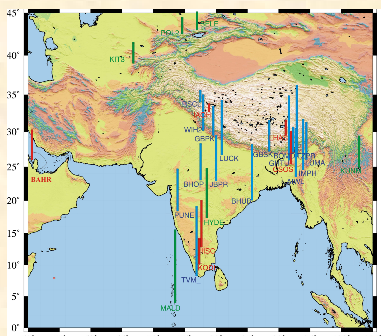
2
Solid Earth Modelling Platform
(SEMP)

Highlights

SEMP over the years have contributed significantly to our understanding of the geotectonic structure of the Indian region. Along with theoretical investigation SEMP has combined GPS geodesy, field campaigns and microzonation to understand and address the earthquake risk over the Indian sub-continent. Significant new results have emerged during 2006-07.



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2.1 Estimates of Anomalies in Triangular Area between C-MMACS GPS Network Stations

The Dec 26, 2004 Sumatra megathrust earthquake has shifted Andaman and Nicobar Islands by 1 to 6 m southwest and several sites in south India by ~15 mm eastward and northeast India by ~ 5 mm southward (Jade et al. 2005, 2006). As the relative change in triangular area between different sites is more sensitive than the relative change in their coordinates, we have attempted to calculate the anomalies in triangular area on daily basis between 10 permanent GPS stations of C-MMACS and 7 IGS stations from 1st Dec 2004 to 30th Jan 2005. Though the analysis doesn't show any significant change in the triangular area between the sites during the earthquake possibly due to their distance from the rupture zone, it highlights notable anomalies due to local seismic events occurred within or closer to the network.

A MATLAB program was written to estimate the anomalies in the area of various triangles and their corresponding strain projected in XY, YZ and ZX planes (3 – dimensional) along with errors using the geocentric coordinates in ITRF 2000 reference frame from GAMIT/GLOBK analysis. The results show an earthquake measuring M4.70 at 25.12□N 98.86□E on 7th Jan 2005 at a shallow depth of 36 km caused anomalies in all 3 planes of GAUHATI-LUMAMI-AIZWAL and GAUHATI-KUNMING-AIZWAL triangles. Similarly, IISC-AIWL-HYDE (Bangalore-Aizwal-Hyderabad) shows a dilatational strain of –4.25 PPM in YZ plane on 19th Jan 2005 where the threshold lies within ±2 PPM. This may be due to M5.00 earthquake at 22.97ºN 94.70ºE on 18th Jan 2005.

As the changes in the area of triangles are more sensitive to local deformation, such a study can be utilized for a better understanding of local deformation of a tectonically significant region. This analysis can be further refined by considering focal mechanism of local tremors to obtain a clearer view of the complicated process of deformation along faults, plate boundaries etc.

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2.2 Kinematics of the South-western Peninsular Shield

Since 2003 C-MMACS in collaboration with Cochin University of Science and Technology (CUSAT) is carrying out a DST funded research program, to quantify the time evolving deformation field in the south-western peninsular India and to model the ongoing tectonic and seismogenic processes using GPS geodesy as a tool. As part of this attempt, periodically GPS data from 36 points have been collected so far. Spatially most of these control points are around the major suspected zones of deformation of the south western part of the Indian stable continental region.

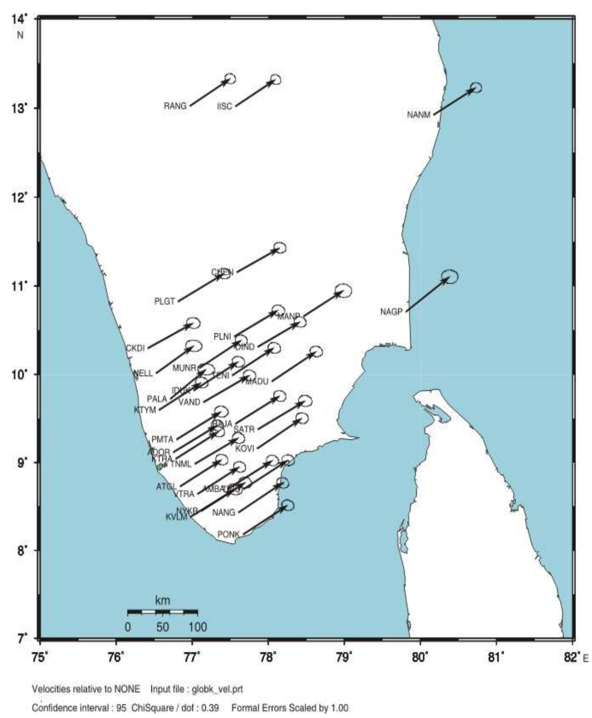

Figure 2.1 South Indian GPS campaign site velocity vectors in ITRF00 frame.

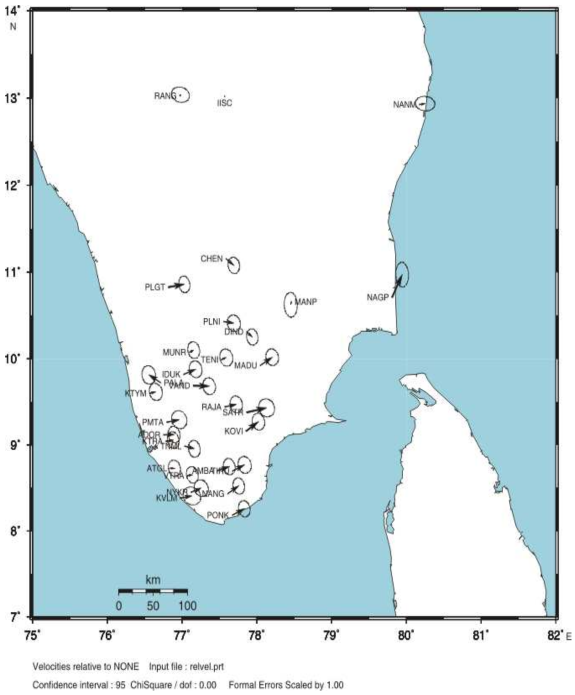

Figure 2.2 South Indian GPS site velocities in a India fixed frame.

The four to five year campaign data sets were analyzed using GAMIT/GLOBK to give velocities for in International Terrestrial Reference Frame-2000 (ITRF 00) reference frame (See Figure 2.1). In Indian reference frame all the stations have insignificant northward velocities and significant eastward velocities which is the coseismic signal of Sumatra earthquake (Figure 2.2). An analysis of one-decade (1994-2004) of C-MMACS campaign measurements in the south India shows insignificant strain rate in NS and EW direction.

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2.3 Co-seismic and Post-seismic Displacements in Andaman Nicobar Islands from GPS Measurements

We calculate the displacements of four sites in Andaman-Nicobar islands (Figure 2.3) from Diglipur (13.16^{o}N) to Car Nicobar (9.22^{o}N), from GPS measurements made at these sites in September 2003 (in collaboration with CESS, Trivandrum) , and repeated in February 2005 by CMMACS, assuming that the inter-seismic displacements at all these sites can be represented by the 14 ± 2 mm /yr convergence between CARI near Port Blair and Bangalore, reported earlier on the basis of GPS measurements made by us between 1996 and 1999. Since the latest measurements were made after about a month of the great Sumatra event of December 26, 2005, and several moderate earthquake ruptures had since occurred adding to the co-seismic surface displacements, the values reported here also represent the contributions of aftershocks. Rigorous analysis of the two epoch GPS data sets from these sites yield precise displacement vectors (Figure 2.3) , of which that at Car Nicobar has the largest horizontal magnitude (6.49±0.009 m to the WSW) with a significant 1.1 meters subsidence. The horizontal displacement at Chatham Island near Port Blair is also similarly oriented but smaller (3.53 ± 0.010m) with reduced subsidence. Further northeast of Port Blair, the Havelock Island site shows an even smaller horizontal displacement (1.6 ± 0.013m) to SW and nothing significant in the vertical whilst Diglipur, the northernmost Andaman site shows a much larger horizontal displacement (4.78 ±0.008m) to the SW, and a significant uplift of ~ 0.6 meters. Whilst these results are broadly consistent with the largely thrust component of earthquake fault slips reported by several workers on the basis of seismic fault mechanism studies, the southern components in the displacements of the northern sites require significant dextral slip contributions that may have been made by some of the moderate aftershocks or by slower ones or by aseismic strike slip movements along the northern subduction boundary.

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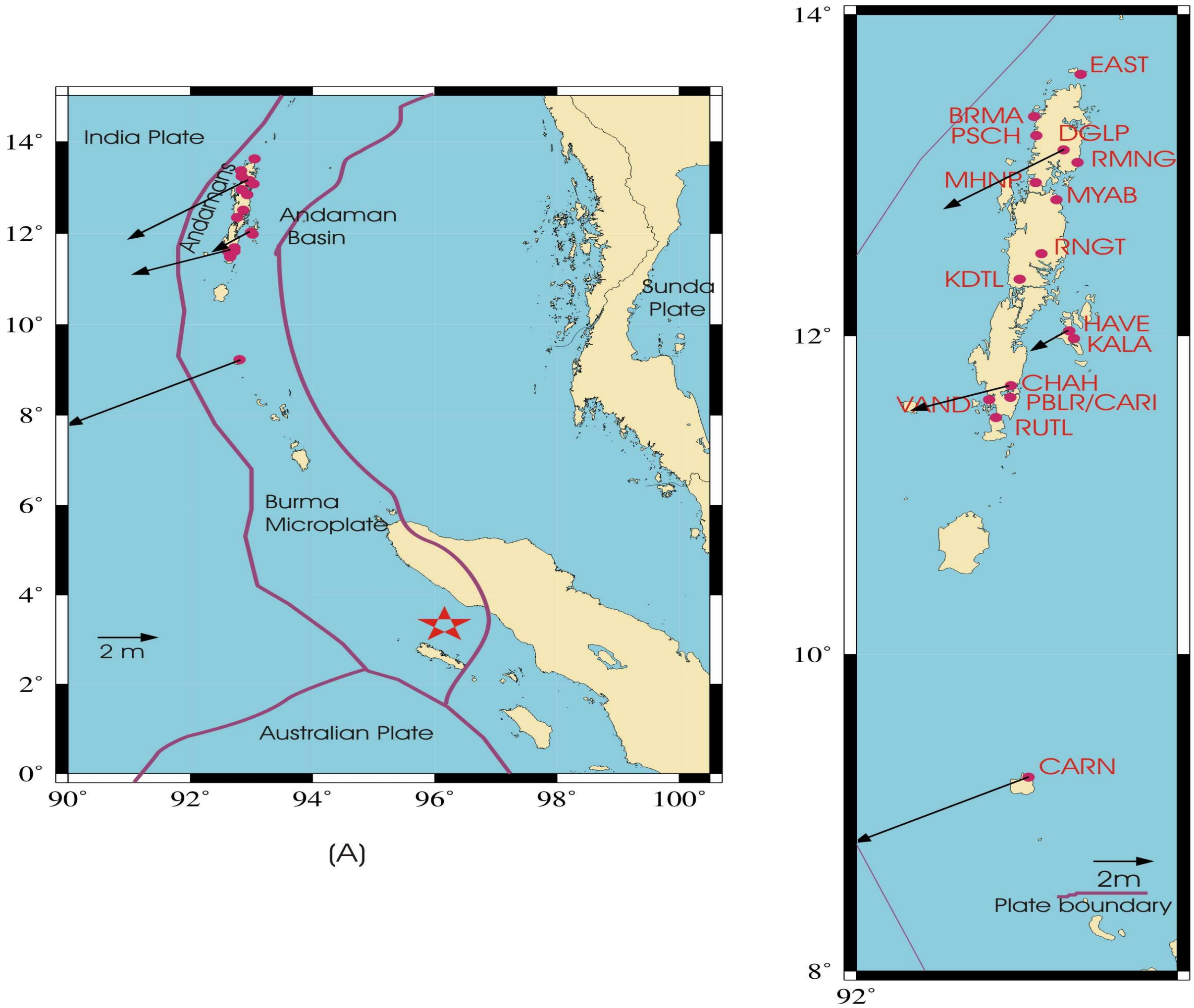

Figure 2.3. Co-seismic horizontal displacement vectors in Andaman's (a) Tectonic setting of the Andaman/ Nicobar region (b) Zoomed view of Andaman/Nicobar Islands with Campaign sites and displacement vectors.

2.4 Effect of Great Sumatra-Andaman Earthquake at some of the GPS Sites in the Indian Continent

The massive December 26th 2004 earthquake of Magnitude 9.3 shook the civilian and research community of India. Several reports on the displacements of sites in India in the wake of this earthquake have been made by various agencies. We report here the results of our analysis of GPS data from our campaign sites in southern India as well as from 11 permanent GPS stations of the DST national network along with the IGS stations (Figure 2.4) to quantify their co seismic displacements. These results show that whilst KodaiKanal and Bangalore almost directly west of the Andamans suffered co-seismic eastward displacements of 15 ± 4mm and 12 ± 3mm respectively , Hyderabad north of Bangalore, moved only by 6 ± 3mm and Bhopal further north by only 1.8 ± 2.5mm. The five campaign sites in southeastern India also show commensurate co-seismic eastward displacements of 14 to 22mm east. Permanent sites in the northeast which lie almost towards the northward extension of the rupture plane, expectedly, show smaller co-seismic displacements ranging from 5 to 10mm in the north component. Sites in the Himalaya, on the other hand, do not show

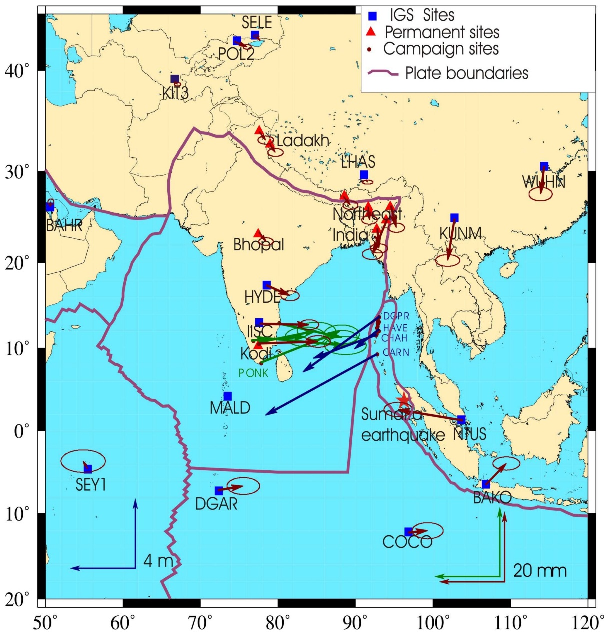

Figure 2.4 GPS sites in the analysis with co seismic displacements plotted with error ellipses

any significant displacement. Expectedly too, the campaign sites in the Andaman and Nicobar Islands show west- south-westward horizontal displacement large co-seismic displacements of 1.6 to 6.49 m intriguingly pointing along the plate velocity vector rather than that of the seismically determined eastward rupture. They also indicate 0.6m uplift in north Andamans, and 1 to 2 m subsidence in Port Blair and Car Nicobar. These observed co-seismic displacements (Figure 2.4) thus obtained have been modeled using Coulomb 2.6 to estimate the slip on the rupture plane. Modeled as a result of slips on a rupture plane made up of 4 segments to approximate to the trench geometry using Coulomb 2.6, these observed GPS displacements require a predominantly reverse slip on the southern most segment slowly translating to an oblique slip in the northern most segment, with diminishing magnitude.

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2.5 Intercontinental and Intra-continental Deformation in Indian Subcontinent

National network of GPS stations (figure 2.5) were established under the national programme of GPS to monitor the seismo tectonic activity in India. CMMACS has established 13 national network stations under this program. Five years of data from national network has been analysed along with the IGS (International GNSS service) data to determine the intercontinental and intra-continental deformation in Indian subcontinent. Long time series of motion and deformation of all national network stations over a period of 5 years has been determined. The GPS derived velocities in India Fixed and ITRF 2000 of 20 permanent stations of DST national network obtained from the data analysis is given in Figure 2.5.

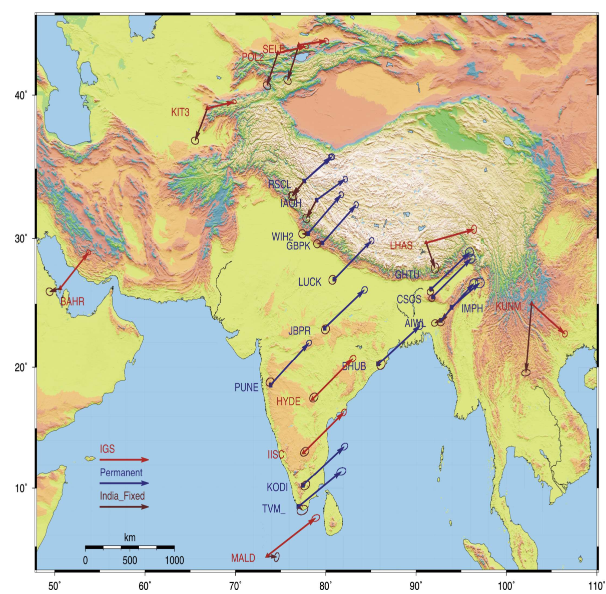

Figure 2.5 GPS derived velocities of DST national network (2001-2005)

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2.6 Estimation of Precipitable Water Vapor in Indian Subcontinent

GPS sites used in the analysis for water vapor estimation are listed in shown in Figure 2.6. These sites on the Indian continent form part of Indian national network of GPS stations established by Department of Science and Technology for monitoring the seismo tectonic activity in India. All the available data at these 21 sites during the four year period of 2000 to 2004 has been analyzed along with the International GPS service (IGS) stations as shown in Figure 2.6.

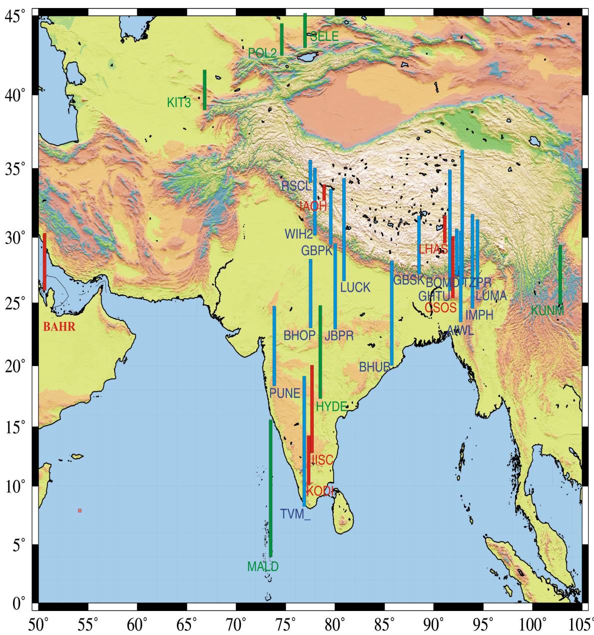

Figure 2.6 Precipitable water vapour estimated for 4 years (2001-2004) from GPS data

Precise orbit files from SOPAC/CDDIS archive along with combined broad cast ephemeris files are used in the GAMIT/GLOBK analysis to estimate the Zenith Total Delay for every two hours at all the stations. Station coordinates and Zenith delays are estimated using typical processing parameters such as (i) elevation cut off angle of 15º, (ii) mapping function of Neil, (iii) a priori tropospheric delay estimate by Saastamoinen model. Data analysis accounted for contributions to signal path delay from ionospheric refraction, orbital accuracy, antenna phase centre variations, signal multi-path and scattering by the receiver environment, the residual delay was modelled and estimated to yield the ZTD along with atmospheric gradients, assuming all of it to have been introduced by the neutral atmosphere. ZTD was estimated as a parameter by piecewise linear function over the session of every two hours by constraining the tabular points of the function using first order Gauss-Markov process. High accuracy and less scatter of results is achieved by selecting the GPS network shown in the figure 2.6 by ensuring the presence of minimum number of baselines of length > 2000 km [*Tregoning et al.*, 1998]. ZTD thus obtained from the GPS data analysis is used estimate the Precipitable Water Vapour in a column over the antennae of the permanent GPS stations (Figure 2.6). The GPS PWV thus estimated is also compared with the PWV estimated using measured meteorological parameters and horizontally interpolated NCEP PWV.

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2.7 GPS Re-measurements to Quantify Deformation in Gharwal and Ladakh Himalayas

Two Campaign measurements were conducted under this project. First GPS campaign was in Gharwal Himalayas the details of which are given in Figure2.7. During this campaign a new GPS campaign site was established in Gwalior (GWAL). Second GPS campaign was in Ladakh Himalayas the details of the sites are given in Figure 2.8. Two new GPS campaign sites (Figure 2.8) are established in Ladakh Himalaya at Tsoltak Village on the Leh-Tangste route close to Changala pass and at Gya village on the Upshi-Manali route.

GPS campaign data collected in Gharwal Himalayas in 2005 (Figure 2.7) has been

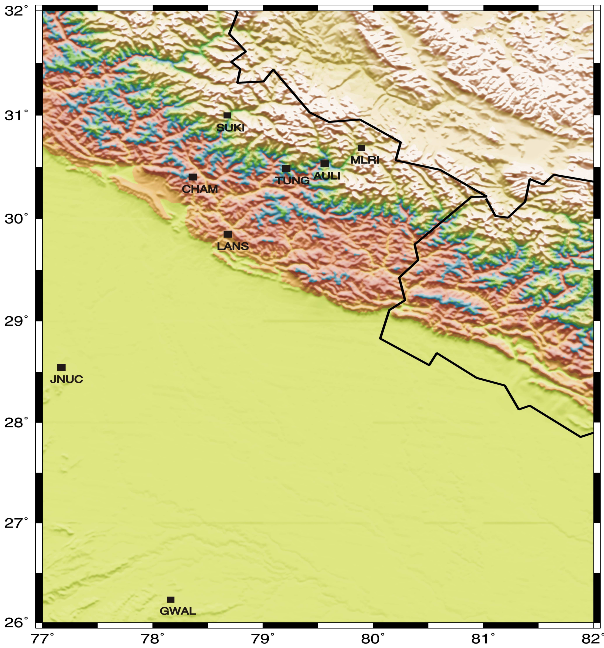

Figure 2.7 GPS sites measured in Gharwal Himalaya

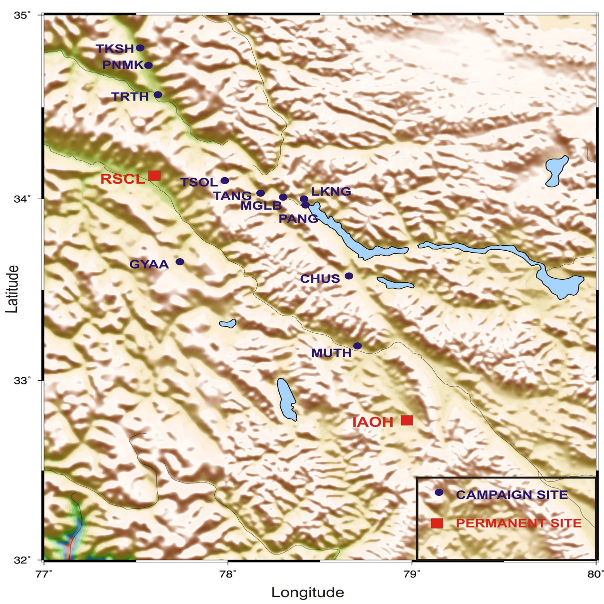

Figure 2.8 The sites of GPS measurement in Ladakh Himalayas during 2006.

analysed along with the earlier GPS campaign data set (1995 to 2004) of Gharwal Himalayas available at C-MMACS to give long term regional deformation over a period of 10 years in Gharwal Himalayas. The results from the analysis indicate a significant regional deformation of 10mm/yr between Gharwal GPS campaign stations in the MCT zone. So it is essential to establish a very dense network of campaign stations in the MCT zone starting from Chamoli-Joshimath area in the east to Uttarkashi-Bhatwari area in the west and to make GPS measurements every six months in this region. GPS campaign data collected in Ladakh Himalayas in 2006 has been analysed along with the earlier GPS campaign data set (1997 to 2002) of Ladakh Himalayas to give the regional deformation in this region and also a well constrained slip rate of Karakoram fault.

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2.8 Active Tectonics of the Northeast India Plateau using GPS Geodesy

This research work was aimed at measuring the rate of deformation in Northeast India in campaign mode along with eight continuously running stations established by C-MMACS and modelling of the observed surface from GPS results using dislocation theory. GPS campaign measurements in Northeast India (Figure 2.9) were first initiated in December 1997 at a site in Shillong plateau and subsequently at Tura GPS site west of Shillong plateau in 1999. In April 2002 some more campaign sites were established over the Shillong Plateau and Arunachal Pradesh which were subsequently remeasured in 2003, 2004, 2005 and 2006. Eight continuously operating permanent GPS stations (Figure 2.9) were installed in 2003 at Shillong, Tezpur, Guwahati, Lumami, Imphal, Aizawl, Bomdilla and Panthang (Gangtok) to determine the deformation rates in and across the region.

GPS data collected at all the above sites has been converted in to rinex observation files and quality check has been performed using TEQC (Translations, Editing and Quality Checking Software). The quality check plots of all the GPS data were carefully examined and the data with high cycle clips, multipath and <12hr observations were removed from the analysis. The GPS campaign style data (1997-2006) was processed along with the eight northeast permanent station data, (Figure 1) and the IGS stations using GAMIT/GLOBK developed by Massachusetts Institute of Technology (MIT), USA. Minimum 2 to 3 days (24hr files) of data per campaign for campaign sites and continuously available daily data of all permanent sites with sampling interval of 30 sec and satellite elevation cut off angle of 15º is used in the data analysis.

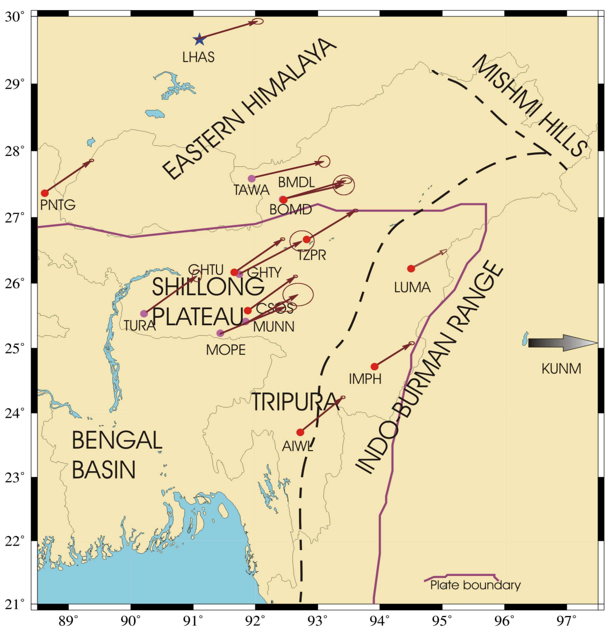

Figure 2.9 ITRF 2000 velocities of Northeast India GPS sites

The daily coordinates and velocities of all permanent and campaign sites were estimated in the ITRF 2000 reference frame by constraining IGS reference station positions and velocities in the region to reported values in that frame with standard errors provided by IGS. The average day to day repeatabilities in the north, east and up components of the estimated coordinates of all the sites used in the GPS analysis show standard deviation (σ) of < 4mm in North and < 6mm in East which is due to the large uncertainties for campaign sites. Also the baseline length repeatability plots indicates σ of < 1 mm for permanent sites and σ of 1 to 6mm for the campaign sites. The horizontal error ellipses are computed by GAMIT/ GLOBK software from the uncertainties in the North and East coordinates / velocities using the correlation between the baseline component estimates. ITRF 2000 coordinates and velocities for all the northeast stations are given Figure 2.9.

Sridevi Jade, Malay Mukul, Anjan Kumar Bhattacharya, M. S. M. Vijayan, Saigeetha Jaganathan , Ashok Kumar , R.P. Tiwari , Arun Kumar, S.Kalita, S.C. Sahu, A. P. Krishna, S. S. Gupta, MVRL Murthy and V. K. Gaur

2.9 Coda Q Estimates on the Andaman Islands using Local Earthquakes

The attenuation properties of seismic wave energy have been estimated using the single back-scattering model around the Andaman seismogenic region analyzing local earthquakes. As the region is not very well understood in terms of seismic attenuation, the December 26, 2004 great Sumatra earthquake has generated considerable interest amongst the scientists to understand the earth medium in terms of heterogeneities, scattering and attenuation properties of the lithosphere for better study of seismic hazard. A total of 32 local earthquakes of magnitude range 2.7- 4.2 have been used from four stations namely TGP, RGT, HVL and PBL to calculate frequency dependent Coda Q (Q_c) applying the time domain coda-decay method at central frequencies 1.5, 3.0, 6.0, 9.0, 12.0 and 18.0 Hz. Eight lapse time windows from 25 to 60 s have been selected for analysis starting at double the time of the primary S wave from the origin time. The average quality factor for Andaman region is estimated as, $Q_c = 129 f^{0.85}$, while the average Q_c values vary from 180±26 at 1.5

Hz to 1548±186 at 18 Hz central frequencies. The variation of the quality factor Q_c has also been estimated at different lapse times to observe its effect with depth and they vary from $101f^{0.91}$ to $143f^{0.84}$ at 25 to 60 s lapse time window length respectively. For 25 s lapse time window, the average Q_c value of the region varies from 137±14 at 1.5 Hz to 1296±132 at 18 Hz, while for 60 s lapse time window its variation is from 205±39 at 1.5 Hz to 1639±238 at 18 Hz of central frequency. The variation of Q_c with frequency and lapse time reflects that the upper crust is seismically more active compared to the lower lithosphere. It has also been observed that Q_c value is increasing from northern station (TGT) to the southern station (PBL) which shows the spatial variation in Coda even for a smaller region like Andaman.

Imtiyaz A Parvez

2.10 Ground Motion at Bedrock Level in Delhi City from Himalayan Earthquake Scenarios

Delhi the capital of India - is prone to a severe seismic hazard threat not only from local events but also from the Himalayan earthquakes at 250-300 km distance. In this study, we simulate the earthquake ground motion, at bedrock level, in Delhi city, by the modeling of the source of Mw=8.0, located in the central seismic gap of Himalayas, at about 300 km of epicentral distance from Delhi city. We simulate the time histories using both point source and extended source models.

The seismic waves due to an extended source are obtained by approximating it with a rectangular plane surface, corresponding to the fault plane on which the main rupture process is assumed to occur. Effects of directivity and of the energy release on the fault can be easily modeled, simulating the wide-band radiation process from a finite earthquake source/fault. The source is represented as a grid of point subsources, and their seismic moment rate functions are generated considering each of them as realizations (sample functions) of a non-stationary random process. Specifying in a realistic way the source length and width, as well as the rupture velocity, one can obtain realistic source time functions, valid in the far-field approximation. Finally, to calculate the ground motion at a site, Green functions are computed with the highly efficient and accurate modal summation technique, for each subsource-site pair, and then convolved with the subsource time functions and at last summed over all subsources. Furthermore, assuming a realistic kinematic description of the rupture process, the stochastic structure of the accelerograms can be reproduced, including the general envelope shape and peak factors. The extended seismic source model allows us to generate a spectrum (amplitude and phase) of the source time function that takes into accounts both the rupture process and directivity effects. In such a way it is possible to perform a speditive parametric study to investigate the dependence of the ground motion (in the time and frequency domain) on source parameters (geometry, energy release etc.). In the central seismic gap of Himalayas, we consider earthquake sources at an epicentral distance of about 300 km from Delhi city with Mw=8.0, depth=10, 15 and 20 km, dip=10 deg, rake=95 deg, length of fault=178 km and width of fault=45 km. The maximum amplitude of ground motion is searched as a function of the strike-receiver angle. The peak values - displacement of 9.1 cm (vertical comp.), velocity of 3.9 cm/sec (vertical comp.) and acceleration of 8.1 cm/sec^2 (NS comp.) - are obtained for the source depth 10 km. Similarly, keeping all other parameters fixed, we estimated the ground motion when the source is at depths of 15 and 20 km and the dip is 20 deg. A similar study will be performed for sources at regional and local distances, to analyze and to assess likely earthquake scenarios driving the seismic hazard in Delhi city.

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