Inter-seismic geodetic motion and far-field coseismic surface displacements caused by the 26 December 2004 Sumatra earthquake observed from GPS data

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The 26 December 2004 great Sumatra megathurst earthquake occurred at the interface of the subsiding Indian plate with the over-riding Andaman microplate. Analysis of the regional GPS data covering both Indian plate and Sunda–South China plate indicates that convergence mechanism changes from nearly arc-normal thursting in the south, to arc-parallel dextral strike-slip faulting in the north. The main event originated in the southern segment, and rupture propagated unilaterally towards north covering almost 1400 km of length. Analysis of the coseismic GPS data from the surrounding regional Permanent GPS stations shows that the earthquake affected at least 4000 km range area surrounding the source zone. Co-seismic static offsets ranging from 138 mm to 2 mm, with directions conforming to the focal mechanism solution, were detected. The South Indian shield shifted towards east by 10–16 mm. Interstation distance between Singapore and Bangalore decreased by ~30 mm, and relative to Dehra Dun, Bangalore shifted towards east by ~16 mm. The maximum offset was observed at the nearest GPS station at Sumatra (SAMP), which shifted towards west by ~138 mm. Far-field co-seismic static offsets provide an independent source of data to model the kinematics of large earthquakes.

The 26 December 2004 (00:58:53 UTC, 06:28:23 IST) Sumatra earthquake of magnitude 9.0 occurred at the southern part of the Andaman arc, on the converging plate boundary between the India plate and Sundaland–South China (SSC) block (Figure 1). It was the fourth largest earthquake since 1900, and the largest since the 1964 Prince William Sound Alaska earthquake.

Sundaland, consisting of Indo-China as well as western and central part of Indonesia, and South China together constitutes the tectonically stable SSC block and is known to be decoupled from the Eurasian plate[1,2]. The India and Australia plate-pair makes an oblique convergence with the SSC block. To accommodate indenting India plate into the Eurasian plate, the material within the Tibetan block moves towards east, rotates clockwise around the eastern Himalayan syntaxis, and then moves towards south[3], thus pushing the SSC plate further down south. The convergence of the India–Australia plate with the SSC block along the Andaman and Sunda arc, is partitioned between nearly arc-normal thrusting and arc parallel dextral strike-slip faulting. The Andaman microplate[4], also known as Burma micro-plate[5], formed as a forearc sliver block between the India plate and the SSC block. The Andaman block is bound on the west by the thrust fault system that outcrops at the Andaman and Sunda trench, and on the east by a zone of right-lateral strike-slip and normal faults, known as the Sumatra fault in the south, and the Sagaing fault in the north.

As inferred from GPS measurements, the Andaman–Sumatra subduction zone shows along-arc variation in geodetically measured inter-plate coupling[6]. South of 0° lat., the alignment of the Sunda arc is almost normal to the Australian plate motion. This zone experienced nearly 600 km long rupture during the 1833 thrust earthquake (Mw 8.7) and is currently almost locked, signifying a strong seismic coupling. Further north, between 0 and 3°N, the ~300 km long rupture zone of the 1861 earthquake (Mw 8.4) shows less coupling and convergence is accommodated by both strike-slip as well as thrust motion. The recent megathrust earthquake (Mw = 9.0) occurred at the northern tip of the 1861 rupture zone (3.32°N). Significantly, the largest aftershocks are confined to the north of the earthquake source zone and the coseismic rupture probably broke a >1000 km length of the plate boundary, up to the northern edge of the Andaman group of islands. Data processed from a number of continuously operating GPS

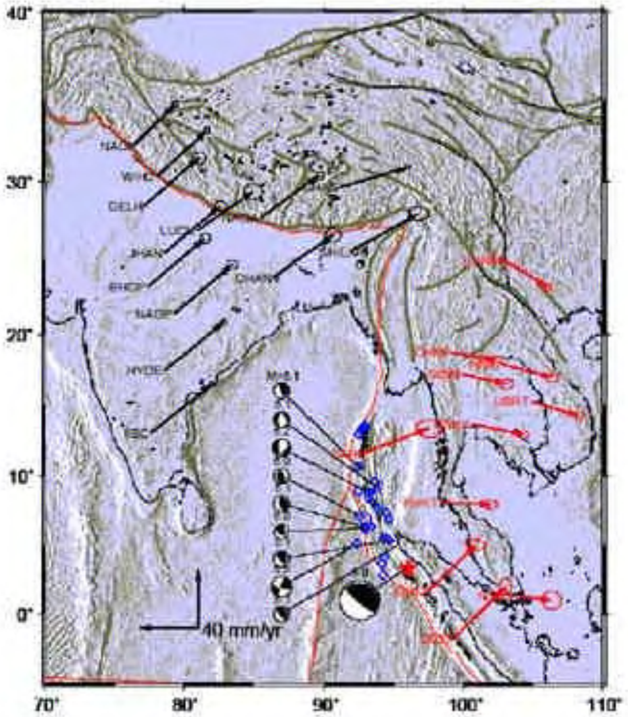

Figure 1. GPS velocities in India and South-East Asia in ITRF2000 reference frame, plotted on bathymetric and surface relief map. Epicentral locations of 2004 Great Sumatra Earthquake (Mw = 9.0), and aftershocks ($M > 6$) till 10 January, along with focal mechanism solutions are also shown.

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stations (CGPS), show that the zone of static coseismic horizontal surface displacement extended at least up to 4000 km range from the epicentre. Almost the entire South Indian shield moved towards east by 10–16 mm, a GPS station in South China (Kunming) moved towards south by ~12 mm, a Singapore station moved west by ~15 mm. The closest GPS station (SAMP, at Sumatra) to the earthquake source zone, moved towards west by ~136 mm. I present here GPS measured far-field static coseismic displacements and interseismic velocities of SSC block and Andaman plate relative to India plate and discuss the inter-seismic strain accumulations.

GPS data collected from a large number of sites in and around the Indian subcontinent during the period 1998–2004 were processed. Data lengths of individual sites vary between 2 and 8 years. These include CGPS sites established by the present author at Delhi (DELH), Dhanbad (DHAN), DehraDun (WIH2), Dharamsala (NADI), Kothi (KOTH), Panamik (PAN2), Bhatwari (BHTW), and campaign mode GPS stations at Jhansi (JHAN), Bhopal (BHOP), and Nagpur (NAGP). The campaign station data were collected for five days each year from each site during 2001–03. Data were collected from continuously operating International GPS Service (IGS) sites included in the processing that are located at Bangalore (IISC), Hyderabad (HYDE), in India, NAGA (Nepal), LHAS, KIT3, POL2 (Eurasia), DGAR (Indian Ocean), SAMP, NTUS, BAKO (SE Asia), and KUNM (South China). In addition, velocity solutions from SHIL (Shillong), CARI (Andaman)[7], D962, D937 (ref. 8) and CHMI, NNKT, SISM, UBRT, BNKK, PHKT[2] were included and these were transformed into a consistent reference frame through a set of common sites between the two systems of velocity solutions. Translation and rotations were applied in the transformation process. This allowed us to study inter-seismic velocities of sites located within, and representing India plate, Andaman micro-plate and SSC block in a common and consistent reference frame.

GAMIT/GLOBK suit of software[9,10] was used to process the data. Precise satellite orbits computed at Scripps Orbit and Permanent Array Center (SOPAC) at Scripps Institute of Oceanography[11] were used. GPS site coordinates, satellite orbits, tropospheric zenith delays, earth orientation parameters and phase ambiguities of the carrier waves were estimated daily and independently by weighted least square technique[9]. Loosely constrained daily solutions from 130 global tracking sites were combined with daily local solutions using GLOBK, resulting in a loosely constrained position time series for the entire survey span. The combined solutions were then passed to a Kalman filter[12], implemented through GLOBK software, to estimate network adjusted site coordinates and velocities. ITRF2000 reference frame was realized through GLORG using 25 IGS global tracking stations. Typical precision of position solution was 2–3 mm for north component, 3–5 mm for east component, and 10–15 mm for vertical component. Uncertainties in the horizontal velocities (1σ standard deviation) are 1–3 mm/yr.

Time series of daily solutions of site positions of selected sites (IISC, HYDE, NTUS, KUNM and SAMP) since 6 October 2004, the 280th day of the year, till 10 January 2005 (376th day since 1 January 2004), are shown in Figure 2. Because no significant signal was found in the vertical component, and also because the precision of vertical component measurement is at least 2–3 times less than that of horizontal components, we discuss here only the horizontal components of both position and baselines. The main event of the Sumatra earthquake took place at 00:58:53 UTC on day 361/2004. As the daily GPS solution pertains to a 24 h period, starting at 00 UTC, the solution of the day 361 may be considered as post-earthquake.

As seen from Figure 2, IISC (Bangalore) site shifted towards east by 16 ± 3 mm and HYDE (Hyderabad) site shifted towards east by 10 ± 3 mm with a small southward component. The SAMP site located at Sumatra experienced maximum offset of 138 ± 6 mm. The NTUS (Singapore) site located on the eastern side of the Andaman arc experienced 15 ± 3 mm displacement towards west. Though its north component does not show any appreciable abrupt dislocation, a gradual northward movement continued for few days before and after the mega event. The KUNM site located in southern China shifted towards south by 9 ± 3 mm, without any east–west movement. The displacements of the north Indian sites, including WIH2 (DehraDun) and NADI (Dharamsala), as shown in Figure 2 *b* and BHTW (Bhatwari, Uttarkashi), diminishes to almost an error level of 2–3 mm though still preserving the direction of motion consistent with the focal mechanism solution. Starting from the pure eastward direction at Bangalore, the directions rotate in clockwise sense around the earthquake epicentre. All the sites on the Indian plate side (footwall) show eastward motion, while all sites on the SE Asia side (hanging wall) shifted towards west.

The static dislocations can be more clearly seen in inter-station baselines (Figure 3). The east component of NTUS–IISC baseline shortened by nearly 30 mm as a result of displacements of both the sites. This is the sum effect of eastward shift of IISC and westward shift of NTUS sites as discussed above. The WIH2–IISC baseline components confirm that IISC shifted towards east relative to WIH2 during the Sumatra event. The fact that some of the sites, e.g. IISC, HYDE, NTUS, KUNM show coseismic offsets, whereas other north Indian sites, e.g. WIH2, NADI, BHTW show considerably lesser displacements, confirm that the offsets are not caused by any sudden changes in earth orientation parameters, e.g. location of the pole position and spin of the earth. Any such change would have affected all these sites almost equally.

The northward position of DGAR station was slightly offset by 2–3 mm, and the eastern coordinate (longitude) shifted towards east by ~10 mm. The distances of WIH2, HYDE, IISC, KUNM, NTUS and DGAR from the Sumatra

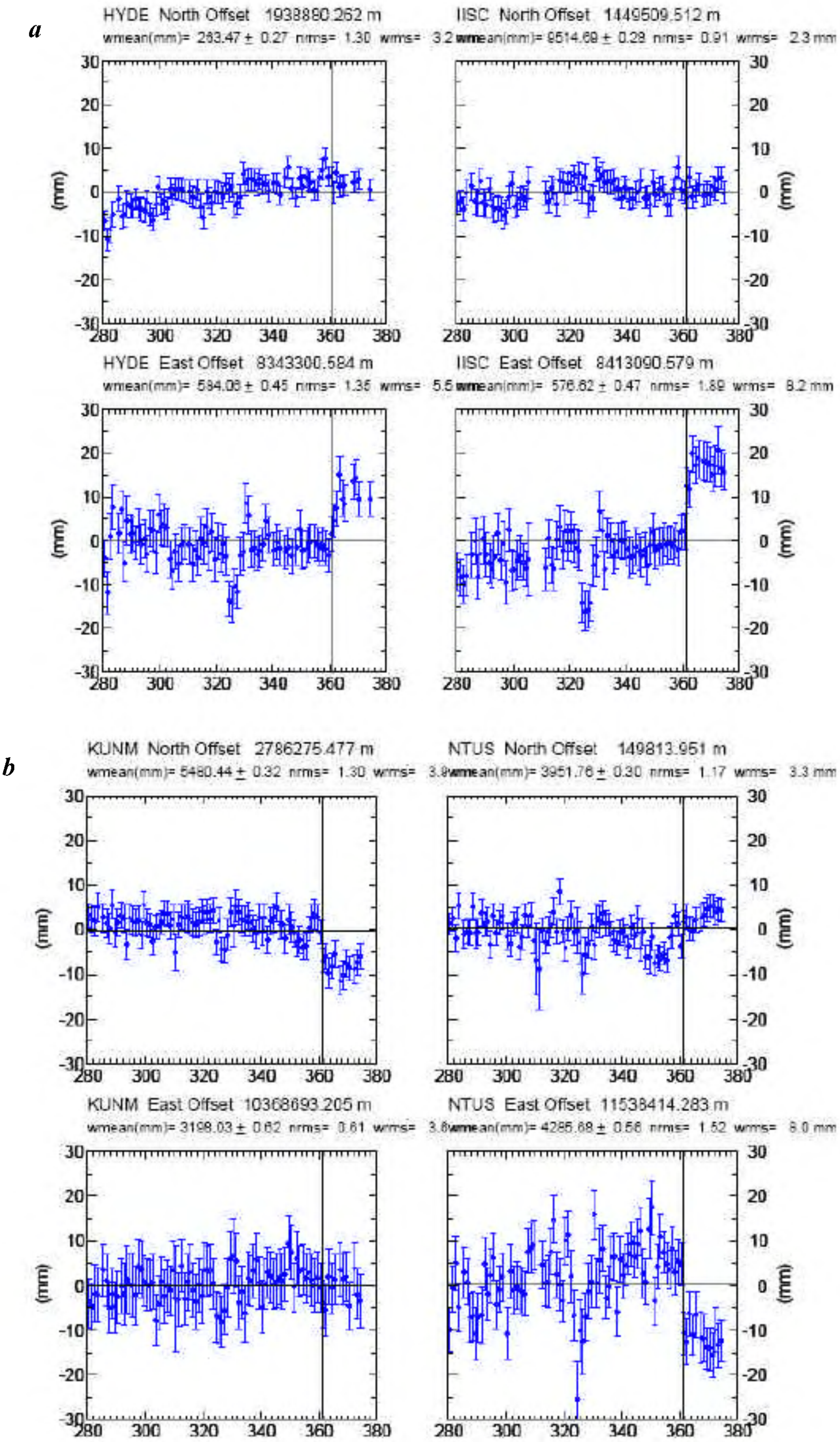

Figure 2. (*Continued*)

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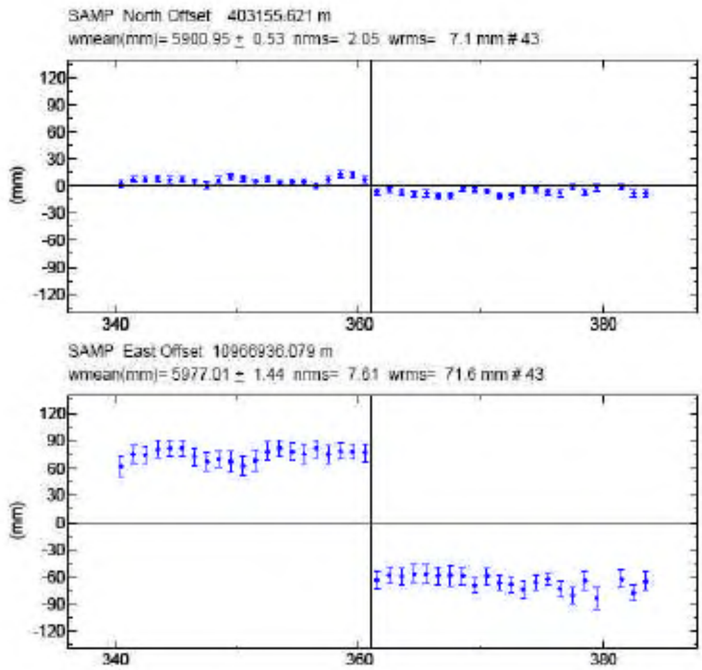
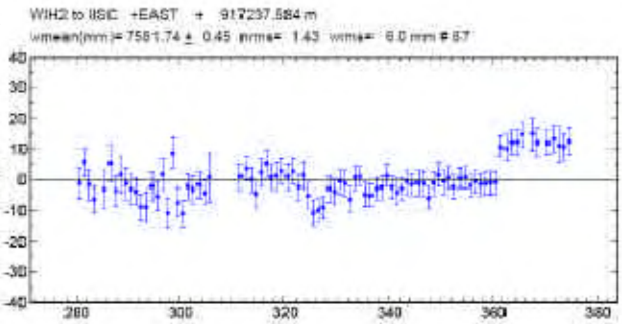


Figure 2. Time series of daily solutions of horizontal components of positions from GPS data. The 2004 Sumatra event ($M = 9.0$) occurred on day 261, and is marked by a vertical line. (***a***) HYDE (Hyderabad) and IISC (Bangalore); (***b***) KUNM (Kunming, South China) and NTUS (Singapore); (***c***) SAMP (Sumatra Island).

a



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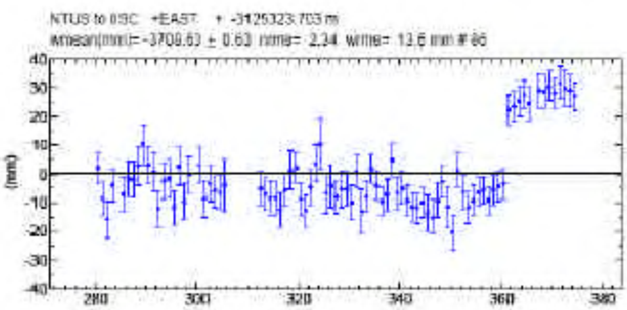

Figure 3. Time series of east components of baseline length solution between (***a***) Dehra Dun and Bangalore and (***b***) Singapore and Bangalore. Day 261 of Sumatra event is marked by an offset in east components. Relative to Singapore, Bangalore shifted towards east by ~30 mm. Relative to Dehra Dun, Bangalore shifted towards east by ~16 mm.

event epicentre are 3550, 2500, 2350, 2550, 900 and 2900 km respectively. The corresponding offsets are 2, 10, 16, 9, 15 and 10 mm respectively. The NTUS (Singapore) site has abnormally low displacement compared to other sites. Figure 4 shows the displacement vectors of all the sites around the earthquake source zone.

The GPS velocities of Indian sites were combined with those published by Bock *et al.*[8] and Iwakuni *et al.*[2], as has been discussed above. All the GPS velocities in ITRF2000 system (Figure 1) were then converted into India reference frame (Figure 5). IISC, HYDE, NAGP, JHAN, BHOP and DELH were used to define India reference frame. The CARI, D962 and D937 sites are located on Andaman microplate, whereas CHMP, SISM, NNKI, UBRT, BNKK, PHKT and NTUS represent the stable SSC block. The relative velocities (to India) of the sites in the SSC block vary between 40 and 44 mm/yr towards SSW direction, with the exception of Phuket (PHKT), where the velocity is 36.6 ± 2.2 mm/yr. The Andaman arc is almost N–S oriented, which then rotates into NW–SE direction to form the Sunda arc. The plate motion is almost arc-parallel along the Andaman arc and arc-normal in the southern part, across the Sunda arc. The arc-normal component of motion is accommodated by thrust faults and the arc-parallel components are accommodated by strike-slip faults in the plate boundary. The western or arc-normal component of the India–SSC block motion is 8–11 mm/yr and the southern component is 35–42 mm/yr in the Andaman arc sector. Almost 50% of this southern motion is partitioned along the Andaman arc as seen from the relative velocity of CARI, which is almost totally southward (17 ± 2.4 mm/yr). However, uncertainty in the CARI velocity keeps the possibility open that the Andaman trench actually accommodates both the eastward ~10 mm/yr motion in addition to westward ~17 mm/yr motion, which fits well with the present knowledge[7,13] that correlates the Andaman trench with oblique convergence and thrust. Further down south, as the trench–arc system orients towards south–east, more strike-slip component converts into arc-normal thrust component.

South of 5°N, D962 and D937 sites have east-directed velocities of 11.16 ± 2.9 and 7.6 ± 2.84 mm/yr respectively. Assuming a N45°W orientation of the Sunda arc, the arc-normal components of these two sites are 7.9 and 5.3 mm/yr respectively, and arc-parallel components are 7.9 and 5.3 mm/yr respectively. The arc-normal values are consistent with 5–10 mm/yr subsidence rates estimated from coral heads[14]. Similarly, arc-normal components of SSC block sites lie within 34–39 mm/yr and arc-parallel components vary between 18 and 22 mm/yr (SE-directed). As we can see, the arc-parallel component remains more or less same throughout the entire length of the Andaman–Sunda arc, whereas normal component increases considerably from north to south. The seismic coupling is stronger for the thrust faults compared to that for the strike-slip faults[6]. Thus, the Sunda arc section of the Andaman microplate accumulates most of the strain energy which was released through great megathrust earthquakes (from south to north: 1833, 1861, 2004) within the last 200 years. The rupture caused by the 1833 event was estimated to be ~600 km (*Mw*   8.7), and that by the 1861 event (*Mw*   8.4)[6] was ~300 km. The 2004 (*Mw* = 9.0) event is likely to have ruptured ~1400 km length, up to the northern tip of Andaman Island.

To accommodate the coseismic offsets observed at distant places as reported here, a simple two-fault representation model of the rupture caused by the 2004 Sumatra event was carried out[15]. The model assumed a dip of 15°, pure thrust mechanism, and rupture from hypocentre to far north in an elastic, homogeneous and isotropic half-space[15]. The predicted motion of CARI site is 2.6 m towards west. Pre- and post-earthquake GPS measurements at Andaman Islands were carried out by the Geodetic and Research Branch of Survey of India, DehraDun, and also by CESS, Trivandram. The results from these measurements, when published, will confirm the fitness of the predicted motion of near-field zone. Predicted displacements at IISC and HYDE fit well with the observed values. Coseismic GPS measured offset data from CARI and other surrounding sites in Andaman Islands and nearby SE Asian islands, augmented by more seismic data will help to better constrain slip estimation of the Sumatra earthquake and better understand the kinematics of the earthquake rupture process.

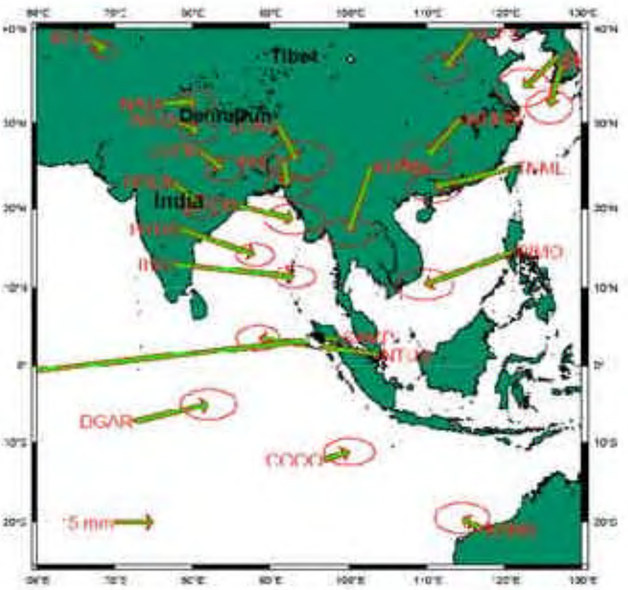

Figure 4. Coseismic static displacement vectors of permanent GPS stations around the 2004 Great Sumatra Earthquake source zone. Displacement vector directions conform to the focal mechanism solution (thrust faulting) of the main event.

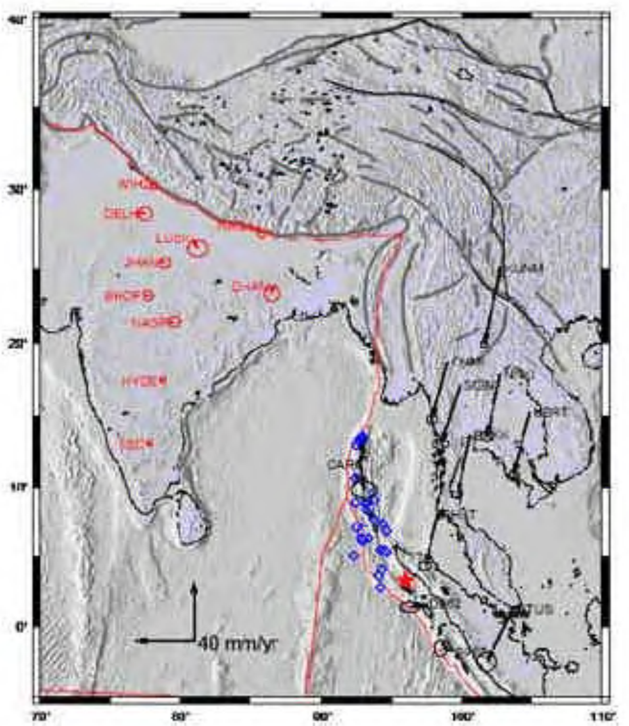

Figure 5. SSC block and Andaman plate GPS velocities relative to India plate. India reference frame was defined using GPS sites IISC, HYDE, NAGP, BHOP, JHAN and DELH. See text for details.

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Amphibian diversity and distribution in Tamhini, northern Western Ghats, India

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Monitoring and mapping of biological resources is a major concern from the conservation perspective, since the depletion of biodiversity is an irreversible change. In this study, we have monitored diversity and distribution of amphibian fauna of Tamhini, northern Western Ghats (18°27′N lat and 73°25′E long), using two methods – habitat ad hoc searches to produce checklists and transects to quantify seasonal change in diversity. First, we surveyed various localities from the study area (25 km^2) using ad hoc search method and prepared a checklist of species from different habitats. The species were categorized as very common, common, occasional, rare and absent. Secondly, transect sampling surveys were conducted and the number of individuals of each species was noted. Ad hoc searches depicted different distribution patterns and habitat specificity, while transects revealed seasonal changes in diversity and occurrence of amphibians.

ECOSYSTEM functioning is dictated to a large extent by diversity and the community structure that results from factors such as richness and evenness of diversity[1]. Thus, recent studies in biology focus more on the quantitative aspects of biodiversity that can be used to understand fluctuations in ecosystem functioning and help in prioritization of areas for conservation[2].

The Western Ghats of India, considered as one of the 25 biodiversity hotspots in the world[2], is rich in amphibian fauna. Among the 224 species of amphibians known from India, 117 (60%) occur in the Western Ghats, 89 being endemic to this region[3]. However, biodiversity of the Western Ghats is under threat due to deforestation[4]. Thus, to assess and measure the biological diversity in Western Ghats, so as to design and implement effective conservation strategies, the Western Ghats Biodiversity Network (WGBN) organized a programme of sampling species-level diversity in number of taxa in 25 different localities distributed over the length of Western Ghats[5]. Current study is a part of the programme and was conducted in one of the 25 localities.

The decline in amphibian population is a major concern throughout the world[6,7]. The causes of catastrophic decline vary and include diseases[8], increased exposure to UV-B radiation[9], impact of urbanization[10,11], habitat destruction[11–14], pollution[14] and specimen hunting[14]. As amphibian inhabit both terrestrial and aquatic habitats, a change in either or both the ecosystems can lead to a catastrophic effect in amphibian diversity. Thus, the widespread approach of surveys and

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