakes (Heki and Tamura, 1997; Ozawa et al., 2012), and may reflect the response of creeping areas adjacent to the coseismic slip area. However, well resolved slip distributions that enable the evaluation of the relationship between coseismic and postseismic slip are not always available. The northern part of the Sumatra–Andaman plate boundary revealed the slow slip it experienced in response to the rapid coseismic stress change on the 26th of December 2004. This earthquake started near Sumatra and the slip travelled upwards towards the Andaman region (Bilham, 2005). Geodetic observations indicate that additional slow slip occurred in this region over a time scale of 50 min or longer (Lay et al., 2004). Based on the first two years of geodetic measurement Paul et al. (2007) modeled postseismic slip beneath the Andaman Islands that released a moment equivalent to a magnitude Mw $\geqslant$ 7.5 earthquake, and suggested deep slip in the stable frictional regime accelerated to catch up to the coseismic rupture. Reprocessing and revisiting results of some of the pre-2004 earthquake GPS data suggest that the Andaman Islands has experienced deformation that may be indicative of preseismic fault slow slip, as well.

2. Data and analysis

Data collection and analysis of CARI, a site in Port Blair was carried out between 1996 and 2000 (Paul et al., 2001). This site consists of a concrete pillar with a stainless steel pin embedded into the top of the pillar. The 1996 measurement was not taken into consideration as a tripod was used to mount the antenna and the antenna height could not be confirmed. Remaining three occupations used a bipod to mount the antenna. After 2000 this site was vandalized and another site (PBLR) was installed by another group in 2002 (Earnest et al., 2005). This site has a concrete monument with a threaded rod embedded. All three site occupations in 2002, 2003 and 2004 had different combinations of antenna and tribachs (see Fig. 1, for details). Such details are important to ensure that there are no instrument setup induced errors.

Data from all the three occupations were analyzed in a single run using GAMIT/GLOBK software with International GNSS Service (IGS) final orbits and 15 fiducial sites in the 2005 International Terrestrial Reference Frame (ITRF2005; Altamimi et al., 2007), and combined using IGS h-files (Herring, 2003). Seven reference frame sites of the ITRF2005 were used to stabilize the network. GNSS antenna phase center variations (PCV) models were used among other products.

CARI shows an uplift rate of 11.4 mm/yr and a horizontal velocity of −12.52, −4.53 relative to Indian plate (Paul et al., 2001). PBLR showed how the uplift slowly reversed into subsidence as the time progressed. Between 2002 and 2003 the uplift at this site was 11.2 mm/yr. But sometime between 2003.7 and 2004.6, PBLR, based on 9 days of GPS measurements in Aug 2003 and 28 days in Aug 2004, started subsiding with a rate of −70 mm/yr. Added to it, just within the twenty-eight days of measurements in August 2004, barely four months before the 2004 Andaman–Sumatra Mw 9.3 earthquake, subsidence of −130 mm/yr was observed. A possible source for errors could arise from using different hardware during each deployment, but that will surely not account for 10–13 cm of vertical displacement.

Horizontal velocity at this site between 2003.6 and 2004.7 has similar amplitude as that at CARI but changed its orientation in the direction of the Dec 26th 2004 co-seismic displacement. The location of Andaman Islands and PBLR/CARI sites along with velocity and displacement vectors and the vertical time series of CARI and PBLR GPS sites are shown in Figs. 2 and 3, respectively. Velocity vectors are respective to Indian plate. The amount of slip and vertical motion recorded at Port Blair sites (CARI and PBLR) at various time periods are given in Table 1. A simple slip model considering the geometry of the thrust fault and the location of Port Blair suggests subsidence at Port Blair when the upper 20–25 km of the fault slips, and the area is uplifted when slip occurs at the lower portion of the fault (Fig. 4). Coulomb 3.3 was used to model displacements. Coulomb (Toda et al., 2011) is designed to let one calculate static displacements, strains, and stresses at any depth caused by fault slip, magmatic intrusion, or dike expansion/contraction. The subsidence at Port Blair can be explained by slip of 1.5 m on the upper portion of the fault, spread across 6–12 months prior to the great earthquake. It is not the amount of slip instead the occurrence of slip that could cause subsidence that is highlighted here.

3. Discussion

In a region so devoid of GPS instrumentation during the pre-earthquake times, a single campaign site in Port Blair, is worth

Fig. 1. PBLR monument and the antenna set up for 2003 and 2004 measurements. This stable setup is shown to showcase the minimized probability of setup errors. The monument consists of a steel bolt protruding out of a concrete pillar. In 2002 a Leica tribrach was used with its adaptor. Vertical reference point is top of the concrete pillar. Antenna height in this occupation was 0.228 m. In 2003 a zephyr geodetic antenna was used along with a Trimble tribrach. Antenna height in this occupation was 0.138 m. In 2004 a Leica choke ring was directly threaded to the bolt. The antenna height here was 0.0195 m.

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