A glimpse of earthquake cycle in the Sumatra region

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We analyse temporal variation of crustal deformation derived from Global Positioning System (GPS) measurement at SAMP, a permanent GPS site in Sumatra, Indonesia. The site is located at about 300 km from the epicentres of the giant 26 December 2004 Sumatra–Andaman (*Mw* 9.0–9.3) and the great 28 March 2005 Sumatra (*Mw* 8.6) earthquakes. It experienced an interseismic displacement at a rate of about 2 cm/yr towards east in the preceding four months of the 2004 earthquake. The 2004 and 2005 earthquakes caused coseismic displacements of about 15 cm towards west and about 18 cm towards southwest respectively. In the period between the two earthquakes and after the 2005 earthquake, slow transients arising due to postseismic deformation are clearly recorded at this site. The postseismic deformation is in the opposite sense to that of the interseismic deformation, indicating either relaxation of the lower crust and upper mantle or afterslip on the subduction interface that lies further downdip of the ruptured part of the subducting interface. The site also recorded probably a slow earthquake that occurred on 9 June 2005, which caused a westward movement of about 2 cm at SAMP. However, more data from other sites are required to further confirm and analyse this event. Together, these displacements provide a glimpse of crustal movement during the earthquake cycle in the region.

Keywords: Earthquake cycle, Global Positioning System, SAMP, Sumatra.

IN 1910, Reid proposed the famous theory of elastic rebound[1], which forms the basic tenet of earthquake occurrence across a plate margin. The theory suggests that elastic strain slowly accumulates across the fault, which is released suddenly during the earthquake. Thus according to this theory, the displacement through an earthquake cycle occurs essentially in two phases, viz. the slow displacement in the interseismic phase of strain accumulation, which is released in the coseismic phase, during the earthquake.

In recent years, particularly following the use of Global Positioning System (GPS) in earthquake deformation studies, it has been observed that immediately after the earthquake temporal variation in displacement is significant, which depends on the rheology of the region and the process responsible for the deformation. Crustal deformation in the postseismic period is distinct from that in the interseismic period and forms an integral part of the earthquake cycle. The transients in displacement during the postseismic phase have been seen for many earthquakes, e.g. the 1994 Sanriku-Oki, Japan earthquake (*M* 7.7); the 1995 Jelisco, Mexico earthquake (*M* 8.0); the 2001 Peru earthquake (*M* 8.4); the 2002 Denali, Alaska earthquake (*M* 7.9), etc.[2–6]. Apart from the above, another mode of deformation through the earthquake cycle has been suggested as that due to slow earthquakes[7–11]. The unambiguous detection of slow earthquake has been possible only through GPS measurements as the deformation is slow and either occurs beyond the seismic band or an anthropogenic noise in seismic records[11].

In this communication, we report various phases of crustal deformation at a permanent GPS site, SAMP, in Indonesia, before, during and after the 2004 Sumatra–Andaman (*M* 9.0–9.3) and the 2005 Sumatra (*M* 8.6) earthquakes. These earthquakes occurred along the Sumatra subduction zone through thrust motion on the frontal arc[12–14]. We also report evidence of occurrence of a slow earthquake in the Sumatra subduction zone.

We processed and analysed daily GPS data from permanent sites in and around the Sumatra region. We expected that since, SAMP, NTUS, COCO and BAKO lie close to the source regions (Figure 1) and experienced coseismic movement[15–18], these sites might be experiencing postseismic deformation as well. We also included other IGS sites, e.g. IISC, LHAS, KIT3, DARW, DGAR, BAHR, GUAM, HYDE, KARR, PERT, POL2 and WUHN (see figure 1 of ref. 15) in the processing using GAMIT/GLOBK[19,20], and tightly constrained the coordinates of IGS stations at POL2, KIT3, DGAR, BAHR, GUAM, PERT and KARR to their ITRF2000 coordinates. We find that the postseismic and coseismic changes at SAMP, the nearest site (only 305 km east of the 2004 earthquake epicentre and 246 km northeast of the 2005 earthquake epicentre) from the earthquake source zone (Figure 1) are most unambiguous. Therefore, though other sites experienced coseismic displacement due to the two earthquakes, postseismic changes, if any, are probably smaller at these sites compared to the errors and scatter in the results. These sites particularly, e.g. COCO and NTUS show their usual plate motion movement.

In Figure 2 we show the variation in north, east and vertical coordinates at SAMP during the inter-, co- and postseismic phases of crustal deformation. Subsequently we elaborate on the various phases of ground displacement and the mechanism involved in causing such movements.

Interseismic deformation occurs due to locking of the seismogenic part of the Plate Boundary Fault (PBF), which is referred as the Main Thrust Zone (MTZ). It is the MTZ that slips episodically during earthquakes at a convergent plate margin. The locking, either partial or full, causes slip deficit on MTZ, which gives rise to a corresponding displacement deficit in the long-term plate motion at the site.

At Sumatra subduction zone, it is expected that before the occurrence of the two earthquakes, the region must have experienced strain accumulation due to locking on

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the MTZ in the interseismic period. With a view to estimate the contribution of strain accumulation at SAMP during the interseismic period, we report results of analysis for the preceding four months of the 2004 earthquake. Though there is scatter in the data, the analysis suggests that the site experienced a movement of about 2 cm/yr in the east direction (Figure 2). The estimate derived here is on the basis of just four months data, and is less than the plate motion (~2.5 cm/yr towards N100°) as obtained from the global plate motion model[21]. It appears that the strain accumulation on the MTZ in the frontal arc of the Sumatra subduction zone, which ruptured during the 2004 and 2005 earthquakes affected this site.

The displacement deficit that takes place over years, decades or centuries during the interseismic period of strain accumulation due to the locking of MTZ is recovered during the coseismic period. Thus the coseismic displacement at a site is the deficit in displacement that occurred over long periods of strain accumulation.

The 2004 Sumatra earthquake caused significant coseismic movement at sites located several hundred kilometres away from the earthquake rupture. In the rupture area, i.e. in the Andaman–Nicobar and Sumatra region[22–25], it caused ground displacement in excess of 5 m. Though the 2005 earthquake did not cause ground displacement in the far-field region, it caused ground displacement of up to 4.5 m in the source region[26,27], i.e. in the Nias and Simuelue islands. At SAMP, the 2004 and 2005 earthquakes caused coseismic displacements of 15 cm towards N264° and 18.6 cm towards N222° respectively (Figures 1 and 2). These estimates are consistent with the earlier estimates derived by several investigators[22–27].

After a large earthquake, the fault zone and the surrounding medium deforms in the postseismic period in response to stress variation induced by the sudden coseismic stress drop. The deformation is manifested by the occur-

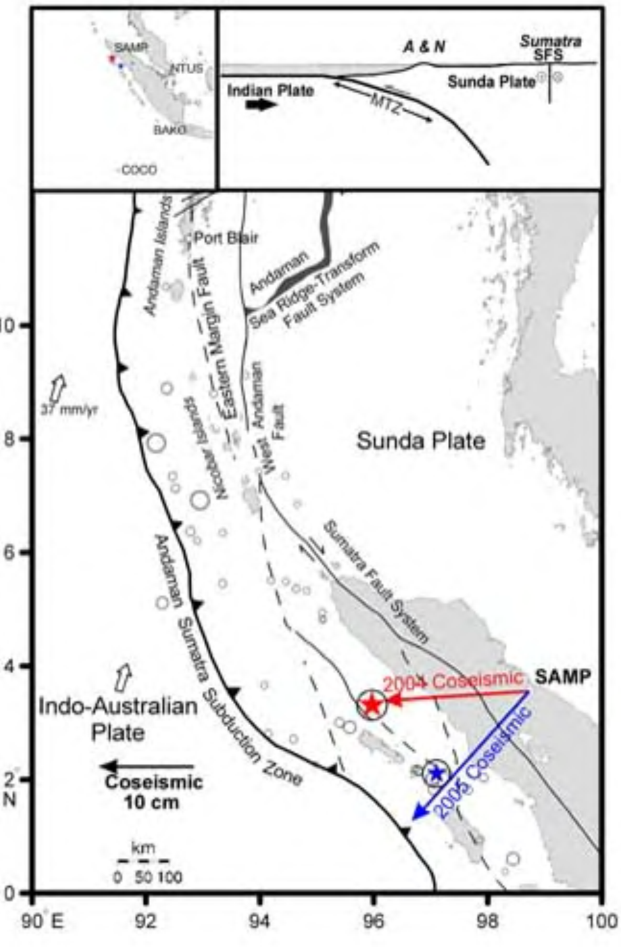

Figure 1. Simplified tectonic map of Andaman–Sumatra region[30]. Red and blue stars denote epicentres of the 2004 and 2005 earthquakes. Coseismic displacements due to the two earthquakes at permanent GPS site SAMP in Sumatra are shown. Epicentres of aftershocks of $M > 6$ are shown with circles. Velocity of Indo-Australian plate with respect to Eurasian plate is also shown. (Inset; top left) Locations of other nearby IGS GPS sites. (Top right) Generalized west to east cross-section across the subduction zone. MTZ, Main Thrust Zone on the Plate Boundary Fault; SFS, Sumatra Fault System; A&N, Andaman and Nicobar Islands.

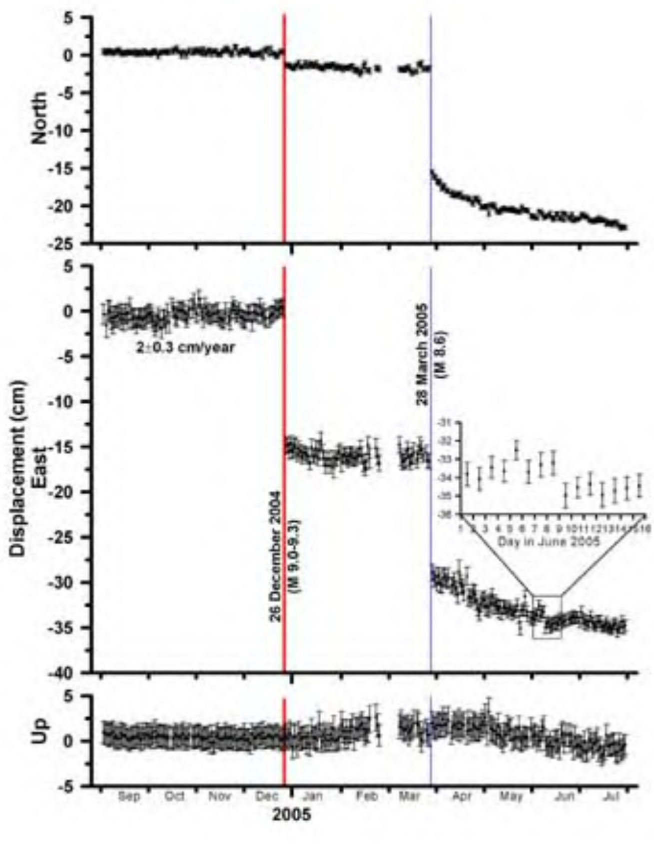

Figure 2. Daily variation in the north, east and vertical coordinates of SAMP. Red and blue lines mark the occurrence of the two earthquakes. Before the occurrence of the 2004 earthquake, in the interseismic period, SAMP moved at a rate of about 2 cm/yr towards east. Note the coseismic offsets corresponding to the two earthquakes and their postseismic deformation in the following periods. In the period between the two earthquakes, the site experienced a predominantly westward movement. In the east component, the significant 2 cm offset on 9 June 2005 is shown inside the rectangle, which has been zoomed in the inset.

rence of aftershocks and also by the observed geodetic strain, but the physical mechanism that governs these processes remains unclear. In a most simplified model it is assumed that postseismic deformation in the early period is dominated by the afterslip on further downdip of MTZ on PBF, that is referred as the meta-stable region. Below this region stable sliding occurs throughout and above this unstable sliding occurs on the MTZ through episodic slip during coseismic periods. In the later part of the deformation, the viscoelastic relaxation of the crust and upper mantle dominates. With the advent of the GPS application in crustal deformation studies, postseismic deformation has been reported for many large earthquakes, e.g. the 1994 Sanriku-Oki, Japan earthquake (*M* 7.7); the 1995 Jelisco, Mexico earthquake (*M* 8.0); the 2001 Peru earthquake (*M* 8.4); the 2002 Denali, Alaska earthquake (*M* 7.9), etc.[2–5]. It has been reported that the postseismic deformation for great earthquakes continues for several decades to centuries[6].

It can be seen in Figure 2 that the postseismic deformation at SAMP after the 2004 earthquake but before the occurrence of 2005 earthquake, though not very prominent, occurred predominantly towards west, i.e. almost in the same direction in which the coseismic displacement at SAMP was observed. However, deformation after the 2005 earthquake is remarkable. Deformation rate appears to decrease logarithmically and the direction is consistent with that of coseismic displacement due to the 2005 earthquake. The possible reasons for less prominent postseismic deformation immediately after the 2004 earthquake are given. First, the SAMP site does not lie on the immediate downdip extension of the 2004 earthquake rupture on the PBF, but lies on the immediate downdip part of the 2005 earthquake rupture. Second, the site is relatively far away from the 1500-km long 2004 earthquake rupture compared to the 2005 earthquake rupture. Finally, the postseismic deformation in the period also contains possible signals of preseismic and interseismic deformation from the 2005 earthquake source zone. It may be noted that high displacement rate after the 2005 earthquake also contains contribution of postseismic deformation from the 2004 earthquake. It may be noted that more than 50% of the 2005 coseismic displacement occurred in the following four months of the 2005 earthquake. Here, for comparison we show the co- and postseismic deformation at a site Kuji due to *M* 7.7 28 December 1994 Sanriku-Oki, Honshu, Japan earthquake and its aftershock of *M* 6.9 (Figure 3). The GPS site lies at a distance of about 100–150 km west of the earthquake rupture[5]. Transients of postseismic deformation after the two earthquakes can be seen in the eastern component of the coordinate. In fact, these postseismic transients that occurred in less than one-month period correspond to about more than 50% of coseismic deformation during the two earthquakes. The sense of postseismic deformation is similar to that of coseismic deformation in this case also.

It is observed that the direction of postseismic horizontal deformation (i.e. SW direction) at SAMP is almost opposite to that in the interseismic period (i.e. predominantly north direction). The SW motion of the site implies afterslip in the updip direction on the part of PBF, that lies further downdip of the MTZ. We expect that the postseismic deformation will continue for several years or decades at all the sites in the source region, e.g. in the Andaman–Sumatra region, as has been seen worldwide for great earthquakes.

Slow earthquakes have been reported from several subduction zones, particularly from the Cascadia region[7–11]. Such events are also termed as silent earthquakes, episodic tremors and slip events[7]. These events generally occur further downdip of the MTZ and may last for a few hours to a few days[8]. These events are now reported globally and constitute a fundamental mode of moment release that both triggers and is triggered by regular earthquakes[10]. Their occurrence can severely modify the seismic hazard in a region by modifying the strain budget in the region.

A notable feature of deformation at the SAMP site is that there appears to be a signature of slow earthquake or ultra-rapid postseismic deformation that occurred on 9 June 2005. The east component of coordinate shows a sudden westward movement of about 2 cm (Figure 2). We checked from the available earthquake catalogues and confirmed that there was no earthquake of $M > 4.5$ on this day within 200 km radius from SAMP. On this day only one earthquake of *M* 4.6 occurred at a location 233 km SW of SAMP. This earthquake is too small and far away from the site to cause such large coseismic displacement at SAMP. The westward direction of movement is consistent with the direction of coseismic movement due to the 2004 earthquake, which implies that slip during this transient possibly occurred on the PBF that lies further downdip of the 2004 earthquake rupture.

The earthquake deformation cycle mainly consists of three phases (Figure 4), namely the interseismic phase of

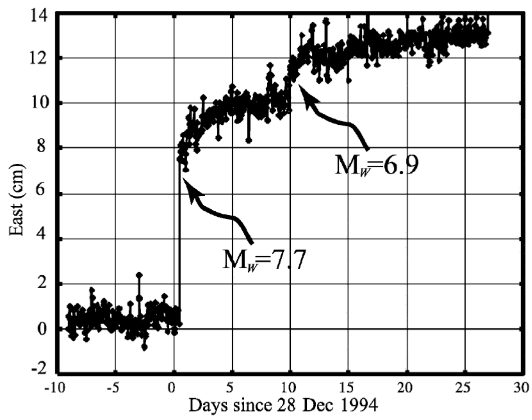

Figure 3. East component of coordinate of a GPS site, Kuji, that lies about 100–150 km west of the 28 Dec. 1994 Sanriku-Oki, Japan earthquake. Note the postseismic deformation after the mainshock and aftershock[5].

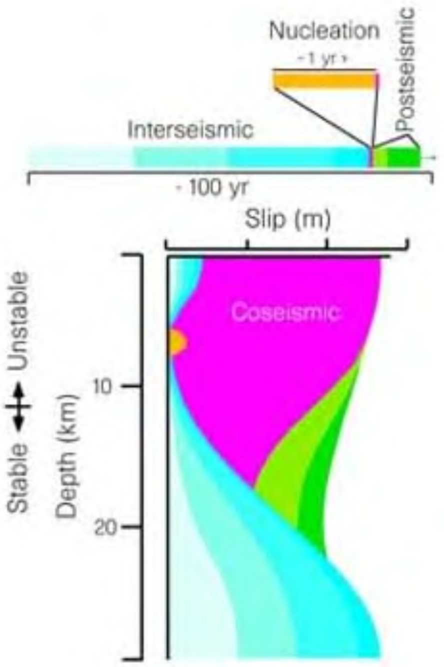

Figure 4. Generalized diagram showing various phases of the earthquake cycle and corresponding slip on PBF as a function of depth[29]. In the interseismic period (blue colour) slip occurs on the PBF that slides in a stable manner. This region lies downdip of MTZ. Coseismic slip (pink colour) occurs on the MTZ (the unstable region), the seismogenic part of PBF, and postseismic deformation (green) in this model is shown to occur as afterslip on the metastable region that lies between the stable and unstable part of the PBF. The nucleation phase (brown colour) is hypothesized to occur on the MTZ.

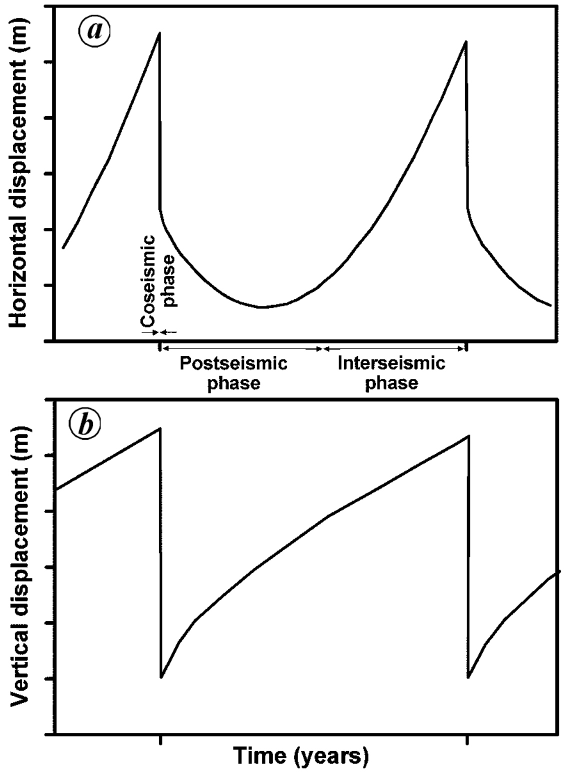

Figure 5. Schematic earthquake cycle showing variation of horizontal (north or east component of the coordinate) and vertical coordinates of sites in the Andaman–Nicobar region. ***a***, Horizontal displacement. In the interseismic period, the NE movement is consistent with the results of Paul *et al.*[31], for a site CARI, near Port Blair. During the coseismic period, the sites moved towards SW and in the postseismic period, the sites continued to move in the SW direction[22]. ***b***, Vertical movement. During the coseismic period, subsidence occurred at most of the sites and in the postseismic period, uplift has been observed[22,32]. Though vertical movement during the interseismic period is not known, we suggest that uplift at a slower rate must have occurred during that period. Figure based on similar studies reported from other subduction zones of the world[3,28].

long periods between large earthquakes during which strain accumulation occurs; coseismic phase of brief period during which the accumulated strain is released during the earthquakes, and the postseismic phase, the period immediately after the earthquake which exhibits higher rates of deformation and during which the material deforms in response to the sudden coseismic release of strain. Recently, it has been debated whether there exists a preseismic phase or nucleation phase that occurs just before (time ranging from a year to a decade) the occurrence of a great earthquake[28,29]. However, geodetic evidence for the existence of such a phase is either not available or not conclusive. Another mode of deformation is through slow earthquakes that occur further downdip of the MTZ. Our analysis of GPS measurements at the permanent site SAMP in Sumatra shows a glimpse of all the above phases. We believe that the permanent and campaign mode GPS measurements in the Andaman–Nicobar region would help in constructing the earthquake cycle in a much similar manner. Analyses of GPS measurements in the Andaman–Nicobar region suggested that the earthquake generally caused SW horizontal movement and subsidence all along the island belt[22]. In the postseismic period these sites are experiencing uplift and horizontal motion in the SW direction[22]. These limited data from the Andaman–Nicobar region suggest an earthquake cycle as shown in Figure 5, which also includes features from the earthquake cycle observed at other subduction zones of the world[3,28]. We hope that analysis of the data and their modelling will help in understanding the earthquake occurrence processes, inferring the rheology of the region and estimating the recurrence periods of great earthquakes in the region.

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ACKNOWLEDGEMENTS. We thank Dr J. R. Kayal, GSI, Kolkata for his in-depth and constructive review, which helped improved the MS. We also thank the Director, NGRI, Hyderabad and Dr R. K. Chadha, NGRI, Hyderabad, for support and DST for financial support.

Received 10 April 2006; revised accepted 7 August 2006

Discovery of volcanic ash bed from the basal Subathu Formation (Late Palaeocene–Middle Eocene) near Kalka, Solan District (Himachal Pradesh), Northwest Sub-Himalaya, India

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Discovery of 1.5 m thick volcanic ash bed is reported from the basal part of the Late Palaeocene–Middle Eocene Subathu Formation exposed along the Koshaliya river near Kalka (Solan District) in the foothills of Himachal Pradesh. The ash bed represents the oldest volcanic ash horizon from this part of the Himalayan Foreland Basin. The ash is fine-grained and consists mostly of kaolinite with trace quantities of glass shards, euhedral and angular β-quartz, sanidine, zircon, biotite and anatase. It has high concentrations of Al_2O_3 as well as incompatible elements (Zr, Nb, Th and Y), and high loss on ignition. Based on lithological as-

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