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 1996-2000 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.

Keywords: pre-seismic, subsidence, slow-slip, megathrust

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, 2010; Yoshida and Kato, 2003). Dieterich (2012) 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 (2005) 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 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 et al., 1997; Ozawa et al., 2011), 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 minutes or longer (Lay et al., 2005). 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 $M_w \geq 7.5$ 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 & 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 Figure. 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 Figures 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 (Figure. 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 its weight in gold. The question addressed here is not the precise amount of slip but rather (a) the presence of deformation/slip, and (b) the region of the fault that slipped. Slow slip usually appears at intermediate depths, roughly 35–55 km (Dragert et al., 2001; Vidalle and Houston, 2012), although slow slip along the up-dip portions of the fault is

also rarely reported (Davis et al., 2011; Foster et al., 2013). Simulation results for a 2D model of earthquakes at subduction zones such as preseismic slip along plate interface just below the seismogenic depths explain some characteristics of observed preseismic slip on the deeper extension of the rupture plane of the 1944 M7.9 Tonankai earthquake (Kato 2003). However, there are no cases, so far, suggesting pre-seismic slow slip in the up-dip portions).

GPS observations at Port Blair, between 1996 and 2004, are the first to suggest pre-seismic slow slip up-dip. Change in vertical deformation from inter-seismic uplift to co-seismic subsidence just before the main slip on 26th Dec 2004, and also the change in direction of the horizontal velocity vector from the inter-seismic to the co-seismic displacement direction are hard to overlook. And complementing these observations, Catherine et al. (2013) have observed 33 mm/yr average subsidence of Port Blair based on tide gauge data from 2001 – 2004. Due to lack of exposed land area along the fault that ruptured on 26th December 2004 and the absence of proper GPS monitoring, odds are placed heavily on this single (or pair) GPS site in Port Blair. The GPS-based constraints, however, are, therefore, reasonable since the tide gauge measurements add further validity to a short-term pre-earthquake subsidence scenario. Horizontally, while the interseismic GPS velocity is in one direction, the direction of preseismic velocity and the coseismic displacement match as seen in Figure 2.

The inter-seismic GPS observation at Port Blair, which suggests overall inter-seismic emergence was also complimented by studies of micro-atolls along the eastern margin of the Andaman-Nicobar Islands (Rajendran et al., 2007). Visual observations made 15 months prior to the 2004 suggest that the microatolls show the indications of emergence by ~10 cm based on 2003 HSL and a previous HSL at Mundapahar near Port Blair. It is thus concluded, with all that we have from various sources, Port Blair was emerging inter-seismically, started subsiding 1-2 year, a trend that would have been preserved in the growth history of the contemporary microatolls, as well, before the abrupt co-seismic subsidence, in the vicinity of Port Blair

The subsidence can be modeled as slip of 1.5 cm in the up-dip portion of the fault, a slip that is equivalent to an earthquake with moment magnitude of 6.3. This is in stark resemblance to geological observations of Hawkes et al. (2005) in Alaska, which experienced an micro-subsidence before the earthquake. The significance of this observation for earthquake prediction

research in subduction zone environments needs to be further understood starting with gathering of data from GPS networks at such regions potentially capable of generating great earthquakes.

4. Conclusions

GPS data before the Dec 2004 megathrust earthquake have revealed a possible precursory deformation signal prior to the 2004 Sumatra-Andaman earthquake. This precursory signal includes subsidence in the vertical and reorientation of interseismic to coseismic in the horizontal. Care was taken to rule out any measurement blunders or record-keeping errors. This bold conclusion may immediately be countered by the fact that it occurred very far from the epicenter. It may be noted that this part of the thrust fault has exhibited slow slip behavior both during and after the Dec 2004 event. There have been cases of preseismic slip along plate interfaces just below the seismogenic zone, but here is a case where a simple plate model is able to suggest preseismic slip along the shallow portions of the fault interface. This is a region devoid of seismic stations to study episodic tremor and slip to complement this result. However, the tide gauge measurements, at a site few kilometers east of the GPS site PBLR, for 3 years before the 2004 earthquake revealed subsidence thus complimenting the GPS result.

It is proposed that thrust fault along Sumatra and North Andaman, which has reached its peak in accumulating stress and was ready to rupture, initially failed in the northern part in the form of slow slip starting sometime in 2003. When the sudden release of energy took place on Dec 26, 2004 at Sumatra and the slip propagated northward, this part of the thrust caught the earthquake running. This part of the thrust fault has latter exhibited slow slip coseismically and postseismically. The big question is whether this precursory signal observed at Port Blair has global significance in terms of its usefulness as a forewarning tool in major subduction zone earthquake zones, elsewhere. The geological indicators from the Alaskan coast suggesting a short-term subsidence prior to the 1964 earthquake compels us to view this not as a localized phenomenon, but as a globally applicable signal at least in some subduction zones. The universality of the precursory GPS signal reported here should be addressed on the basis of assessing similar set of data from regions marked for potential future earthquakes..

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Figure Captions:

Figure 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.

Figure 2: Map showing southeastern part of India, Sri Lanka and Andaman Islands with coseismic displacement and preseismic GPS velocity vectors. Solid arrow are interseismic GPS velocity of CARI relative to India based on 1996-2000 data (Paul et al., 2001), unfilled arrow is preseismic GPS velocity of PBLR relative to India using 2003-2004 data, grey solid arrow is the 2004 coseismic displacement (Earnest et al., 2005). The direction of preseismic velocity and the coseismic displacement match

Figure 3: Vertical GPS Time series at CARI (top frame) and at PBLR (middle and bottom frame). PBLR time series shown twice with different y-axis.

Figure 4: Simple slip model calculating vertical displacement due to slip along the upper portion (solid line) and along the lower portion (dashed line). Locations of PBLR site, tide gauge and microatoll referred in the text are shown.

Figure 1

Figure 2

Figure 3

Figure 4

Table 1. Amount of slip and vertical motion recorded at Port Blair sites (CARI and PBLR) during various time periods.

Time Frame	Slip	Vertical	References
2003.7 – 2004.98	1.5 m upper portion of fault	-10.0 cm	This study
2004.98 (Rapid)	2.0 m upper portion of fault	-70.0 cm	Lay et al., 2005
2004.98 (Slow)	5.0 m upper portion of fault		
2004.98 – 2007.0	0.6 m upper portion of fault 1–3 m lower portion of fault	+23 cm	Paul et al., 2007
2008.5 – 2010.5	1.2 m lower portion of fault	+12 cm	Paul et al., 2012