2

Earthquake Hazard and Tectonics

Indian subcontinent is one of the most seismically active areas of the world. The Himalayan mountains in the north, mid-oceanic ridges in the south and earthquake belts surrounding the Indian plate all show the subcontinent has undergone extensive tectonic deformation in the geological past. GPS (Global Positioning System) Geodesy is used all over the world to quantify and monitor present tectonic deformation due to its capability of positioning of a point to sub-cm precision, which when re-measured over a number of years would give the displacements, strain and velocities with the same precision. C-MMACS first initiated systematic GPS studies in 1994 to determine the displacement and strain rate fields in some significant tectonic provinces of the Indian continent to measure the active tectonic deformation in these regions. As a part of GPS programme, C-MMACS has set up 11 continuously operating GPS stations in remote locations of the country to serve as reference stations and to monitor the strain gradients from north to south and east to west. GPS derived motion of sites form a key input for earthquake hazard analysis.

To mitigate the destructive impact of earthquakes is to conduct a seismic hazard analysis and take remedial measures. Research in C-MMACS involves the study of seismicity, probabilistic and deterministic seismic hazard assessment of Indian subcontinent and site-effects. The other side of quantifying and monitoring tectonic deformation is to understand its kinematics so that quantitative modeling using this data is based on realistic concepts. The Earth Science Research at C-MMACS has rapidly grown in the past few years resulting in a number of international and national collaborators.

Inside

2.1 Modeling of Site-Specific Ground Motion of Delhi City

The seismic ground motion in part of Delhi City has been computed with a hybrid technique based on the modal summation and the finite difference scheme for site-specific strong ground motion modeling along two cross-sections (1) North-South, from Inter State Bus Terminal (ISBT) to Sewanagar and (2) East-West, from Tilak Bridge to Punjabi Bagh. The first order result of this study was discussed and explained in detail in the previous C-MMACS annual report of 2002. In the present study, the same has been extended by placing the source at other sides of each profile, in order to analyze the variation in the obtained amplification patterns.

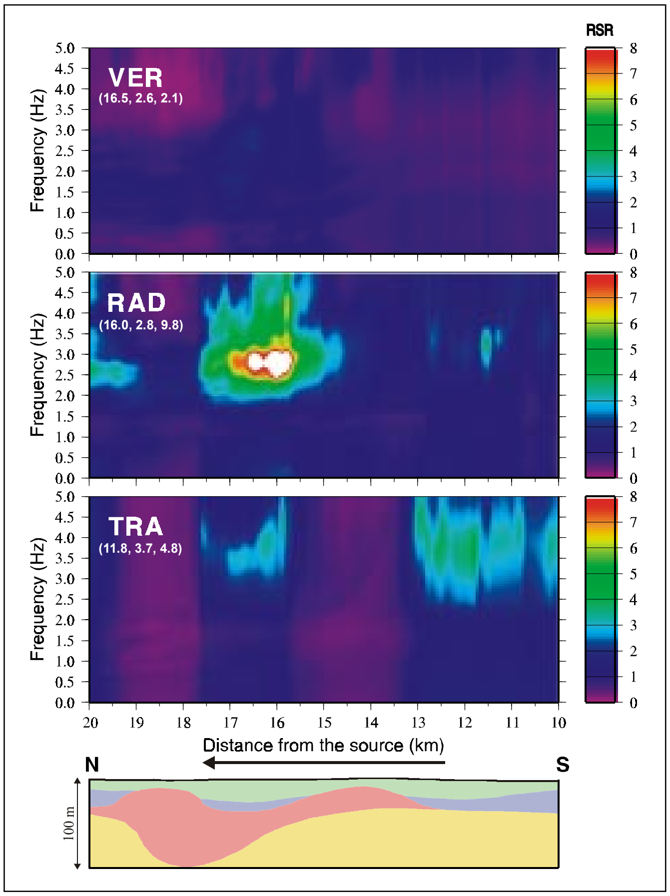

Fig.2.1 The NS cross-section and the corresponding plot of response spectra ratio (RSR) versus frequency and distance when the source is in south. The numbers in brackets represent maximum amplification, in the order, the distance in km, frequency in Hz and value of the peak RSR.

The response spectra ratio (RSR), i.e the response spectra computed from the signals synthesized along the laterally varying section normalized by the response spectra computed from the corresponding signals, synthesized for the bedrock reference regional model, have been determined. As expected, the sedimentary cover causes an increase of the signal amplitude particularly in the radial and transverse components. To further check the site-effects, we reversed the source location to the other side of the cross-section and re-computed the site amplifications. The distance from the source in km, the frequency in Hz and the value of RSR are shown in Fig. 2.1 and 2.2 for NS and EW cross-sections respectively, when the source is to the other side of the cross-sections. A 5% damping of the response spectra is considered since reinforced concrete buildings are already or will be built in the area. There are only a few sites where a large amplification is invariant with respect to the two source locations considered. The RSR ranges between 5 to 10 in the frequency range from 2.8 to 3.7 Hz, for the radial and transverse components of motion along the NS cross-section. Along the EW cross-section RSR varies between 3.5 to 7.5 in the frequency ranges from 3.5 to 4.1 Hz. The amplification of the vertical component is large at high frequency (> 4 Hz.) whereas it is negligible in lower frequency range.

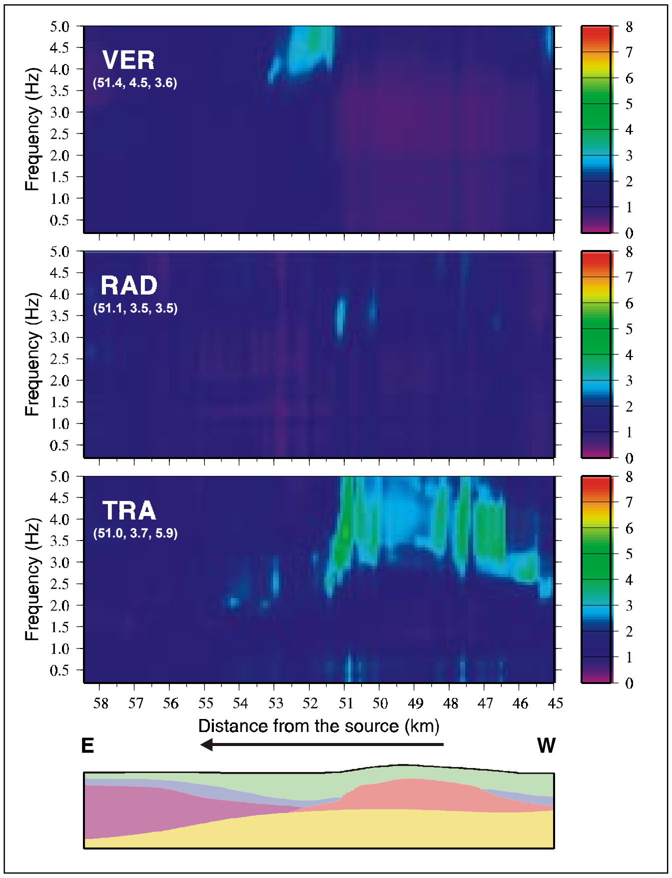

Fig.2.2 Same as figure 2.1 for EW cross-section when the source is in the west of the profile.

If we compare the results of NS profile keeping source in reverse direction, we see that the direction of propagation of the waves influences the pattern of amplification significantly. We can notice a shift both in the frequency and the location of the peaks. For instance, if we look at the position of the absolute maximum, found in the radial component for the southern source, we see that for the northern source we have amplification around 3 instead of about 10. Large differences can be seen in the patterns of the vertical component as well. Almost no amplification is observed for the southern source in the region where the largest amplification of almost 4 is obtained with the northern source. Such differences could not be predicted by the widely used convolutive approaches, most of which are based on the treatment of vertically propagating wavefields.

If we compare figures of EW profiles, they look almost alike. Contrary to the case of the NS profile, even if we reverse the propagation direction, the response spectra ratio along several parts of the EW profile is practically the same for all the three components. Part of the explanation could be searched in the larger epicentral distance adopted for the EW profile (45 km instead of 10 km).

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2.2 Earthquake Hazard Assessment in the North-East Indian Peninsula

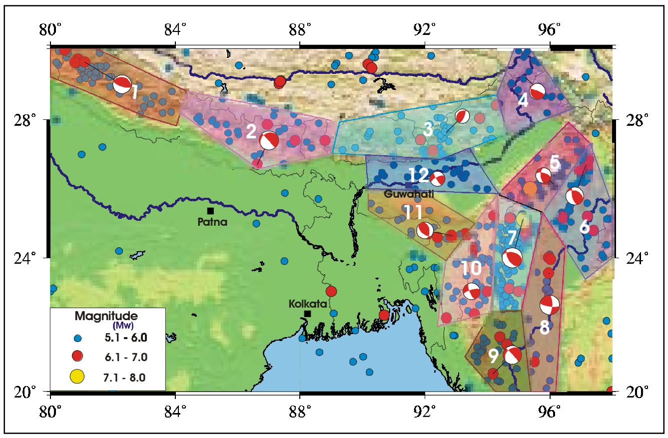

Figure 2.3 A topographical and geological map with twelve seismogenic zones of Northeast Indian peninsula for computation of the Bayesian probabilities of occurrence of earthquakes with Mw^3= 5.0.

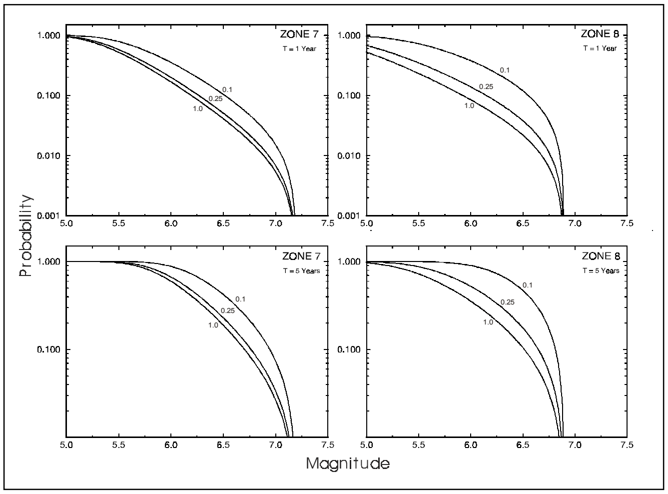

Figure 2.4 Probability of occurrence of earthquakes with Mw= 5.0 for zone 7 of Northeast Indian peninsula. The upper graph indicates T=1 year and lower for T=5 years and the numbers on each curves represent the value of coefficient of variation at Vv'=0.1, 0.25 and 1.0.

Assessment of earthquake hazard represents a very crucial and important problem. The earthquake prediction in terms of location, time and magnitude of a future event in a seismogenic zone is difficult because of the complexity and incomplete understanding of the mechanism which generate earthquakes. However, in this complexity, there is also some order which can be described by statistical summaries or by probability of occurrence of events of various magnitudes in the region under investigation. In the present study, Bayesian probabilities of earthquake occurrences in the North-East Indian peninsula (Fig 2.3) have been prepared. Bayesian probability theory provides a means of incorporating the statistical uncertainty, associated with the estimation of the parameters used to quantify seismicity, in addition to the probabilistic uncertainty associated with the inherent randomness of earthquake occurrences. Bayesian probability theory constitutes the fundamental theorems of probability; its most important aspect being that of updating current probabilities when new information becomes available. This feature allows the user to combine seismotectonic information on seismicity, such as geological data with historical observations. Such application is very useful when historical data are incomplete, cover too short a period of time or is insufficient to define rates of seismicity.

The seismicity data are chosen for the period of 1963-2001 because for the Indian subcontinent, the reliable catalogue of magnitude 5 and above is available only in this period. The zoning is done on the basis of clustering of events, geological and tectonic trends and possible similar focal mechanism, which permits to divide the area of study into twelve seismogenic zone (Fig 2.3). The maximum number of events is found in Zone 7 (109) and minimum in Zone 4 (20). The probability of occurrence of Mw=5.0-5.5 is more than 0.9 for all zones for T=5 years and coefficient of variation $V'_V = 0.1$ whereas for Mw=6.0 with the same parameters four zones namely Z1 (Central Himalayas), Z5 (Indo-Burma border), Z7 (Burmese arc) and Z8 (Burma region) exhibit very high probabilities, more than 0.9. The other regions like Z2, Z3, Z6, Z9, Z10 and Z11 also show high probabilities ranging between 0.7 and 0.9, however Zone 4 and Zone 12 do not estimate probability till Mw=6.0 because the maximum magnitude observed in these regions are less than 6.0. If we consider the coefficient of variation $V'_V = 1.0$ the probability of occurrence of magnitude Mw=6.0 is low to moderate in all zones, whereas for Mw=5.5 it gives high probability (>9.0) in Z1 & Z7 (Fig 2.4) and low probability in Z4 and Z12. The rest of the zones come in the moderate probabilities.

(I A Parvez and Praveena G)

2.3 A Homogeneous Moment Magnitude Earthquake Catalogue for the Indian Subcontinent

One of the most important tools to study the seismic hazard in any part of seismogenic world is an earthquake catalogue. Unfortunately the earthquake catalogue for the Indian subcontinent is niether very up-to-date nor comprehensive. There are several research articles related to earthquake catalogue for India available in the literature. However, in these catalogues, many events are missing, many are listed without their sizes and origin time. There are several International organisations which have an archive of the Indian earthquake catalogue like National Oceanic & Atmospheric Administration (NOAA), National Earthquake Information Centre (NEIC) of USGS, International Seismological Centre (ISC), Harvard CMT catalogue and Council of the National Seismic System (CNSS), but they are also not complete beyond a period of time in terms of size, location and origin time.

We have compiled the earthquake catalogue of the Indian subcontinent using all available information mentioned above and from published catalogues/literature, which can be used for hazard and risk assessment related studies. In order to establish the homogeneous moment-magnitude (Mw) earthquake catalogue for the Indian subcontinent, we establish the following relationship between Mw, Ms and Mb for three broad subregions of the Indian subcontinent, namely Kirthar- Sulaiman-Himalayan mountain ranges, Indian Peninsular Shield and Indo-Burmese Arc on the basis of their geological and tectonic setting.

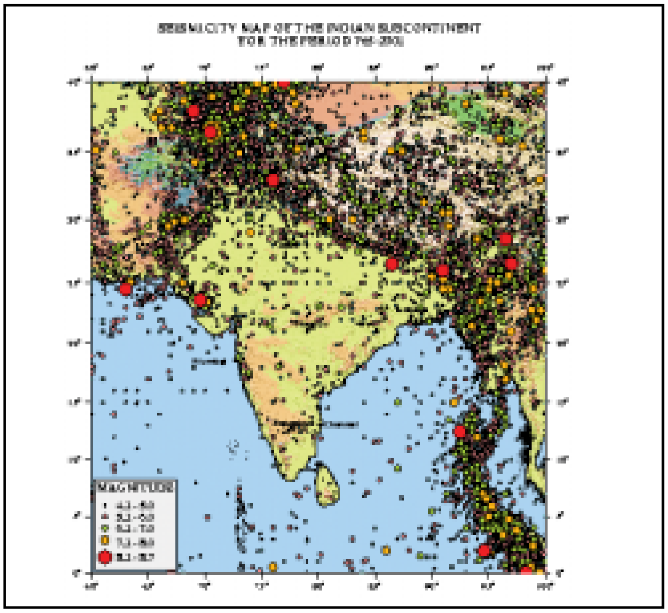

Fig. 2.5 The seismicity map of the Indian-subcontinent for the period 765-2001

Kirthar-Sulaiman-Himalayan Mountain Range

$$Mb = -0.035Ms^2 + 0.941Ms + 1.204$$
$$Ms = 1.329Mw - 2.058$$
$$Mb = 0.683Mw + 1.545$$

Indo-Burmese Arc

$$Mb = -0.034Ms^2 + 0.941Ms + 1.204$$
$$Ms = 1.384Mw - 2.427$$
$$Mb = 0.672Mw + 1.590$$

Indian Peninsular Shield

$$Mb = -0.029Ms^2 + 0.904Ms + 1.409$$
$$Ms = 1.372Mw - 2.393$$
$$Mb = 0.750Mw + 1.279$$

The ISC locations and depths, which are more reliable and accurate compared to others, are used wherever available and the omissions of wrong and duplicate entries have been done. Fig 2.5 shows the seismicity map of the Indian-subcontinent for the period 765-2001.

(I A Parvez and Geeta Bagga)

2.4 Kinematics of Neotectonic Duplex Formation: Constraints from Luminescence Dating

Hitherto it was believed that compressive neotectonics in the Himalayan mountain belt occurred by the reactivation of major boundary faults such as the Main Boundary Fault. This is not true universally and alternative neotectonic deformation mechanisms exist in the frontal part of the Himalayan wedge. The Main Boundary thrust (MBT) in the Darjiling-Sikkim-Tibet (DaSiT) Himalayan wedge has been folded by fault propagation folding related to a footwall imbricate (South Kalijhora thrust) indicating that it is now a passive plane which cannot be reactivated along its entire length. Formation of neotectonic duplexes by faults that cross-cut or join older thrusts (connective splays) in the footwall Siwalik rocks of the MBT and parts of its hanging wall appears to be the alternative mechanisms of neotectonic deformation in the Darjiling-Sikkim Himalayas; this structure has modified the geometry of the fold in the MBT without reactivating it.

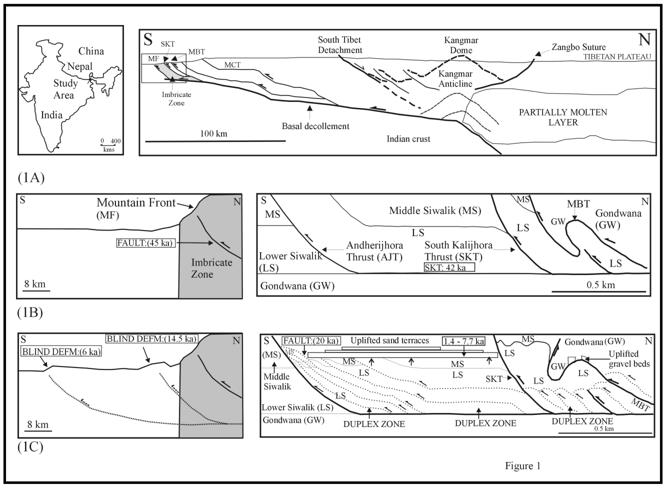

Fig. 2.6 First order geometry of the DaSiT wedge (1A). The formation of the Kangmar structure drove the frontal folding and thrusting (D1) in the wedge. D1 frontal thrusts are shown in 1A & B and were in place by 40-45 ka (1B). The study area is boxed in 1A and the geometry of the frontal thrusts at the end of 40 ka is given in 1B. Formation of out-of-sequence Connective Splay Duplex (CSD) between > 20 ka and < 1.5 ka caused at least two recognizable events of wedge advance (1C) around 14.5 ka and 6 ka. D1 faults and splays are shown as bold and dashed lines respectively in 1C.

Now, Thermoluminescence (TL) dating and Optically Simulated Luminescence (OSL) provide a way to date deformation events provided they have occurred in the past 150 k years. TL dating of elastico-frictional fault zone rocks estimate the time of the last motion on the fault whereas OSL dating of fluvial sediments give their last burial age. TL and OSL dating of fault zones and raised river terraces in the neotectonically active connective splay duplex (CSD) in the frontal DaSiT wedge indicates that the CSD formed between 20± 6.2 ka and 1.4±0.3 ka and was an out-of-sequence structure because the southernmost fault near the exposed mountain front (Fig 2.6) was dated to be active around 45±7 ka. The wedge taper gained during this process caused the DaSiT wedge to advance into the foreland at least twice around 14.5±2.4 ka and 6±0.6 ka. The neotectonic out-of-sequence duplex building and wedge advance events are most likely to be major seismic events that increase the seismic risk in densely populated regions in NW Bangladesh, north Bengal and western Bhutan. Moreover, this also implies that inversion of surface deformation data in the Himalaya that are carried out using dislocation models simulating slip along major boundary faults, need to also account for alternative neotectonic deformation mechanisms.

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** Physical Research Laboratory, Ahmedabad*

2.5 The Kinematics of Quaternary Neotectonics in the Darjiling-Sikkim-Tibet (DaSiT) Himalayan Wedge

Wedge scale compressive deformation in active fold-and-thrust belts like the Himalayas can be best studied by looking at paleotectonic, neotectonic and seismological data in the backdrop of the critical wedge theory. A first-order application of this approach to the Darjiling-Sikkim-Tibet (DaSiT) wedge reveals signatures of Quaternary deformation in the wedge in three distinct zones as evident from occurrence of raised, unpaired, fluvial strath terraces mostly along present-day drainage (Fig 2.7).

Quaternary deformation is observed south of the exposed mountain front, in the transition zone from Lesser Himalayas to the Outer Himalayas, and also the High to Lesser Himalayas transition zone in the DaSiT wedge. Out-of-sequence connective splay duplexes are observed in these transition zones; these have modified pre-existing structural geometries and raised the Quaternary river gravels and sands nearby forming several raised river terraces.

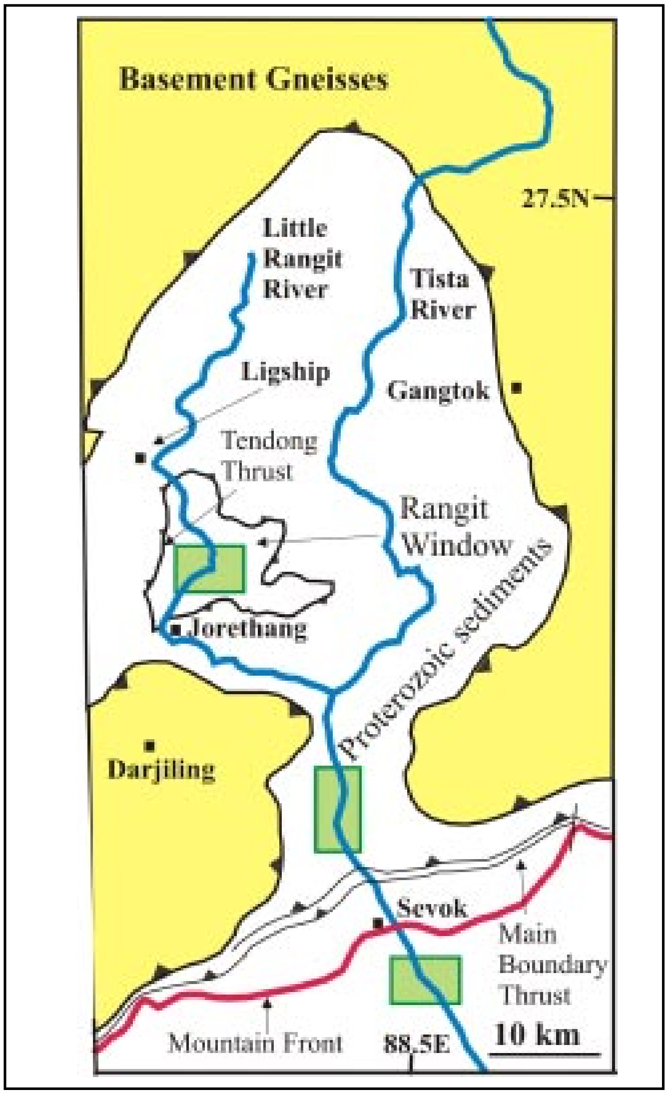

Fig. 2.7 Regional structure of the Darjiling-Sikkim-Himalayas in the frontal and middle part of the Darjiling-Sikkim-Tibet (DaSiT) wedge. The sites where Quaternary neotectonics has been observed are boxed in green. Three such areas exist. The Quaternary deformation observed north of the mountain front in the wedge, are duplex related. These are also the sites where earthquake epicenters are concentrated in the wedge (Figure 2.8).

Earthquake epicentres also plot in these three zones (Fig 2.8); this suggests that the DaSiT wedge was reactivated in the Quaternary in response to variation in wedge parameters along transport direction. The Quaternary reactivation of the DaSiT wedge was an attempt to restore taper at the transition zones by duplex formation because the wedge taper had become sub-critical due to reduction in basement slope, topographic slope and material strength in these transition zones.

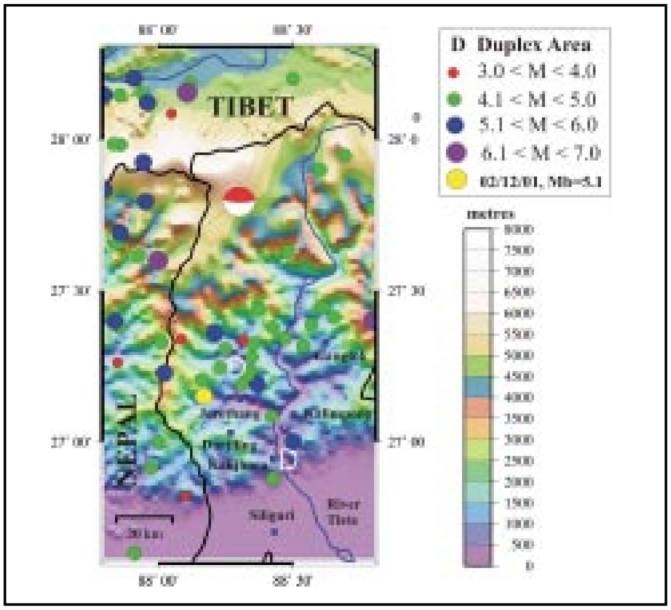

Fig. 2.8 Distribution of earthquake epicenters in the Darjiling-Sikkim-Tibet (DaSiT) wedge superposed on the regional topography. Epicenters around Kalijhora and Jorethang where structural duplexes and Quaternary raised terraces have been observed are clearly discernible. This indicates that the areas showing Quaternary raised terraces (Figure 2.7) in the wedge are also seismically active and deformation related to the reactivation of the DaSiT wedge continues today.

(Malay Mukul, I A Parvez)

2.6 Dynamics of the Intercontinental and Intra-continental Deformation Zone through Experimental Determination of South-North Strain Rate Gradients in India

The Indian plate is bounded by transform boundaries to the east and west and a continental collision boundary to the north and spreading centers to the south west. Persistent collision of the Indian Plate with Eurasia over the past 50 Ma has made the tectonics of Indian subcontinent very dynamic and complex. Indo-Eurasian collision processes still operating in the convergence zone mark the region as being potentially the most diagnostic for modelling them. For, an understanding of these processes that drive and absorb collision is crucial to reconstructing the evolution of older collision systems which have fashioned the continents through geological time. GPS derived velocities obtained over the years at 60 sites in different regions of Indian subcontinent (Southern peninsula, Ladakh, Gharwal and Kumoan, Darjeeling Sikkim, Gujarat, Andamans and Shillong regions) using GPS geodesy were used to get an overall picture of deformation in this convergence zone and to give insight into the motion across the Indian Plate.

Fig 2.9 shows campaign style, reference and permanent GPS sites along with the IGS stations in the region. Leh, Hanle, Almora, Bangalore and Kodaikanal are permanent stations which run 24hrs a day and 365 days a year. Delhi, Jamanagar, Bhopal and Shillong are reference stations where more than 10days GPS measurements are available every year. Rest of the sites are campaign style sites with 3 days of measurement every year. All the GPS data has been used along with the IGS stations in the network to arrive at the coordinates and velocities (figure1) in the ITRF 97 reference frame and Indian reference frame and relative to IISc. The velocities are summarized in Table 1 for different regions.

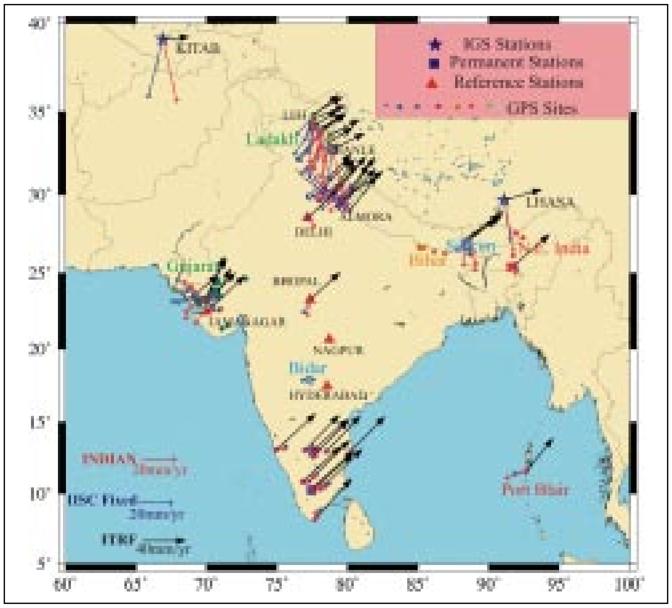

Fig. 2.9 GPS sites and their velocities

Region	ITRF 97 Velocities	Velocities in Indian reference frame	Velocities relative to IISc station	Convergence rates
S. India	57 to 64mm/yr ± 5mm at N46 ° E± 3°	0 to 6mm ± 5mm/yr ≈ 0	0 to 6mm ± 5mm/yr ≈ 0	zero
Gujarat	28 to 56mm/yr ± 4mm at N22-49 ° E	12 to 24mm/yr± 4mm at N200-320 ° E	10 to 24mm/yr± 4mm at N200-310 ° E	10 to 24mm/yr
Ladakh	31 to 40mm/yr ± 3mm at N50-67 ° E	16 to 24mm/yr± 3mm at N170-190 ° E	14 to 24mm/yr± 3 mm at N190-220 ° E	14 to 20mm/yr
Gharwal & Kumaon	40 to 50mm/yr± 5mm at N 34 - 44 ° E	8 to 15mm/yr± 5mm at N190-220 ° E	10 to 18mm/yr± 3 mm at N 230-245 ° E	10 to18mm/yr
Sikkim	46 to 52mm/yr± 4mm at N52 to 60 ° E	14 to 20mm/yr± 4mm at N155 - 170 ° E	5 to 12mm/yr± 4mm at N 160 - 180 ° E	10 to 12mm/yr

Table 1: Summary of GPS derived motions in the Indian Subcontinent

Significant conclusions that arise from the above study (Fig 2.9) are Southern peninsula and Delhi moves as a rigid plate with the velocity approximately equal to Indian plate. All the convergence occurs in the 2500 km stretch of the Himalayan arc from Kashmir to Arunachal and the convergence rates vary significantly from west to east. This substantiates the fact stated by Bilham et al., 2001 that the Himalayan arc can be divided into 10 regions with lengths roughly corresponding to those of great Himalayan ruptures (~220km). Significant conclusion cannot be drawn from the GPS measurements available in the North West and North east India as the data is insufficient, nevertheless velocities of Jamnagar and Shillong do give a clue to the deformation in these regions.

(Sridevi Jade)

2.7 Pre-seismic, Co-seismic and Post-seismic Displacements Associated with the Bhuj 2001 Earthquake

The 26 January 2001 Bhuj earthquake occurred in the Kachchh Rift Basin which has a long history of major earthquakes. Geodetic triangulation survey points (GTS) were first installed in the area in 1856-60 and some of these were re-measured using Global Positioning System (GPS) methods (Fig 2.10) in the months of February and July 2001. Despite uncertainties associated with repairs and possible reconstruction of points in the past century, the re-measurements reveal pre-seismic, co-seismic and post-seismic deformation related to Bhuj earthquake. A >25 μ-strain contraction north of the epicenter appears to have occurred in the past 140 years corresponding to a linear convergence rate of approximately 10 mm/yr. across of the Rann of Kachchh. It is not possible to say whether the convergence has been uniform during this time or whether is has been associated with earthquake activity in the past 140 years.

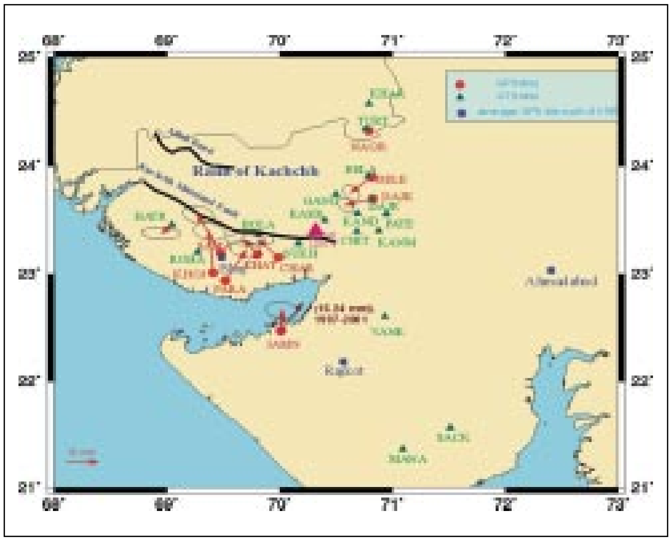

Fig. 2.10 Sites measured using GPS geodesy and the GPS derived co-seismic and post seismic vectors with associated error ellipses.

Motion of a single point at Jamnagar 150 km south of the epicenter in the 4 years prior to the earthquake and GTS-GPS displacements in Kathiawar suggests that pre-seismic strain south of the epicenter was small and differs insignificantly from that measured elsewhere in India. Of the 20 points (Fig 2.10) measured within 150 km of the epicenter, 12 were made at existing GTS points which revealed epicentral displacements of up to 1 m, and strain changes exceeding 30 μ-strain. Observed displacements are consistent with reverse co-seismic slip. Re-measurements in July 2001 of one GTS point (Hathria) and eight new points established in February reveal post-seismic deformation consistent with continued slip on the Bhuj rupture zone. We note that prior to the earthquake convergence across the Rann may have attained higher values than those we measured after the earthquake, Post-seismic surface displacements indicate that aftershock activity continued to permit NE/SW contraction in the months following the earthquake.

Remeasurements were carried out in Bhuj region (Fig 2.10) during March 2003 which may give more insight in to modelling the post seismic deformation due to 2001 earth quake.

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2.8 Establishment of Continuous Recording GPS Sites in North-Eastern India

In 2002, C-MMACS has installed five permanent stations (Fig 2.11) at Aizawl, Gauhati, Imphal, Lumami and Shillong and provided technical support to Tezpur University in making their permanent station operational. All the sites shown in Fig 2.11 are now operational collecting 24 hr data. The above 6 stations established form part of the national network of GPS stations envisaged by Department of Science and Technology for monitoring the geotectonic activities in the Indian subcontinent. On a regional scale these stations provide GPS data which will help answer the questions related to Indo- Burma Convergence, the tectonic relationship of the Shillong Plateau with the Himalayas. Brief description of the sites established follows:

Aizawl Station(AZWL: It is set-up within the Mizoram University, Pachhunga University College campus at Aizwal located on a pillar approximately 8-9 m high. This station is located in the Tripura Salient of Indo-Burman Fold-and-Thrust belt.

Imphal Station (IMPH): It is set-up on a hill within the Manipur University Campus located on a pillar approximately 7 m high. ; A unit of Assam Rifles occupies the hill. This station is in the central part of Indo-Burman Fold-and-Thrust belt.

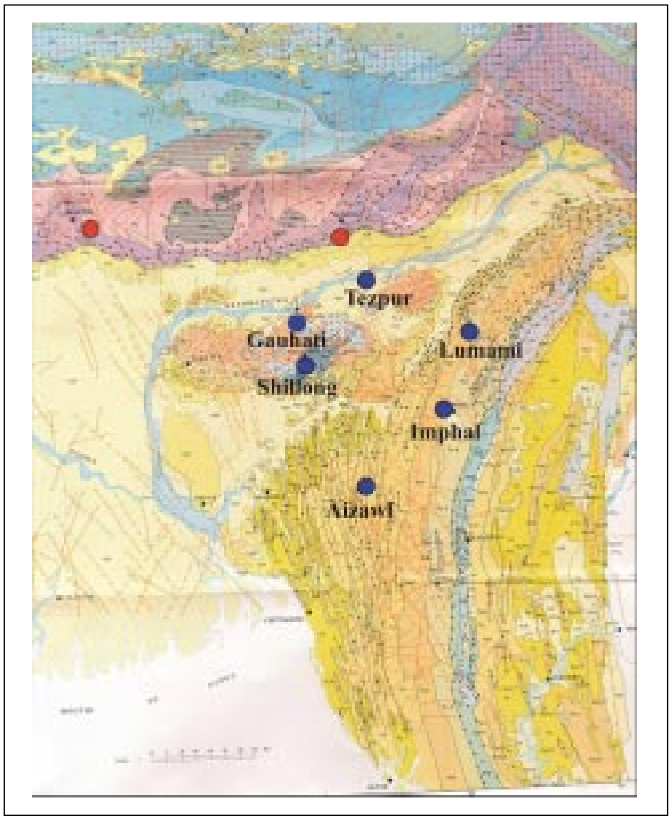

Fig 2.11 Permanent GPS Stations in North-East India

Guwahati Station (GHTU): It is set-up within the Guwahati University Campus located on a pillar approximately 7 m high. This station lies immediately north of Shillong Plateau.

Lumami Station (LUMA): It is set-up within Lumami Campus of the University of Nagaland located near the entrance to the campus on a pillar 6-7 m high.
This station lies in the Naga Schuppen belt within the Indo-Burman Fold-and-Thrust belt.

Shillong Station (CSOS): It is setup within the campus of the Central Seismological Observatory at Shillong, located on a pillar approximately 6m high. This station is located on the Shillong Plateau.

Tezpur Station (Tezp): It is setup on the northern bank of Brahmaputra River and lies between the Himalayan Fold and Thrust belt and Shillong Plateau.

Training has been imparted to local scientists and technical staff for operating the stations and in GPS data processing and analysis. GPS derived coordinates of these sites along with the rms errors (Fig 2.11) are given below

Station	Latitude ± rms (Degrees±mm)	Longitude±rms (Degrees±mm)	Height ± rms (Degrees±mm)	Remarks
Gauhati	26.1 ± 2.3	91.6 ± 1.6	13.1 ± 8.1	10 days
Lumami	26.2	94.4	94	Only 6hr
Imphal	24.7 ± 1.6	93.9 ± 4.2	762.2 ± 8.2	10days
Aizwal	23.7 ± 2.6	92.7 ± 2.1	768.0 ± 5.2	10days
Shillong	25.5 ± 4.1	91.8 ± 4.6	1937.0 ± 11.9	10days

Based on these permanent sites, specific regional GPS studies were taken up by collaborating universities to answer questions related to deformation in the Shillong plateau, the Himalayas and the Indo-Burmese arc. The GPS derived precise coordinates of these sites can be used as reference coordinates for the Campaign mode GPS surveys in the North eastern region. Also the Zenith troposphere delay derived by analyzing the GPS data at these sites can be used for the calculation of precipitable water vapour in the atmosphere.

(Sridevi Jade, Malay Mukul, V K Gaur)

2.9 Active Tectonics in the Arunachal Himalayas

C-MMACS and Tezpur University have initiated GPS study in the Himalayas of Arunachal Pradesh to get a first order estimate of the strain accumulation between the major thrust faults in the area. To begin with, a permanent GPS station has been set up at Tezpur, Assam in the foreland basin of the Arunachal Himalayas in Granites on the northern bank of the Brahmaputra River (Fig 2.12). Next, a campaign mode station was set up at Bomdilla (BOMD), Arunachal Pradesh off the Bomdilla-Dirang Highway in the hanging wall gneisses of the Main Central Thrust (MCT) in the area (Fig 2.12).

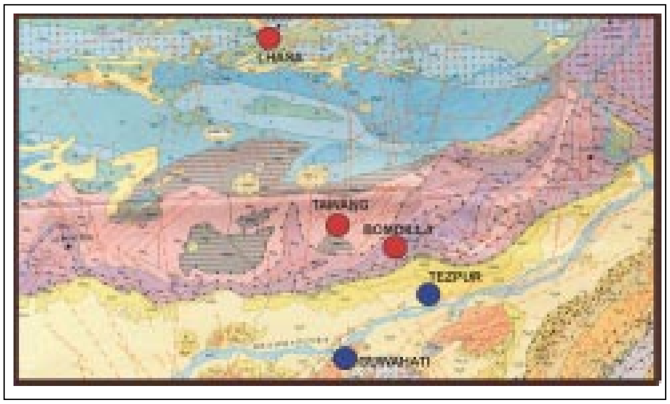

Fig. 2.12 Location of the Tezpur permanent GPS station and the campaign mode stations at Bomdilla and Tawang superimposed on the regional geology of the region. The IGS station at Lhasa and the permanent station at Guwahati on the northern edge of the Shillong Plateau are also shown.

The changes in the length of the Tezpur- Bomdilla baseline computed from future GPS measurements at these sites would provide would estimate the active slip on the Main Boundary Thrust (MBT) in the region. A campaign mode station was also set up at Tawang (TAWA), Arunachal Pradesh on almost sub-horizontal gneiss in the hanging wall of the Main Central Thrust (MCT) in the area (Fig 2.12). The changes in the Bomdilla-Tawang baseline from future GPS measurements would estimate the active slip on the MCT. The changes in the Tawang-Lhasa (IGS Station) baseline would allow us to estimate the active slip in the hinterland of the Arunachal Himalayan Fold-and-Thrust belt. GPS derived coordinates of these points from a single epoch of measurements are given in Fig 2.13 along with their error ellipses. One more epoch of measurements at these sites will give results on baseline changes, velocity vectors as well as deformation in this region.

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2.10 Active Deformation and the Origin of the Shillong Plateau

The Shillong Plateau has been the subject of extensive study over the past decade or so and its origin and deformation history are still being debated. Traditionally, the Shillong Plateau was considered to be a part of the basement involved Dauki Thrust sheet that was transported by the Dauki Thrust in a thin-skinned manner. More recently, it has been suggested that the Plateau was formed by thick-skinned "pop-up" tectonics along two reverse faults; the Dauki and the blind Oldham fault. These two scenarios would require that the Shillong Plateau was formed due to compressive tectonics in the region. However, recent Broadband Receiver Function work has indicated that the crust under the Shillong Plateau is arched into a regional antiform, the top of which constitutes the Shillong Plateau.

To resolve these questions, C-MMACS has initiated GPS Measurements on the Shillong Plateau in collaboration with Tezpur and Gauhati Universities, Assam and Central Seismological Observatory, Shillong. A permanent station was established at Shillong (Fig 2.13) inside the CSO compound in the centre of the Shillong Plateau. Another permanent station was established on the northern edge of the Shillong Plateau in the Gauhati University Campus (Fig 2.13) In addition, 4 campaign mode GPS stations (Fig 2.13) were measured/re-measured in the Shillong Plateau. The GPS station at Shillong Peak was measured for the fourth time. This station indicated southward motion at a rate of 6.3 ± 3.8 mm/year relative to IISc, Bangalore during 1997-99 measurements and remains the highest velocity measured in peninsular India except for the Kachchh Basin. GPS derived ITRF velocity from 2002 measurement of this station is 40± 5 mm/year N39°E and is very different from the velocity of 59±6 mm/year N60°E obtained from 1997-1999 measurements. This may be due to removal of Selective Availability in May 2000. One more epoch of measurement at this station will give more insight in to the problem. The GPS stations (Fig 2.13) at Mun [MUNN],

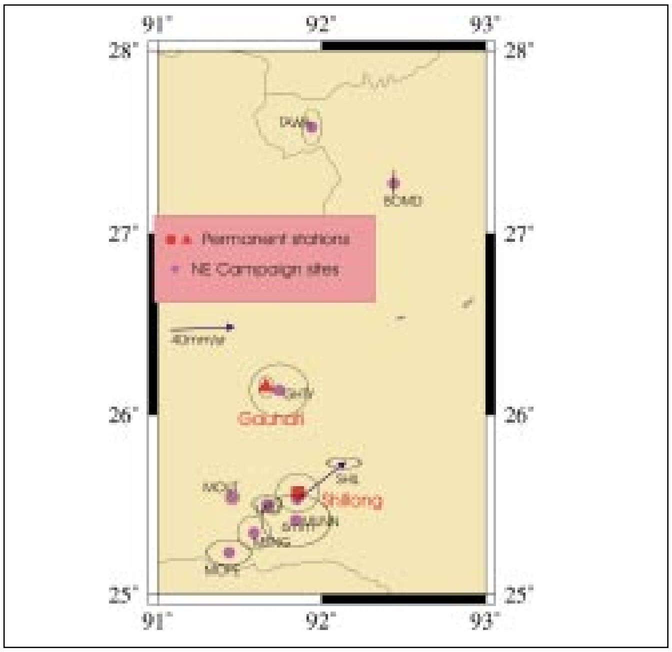

Fig. 2.13 GPS derived coordinates and velocities in Arunachal Himalayas and Shillong Plateau.

Mawpen [MOPE] and Gauhati [GHTY] were set-up during this campaign and measured for the first time. Finally, 3 Great Trigonometrical Survey (GTS) stations (Fig 2.13) of the North East Longitudinal Series were also occupied at LAIDERA [LAID], MAUTHERRICHAN [MOUT], and MOSINGI [MSNG]. Three other GTS stations have also been identified for future occupation at MOPEN, DINGHEI and RANGSANBO. GPS derived coordinates of all these points from a single epoch of measurements are given in figure 5 along with their error ellipses. One more epoch of measurements at these sites will give results on baseline changes, velocity vectors as well as deformation in this region.

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2.11 Active Tectonics in the Darjeeling-Sikkim Himalayas

Seismic data from the Darjeeling-Sikkim Himalayas indicates that several thrust faults and the Gish transverse fault are active in the region . To understand the kinematics of this deformation, C-MMACS set-up three campaign mode GPS stations (Fig 2.14) at DELO, LABHA, MUNGPU in the Darjeeling Himalayas and, in collaboration with GBPIHED, Gangtok, stations at KYONGNOSLA and NAMCHI in the Sikkim Himalayas. The KYONGNOSLA and the LABHA stations are within the Gish Transverse fault zone and measurements made in 2000-2002 at these stations indicate active oblique slip in the Gish fault zone. A new station east of the Gish Transverse Fault (NIMC) was set-up by C-MMACS in 2002 to estimate the slip across the Gish Fault.

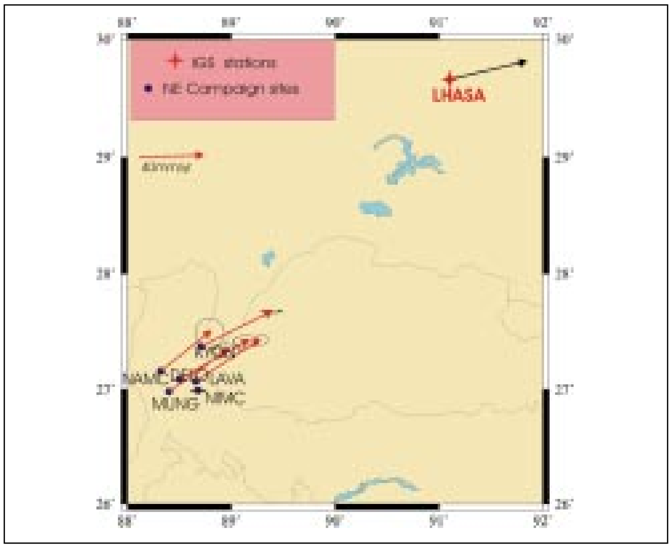

Fig. 2.14 GPS sites and their velocities in Darjeeling-Sikkim Himalayas

Measurements of baselines between the IISC station at Bangalore and the stations in the Darjeeling-Sikkim Himalayas indicates shortening ranging from 2 to 15 mm in the period 2000-2002; the detailed kinematics of this shortening is being currently studied. Preliminary results also seem to suggest that most of this shortening is being taken up in the higher Himalayas. GPS derived ITRF velocities from 2002-2000 GPS measurements of these sites and IGS station (LHASA) is shown in Fig 2.13 along with error ellipses.

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2.12 Active Tectonics in the Narmada Rift Based on Re-measurements of Great Trigonometrical Survey (GTS) Points

The Narmada Rift Basin (NRB) is an east-west basin oriented approximately parallel to the Kachchh Rift Basin. The work done after the 2001 earthquake in the Kachchh Basin has revealed that shortening related to compressive stresses in the Indian Plate gets concentrated in the rift zones that are oriented at high angles to the overall direction of these stresses. Given that earthquakes have occurred within the NRB in the recent past at Jabalpur and Bharuch, the possibility of occurrence of Bhuj type calamity in the NRB needs to be looked into. C-MMACS, in collaboration with the University of Colorado at Boulder, USA, and NGRI, Hyderabad has initiated this work and re-measured 25 GTS stations from the Abu Meridional Series (5), Guzerat Longitudinal Series (12) and Singi Meridional Series (8) of the 1850 Great Trigonometrical Survey during February-March 2003. The stations were chosen along an N-S traverse from Mt. Abu, Rajasthan to Valsad, Gujarat both within and outside the NRB. The initial traverse was done across the western part of the NRB near Bharuch. Future effort will be centered near the central and eastern part of the NRB around Bhopal and Jabalpur respectively.

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2.13 Active Tectonics in the Higher and Tethys Himalayas of Kumaon Region, Uttaranchal

The Malari-Martoli Fault in the Garhwal Region acts as the transition zone between compressional active tectonics in the Higher Himalayas and the extensional active tectonics in the Tethys Himalayas. In an effort to quantify these deformations and look at the kinematics of their transition C-MMACS, in collaboration with the GBPIHED, Almora have set-up 15 campaign mode GPS stations (Fig 2.15) in the region along an approximately N-S traverse. GPS stations have been set up and measured at Chaukadi, Pithoragarh and Bala in the Lower Himalayas Proterozoic sediments, Khaliatop, Munsiari, Lilam, Railgadi, Bog Udiyar, Laspa, Martoli in the Higher Himalayan rocks and Burfu, Berju, Milam and Dung in the Tethys Himalayan rocks. Chaukadi, Pithoragarh and Bala are stations in the footwall of the Main Central Thrust (MCT) where as Khaliatop and Munsiari stations are in the MCT fault zone. Lilam, Railgadi, Bog Udiyar are in the hanging wall of the MCT. Martoli and Burfu are stations in the Martoli fault zone and Berju, Milam and Dung are stations in the hanging wall of the Martoli fault. Future re-occupations of these stations should allow us to look into the kinematics of shortening and elongation in the region and the transition between the two.

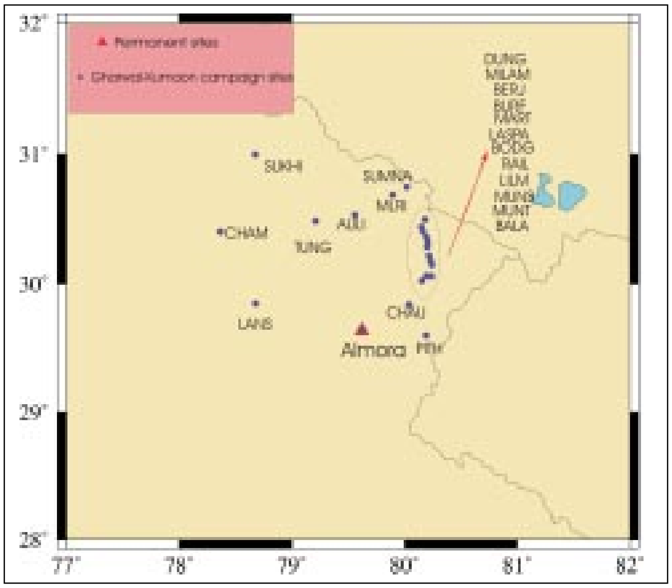

Fig. 2.15 GPS Campaign and permanent sites in Central Himalayas

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2.14 Analysis, Interpretation and Modelling of the GPS Data Generated from National Network Stations

These GPS sites established as a part of envisaged national network (Fig. 2.16) can answer specific questions related to regional deformation. The GPS data collected at these sites when processed will give precise coordinates and velocities of these sites which can be used as reference coordinates for the regional Campaign mode in the country. Also the Zenith troposphere delay derived by analyzing the GPS data at these sites can be used for the calculation of Precipitable water vapor in the atmosphere. The GPS derived velocities of these sites form a key input for the earthquake hazard quantification in the north-east.

As a first step towards analyzing the GPS data collected at the permanent network sites, C-MMACS has processed the GPS data of year 2000, 2001 and 2002 of the network sites established by C-MMACS (Fig 2.16) to give the precise coordinates and velocities. Preliminary results of GPS derived coordinates and velocities in the ITRF 2000 reference frame of the network sites along with the IGS sites are given in Fig 2.16. ITRF velocities of Bangalore and KodaiKanal are approximately same as Indian plate velocity and the motion of Leh, Hanle and Almora are consistent with the regional deformation in that region.

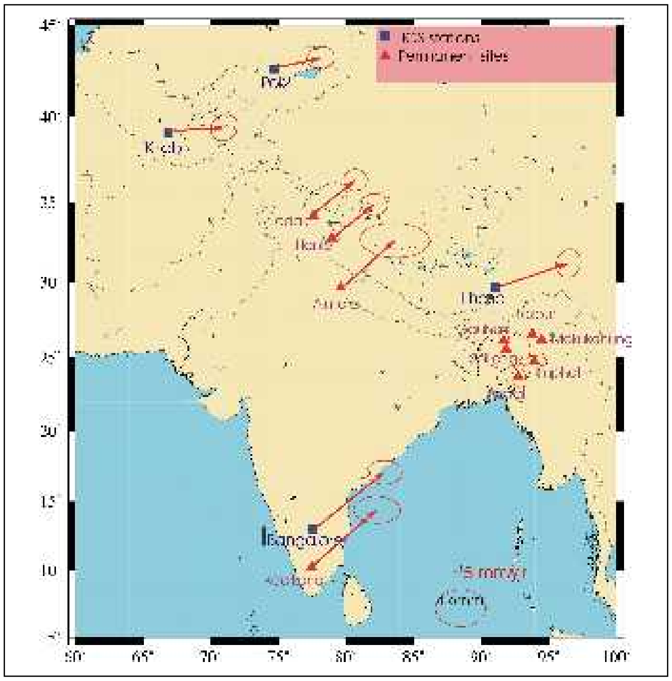

Fig. 2.16 GPS derived coordinates and velocities of C-MMACS Permanent network sites and IGS sites

This analysis when extended to national network stations on a regular basis would give good reference points for regional campaigns as well as to get an overall picture of deformation in Indian subcontinent. The results arising from GPS data analysis of permanent stations of the national network will also help model the dynamics of Indian Subcontinent.

Precipitable Water vapor content (PWV) in the atmosphere has been estimated using the GPS data at IISc and Hanle to study the feasibility of such an exercise. The PWV for one month for both the stations has been determined (Fig 2.17). Precipitable Water vapor content (PWV) in the atmosphere has been estimated using the Total troposphere delay obtained from the analysis of GPS data at two permanent sites at Bangalore and Hanle (Fig 2.17).

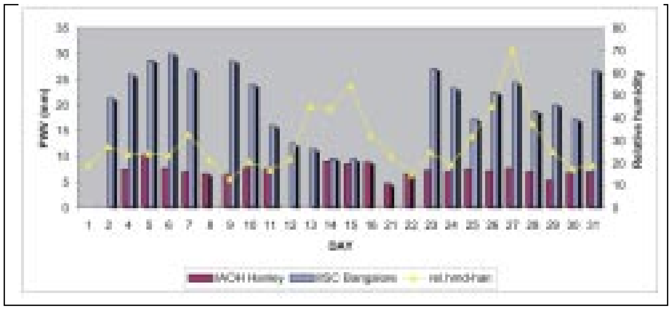

Fig. 2.17 PWV over IISC and IAOH in comparision with relative humidity

PWV estimation needs to be extended to see the variation of water vapor content for one year i.e. January to December at these two sites. Estimation of Precipitable Water vapor content (PWV) in the atmosphere using the GPS data of national network stations will go a long way to design experiments to implement troposphere water vapor tomography. PWV estimation can be extended to all the C-MMACS run permanent GPS stations to see the variation of water vapor content at these sites. If daily pressure, temperature and relative humidity can be measured at some of the national network sites in north east would help a long way in determining the variation of water vapor content in the atmosphere.

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