JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.75, January 2010, pp.302-312

Crustal Shortening in Convergent Orogens: Insights from Global Positioning System (GPS) Measurements in Northeast India

MALAY MUKUL[1,4], SRIDEVI JADE[1], ANJAN KUMAR BHATTACHARYYA[2] and KUNTALA BHUSAN[3]
[1]CSIR Centre for Mathematical Modelling and Computer Simulation, Bangalore - 560 037
[2]Department of Physics, Tezpur University, Tezpur - 784 028
[3]North East Space Application Centre, Umiam - 793 103, Meghalaya
[4]Department of Earth Sciences, Indian Institute of Technology-Bombay, Mumbai - 400 076
Email: mlym@cmmacs.ernet.in; malaymukul@iitb.ac.in

Abstract: Deformation in active mountain belts like the Himalaya is manifested over several spatial and temporal scales and collation of information across these scales is crucial to an integrated understanding of the overall deformation process in mountain belts. Computation and integration of geological shortening rates from retrodeformable balanced cross-sections and present-day convergent rates from deforming mountain belts is one way of integrating information across time-scales. The results from GPS measurements carried out in NE India indicate that about 15-20 mm/yr of convergence is being accommodated there. Balanced-cross sections from the NE Himalaya indicate about 350-500 km of shortening south of the South Tibet Detachment (STD). Geothermobarometry suggest that the rocks south of the STD deformed under peak metamorphic conditions at ~ 22 Ma. This indicates a geological convergence rate of ~ 16-22 mm/yr which appears to be fairly consistent with the GPS derived convergence rates. Approximately 1.5 to 3.5 mm/yr (~ 10-20 %) of the total N-S of the present-day convergence in the NE Himalaya is accommodated in the Shillong Plateau. In addition, ~ 8-9 mm/yr of E-W convergence is observed in the eastern and central parts of the Shillong Plateau relative to the Indo-Burman fold-thrust belt. Balanced cross-sections in the Indo-Burman wedge together with higher resolution GPS measurements are required in the future to build on the first-order results presented here.

Keywords: GPS Geodesy, North East Himalaya, Geological Shortening, Convergence, Active Tectonics.

INTRODUCTION

Deformation in mountain belts like the Himalaya is manifested over several different spatial and temporal scales. Spatial scales range from Plate scale (1000s km) to Fault zone scale (< 1 km) and temporal scales range from deformation in rocks and sediments in geological time scale (tectonics, structural geology and neotectonics) to earthquakes (seismology) in recent time scales (e.g. Mukul, 2005 and references therein). Global Positioning System (GPS) based geodesy has provided additional insight into the traditional sources of knowledge on continental deformation by providing data related to youngest or present-day time scales (active or contemporary tectonics). This makes it an invaluable tool for studying deformation in mountain belts over time-scales that affects the human society. It has implications for the understanding of seismic hazard that directly affect the human society. Nevertheless, the various components of information related to deformation in mountain belts over different space and time scales have not been integrated to the extent necessary. This is despite the fact that all the data collected over different space and time scales are manifestations of the same deformation and an integrated understanding of the deformation in mountain belts is necessary for addressing related hazards that the human society is likely to encounter. The challenge, therefore, is to work towards finding ways to integrate data across space and time scales, both qualitatively and quantitatively, to understand deformation in mountain belts. This paper suggests that in convergent mountain belts like the Himalaya, the computation of shortening accommodated over geological and recent time scales is one way to integrate deformation through time. The role of GPS based convergence computations and their comparison with geologically computed shortening rates has been discussed. Finally, this methodology has been applied to studies in North Eastern India and resulting insights and implications have been highlighted.

Geological Crustal Shortening

Relative motion between converging plates results in stress accumulation within the plates as well as along their common boundary. The plates undergo rotational motion on a spherical earth. Therefore, poles along which the plates rotate as well as the rates at which the plates converge are important questions to address at the Plate scale (e.g. Mukul et al. 2009; Jade et al. 2007 and references therein). The boundary between two convergent plates is subject to intense shortening that typically develops into a wedge-shaped (Fig.1) fold-thrust belt (e.g., Dahlen, 1990; Mitra, 1997 and references therein). The dimension of this wedge is typically of the order of 100 km. The critical wedge theory has evolved as the paradigm for understanding the deformation in compressive wedges. The critical wedge theory invokes cyclic deformation in the wedge in dynamic equilibrium with erosion (Dahlen, 1990; DeCelles and Mitra, 1995). Thrust faults and fault-related folds develop in the wedge defining a fold-thrust belt. The geometry of these fault-related structures (e.g. Boyer and Elliott, 1982) is primarily controlled by the relative difference between the propagation and slip rates on the thrust faults that develop in the wedge

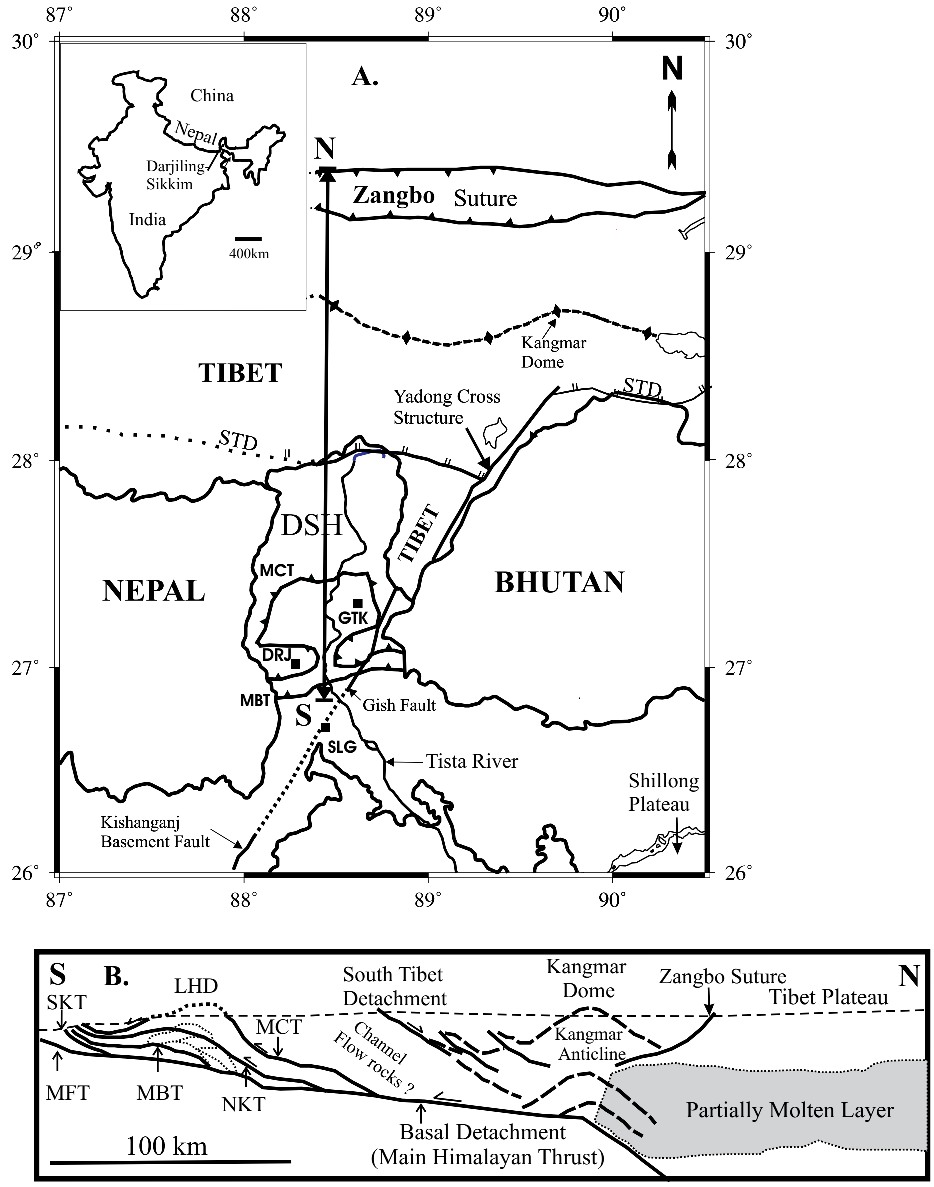

Fig.1. The Darjiling-Sikkim-Tibet (DaSiT) Himalayan wedge (A) Map-view of the DaSiT Himalayan wedge. The Himalayan wedge is best constrained in the DaSiT area as the hinterland geometry has been worked out during the INDEPTH project (Nelson et al. 1996). *Symbols:* Main Boundary Thrust (MBT); Main Central Thrust (MCT); DRJ-Darjiling; DSH-Darjiling-Sikkim Himalaya; GTK-Gangtok; MBT-Main Boundary Thrust; STD-South Tibet Detachment; LHD-Lesser Himalayan Duplex. (B) Cross-sectional view (N-S in (A)) of the Darjiling-Sikkim-Tibet wedge showing the major faults and first-order structures (*after* Nelson et al. 1996; Mukul, 2000). MFT-Main Frontal Thrust; NKT-North Kalijhora Thrust (Equivalent to Ramgarh Thrust of DeCelles et al. 1998).

(McNaught and Mitra, 1993). A compressive wedge can, consequently, be visualized as an aggregate of thrust sheets that are transported by thrust faults. A thrust fault and the volume of rock or sheet carried by it is, therefore, the basic structural unit of a wedge. A thrust sheet typically has a dimension in the order of 10s of km and the thrust fault that transports the sheet in its hanging wall has a fault zone typically in the order of 1 km or less.

The shortening accommodated in the deforming wedge-shaped boundary can, therefore, be measured by computing the sum total of the total displacement vector associated with each of the thrust sheets in the wedge. The total displacement vector consists of translation, rotation and pure strain components (Mitra, 1994) and the quantification of each of these components for every thrust sheet in the wedge is the key to computing the total shortening in the wedge. The wedge can be retrodeformed to its initial geometry using these numbers and retrodeformable balanced cross-section of the wedge constructed (e.g. Mitra, 1994; McNaught and Mitra, 1996). Balanced cross-sections have been constructed for the Himalayan wedge too (e.g. Srivastava and Mitra, 1994; DeCelles et al. 2002; McQuarrie et al. 2008; Mitra et al. 2010) but all of them are based on removal of only the translation and rotation components of the total displacement vector and not the pure strain component. Given that strain accommodation in mountain belts takes place over different spatial scales (e.g. Wu, 1995; Mitra, 1994; Mukul, 1998; Mukul and Mitra, 1998; Mukul et al. 2004) the shortening estimates in the Himalaya from balanced cross-sections can only be a minimum estimate. In addition, it has been established that strain in mountain belts is likely to be three-dimensional in its hinterland (e.g. Mukul, 1999; Mookerjee and Mitra, 2008). This suggests that although across-strike or along-transport shortening rates are typically computed, eventually, both along- and across-strike shortening rates need to be looked at.

Accommodation of Geological Shortening in a Deforming Wedge: An insight into the along-transport accommodation of shortening in a deforming wedge has been provided by the symptomatic critical wedge theory (DeCelles and Mitra, 1995; Mitra, 1997). This theory postulates three stages in a naturally deforming wedge; the wedge cycles through these stages in time until it is no longer active. The equilibrium stage of a deforming wedge is the critical state (Fig.2) where the wedge is able to move along its basal-detachment in a stick-slip manner. Minimal internal deformation is observed within the existing geometry of the deforming wedge during this stage implying

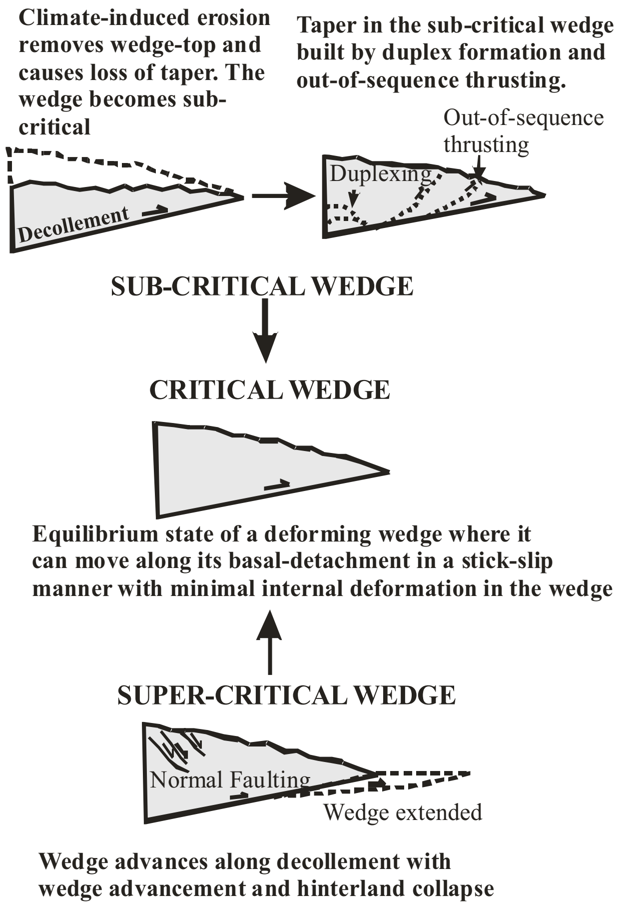

Fig.2. Critical wedge model for deformation in a wedge (*after* Mitra, 1997), showing deforming wedge cycles through super-critical, critical and sub-critical states. Only critical, steady-state wedges can advance along the décollement with minimal internal deformation.

that most of the shortening is accommodated in overcoming the basal friction for foreland-ward slip along the basal detachment. According to the critical wedge theory (Dahlen, 1990), the wedge deforms in dynamic equilibrium with climate which induces erosion of the wedge-top. Erosion of the wedge-top results in loss of taper in the wedge causing it to become sub-critical, which needs to deform internally and build taper to reach the critical state (DeCelles and Mitra, 1995). Therefore, shortening in a sub-critical wedge is accommodated in rebuilding lost taper. This accommodation typically occurs at the back-end of the wedge through formation of duplexes or fault-related-folds (Mitra, 1997) and/or out-of-sequence deformation (e.g. Mukul, 2000; Mukul et. al. 2007).

Shortening or Convergence Rate Computations from Global Positioning System Based Measurements

The Global Positioning System (GPS) has been used in high-precision geodesy and for continental deformation studies to measure tectonic motions during and in between earthquakes (e.g. Hoffmann-Wellenhof et al. 1997; Bilham and Gaur, 2000). A GPS based network measures the millimeter-scale movements of the crust between and during great earthquakes (Magnitude ≥ 7.0). This is done by examining the total distance that a station has moved during a great earthquake by comparing its position prior to the event with its position following the event (e.g. Jade et al. 2002; 2003). For measurements made in between two great earthquakes (or interseismic deformation), displacement of a station through time is studied (e.g. Jade et al. 2007 and references therein).

***GPS based Geodesy in continental deformation studies*:** In GPS measurements, the vertical accuracies are lower than the horizontal. The former are often too low to be useful for deciphering vertical motions. Given this, the use of GPS for continental deformation studies is likely to work best in settings where the dominant displacement due to deformation is horizontal as in strike-slip settings such as the San Andreas Fault system in the western United States. In other settings, such as the Himalaya, such studies suffer from the drawback that vertical component of the total displacement vector of a given station, typically, cannot be ascertained to the required level of accuracy and only the horizontal velocity and the longitudinal shortening of baselines (convergence) is reported.

GPS measurements involve the estimation of very short-term, active deformation starting from the day a station is set-up and measured for the first time. Given that the GPS methodology became reliable only by 1994, GPS gives information on the on-going deformation in any part of the earth through a maximum time period of 15 years (1994-2009). Displacement of stations is monitored from the day a station is initially set-up either in permanent station mode or in campaign mode wherein the station is measured, typically, once every year. The deformation path associated with the GPS measurements is multi-state, dated and almost continuous limited only by the discrete sampling interval specified for data collection (Mukul, 2005). The convergence or shortening between any two stations is computed by the change in length of an imaginary baseline joining the two stations as a result of their displacements over a period of time. This is the best form of deformation path data available and readily allows computation of averaged daily, weekly, monthly, quarterly, half-yearly, yearly etc. convergence rates between stations as well as variations in the rates before, during and after great seismic events. The only limitation we have is that in terms of the time-scales involved. In the geological deformation of even the youngest mountains on earth such as the Himalaya (deforming since ~ 50 Ma), GPS data does not cover any significant time-span. Despite this, it has already given considerable insight into the current on-going deformation patterns in different parts of the earth (e.g. Wang et. al. 2001). However, caution must be exercised in attempting to extrapolate GPS results in space and time because it is likely to involve simplifications that may not be realistic. In a setting like the Himalaya, where there is complex interaction between different mechanisms of deformation in space and time, GPS convergence rates and velocities must be sufficiently time-averaged to make them representative and realistic.

GEOLOGICAL SHORTENING IN THE HIMALAYAN WEDGE

Shortening Estimates in the Himalayan Wedge

The Himalayan orogen forms an almost perfect arc (Bendick and Bilham, 2001) and extends for ~2500 km between the northwestern Hazara and southeastern Namche Barwa syntaxes. It is generally accepted that the convergence in the Himalaya is arc-perpendicular (e.g. Ni and Barazangi, 1984; Molnar and Lyon-Caen, 1989) and the convergence between India and Eurasia progressively increases from west to east (e.g. Klootwijk et. al. 1985; McCaffrey and Nabelek, 1998). Much of the Indo-Eurasian convergence is accommodated in the uplift of the Tibet plateau. However, a significant portion is accommodated in shortening structures in the Himalayan orogen (DeCelles et. al. 2002). In fact, 770 ± 190 km (DeCelles et. al. 2002) of shortening is estimated for the total shortening south of the Indus suture in the entire Himalayan wedge range. About 75% of this shortening is actually accommodated south of the South Tibet Detachment (STD) in the Himalayan wedge as evident from 350-400 km shortening in Garhwal-Kumaon Himalaya (Srivastava and Mitra, 1994), and 400-500 km in western Nepal (DeCelles et al. 1998; 2001).

Shortening Estimates in the NE Himalayan Wedge

Balanced cross-sections have not been constructed in the northeastern Himalaya until very recently (McQuarrie et al. 2008; Mitra et al. 2010). In the NE Himalaya, a minimum shortening of 359 km in the Bhutan Himalaya from 22 Ma to present (McQuarrie et al. 2008), and ~ 500 km in the Darjiling-Sikkim Himalaya (Mitra et al. 2010) have now been recognized. This implies variations in shortening accommodated in the NE Himalayan wedge. Other deformation mechanisms such as slip along transverse faults

(Mukul et al. 2009) that also accommodate some of the convergence in the northeastern Himalaya have also been postulated. These uncertainties need to be addressed in the region to understand how convergence between the Eurasian and Indian plates is accommodated across and along their wedge shaped Himalayan boundary.

CONVERGENCE RATES IN THE NORTHEAST INDIAN REGION

First order GPS based convergence rates have earlier been computed and reported from the NE region (Jade et al. 2007; Mukul et al. 2009). The convergence rate in the western Arunachal Himalaya and the Bhutan Himalaya was measured as ~15 mm/yr and ~ 16.6 mm/yr respectively relative to Lhasa (Jade et al. 2007). The convergence rate measured by GPS and computed from balanced cross-section (McQuarrie et al. 2008) in the Bhutan Himalaya are, therefore, very similar indicating that the convergence rate of 16 mm/yr has been fairly consistent over time in the Bhutan Himalaya. In addition, varying degrees of convergence are observed between the stations in the eastern flank of the Indo-Burman range and the rest of the foreland in northeast India (Jade et al. 2007). Finally, in the Darjiling-Sikkim Himalaya, a convergence of 12.32±1.16 mm/yr has been observed relative to Lhasa. However, the Darjiling-Sikkim and Lhasa baselines are oblique (trend N 40 E) to the arc and cannot yield shortening rates across the Himalaya. Assuming that the maximum convergence would be accommodated perpendicular to the arc (e.g. Ni and Barazangi, 1984; Molnar and Lyon-Caen, 1989) and that the oblique convergence observed along the Darjiling-Sikkim and Lhasa baselines is a component of the maximum convergence, the arc perpendicular convergence is estimated to be ~16 mm/yr. This is consistent with the arc-perpendicular shortening estimated in central Bhutan (Jade et al. 2007). However, arc-perpendicular convergence estimates must be made by actual measurements to validate this computation.

This section presents additional GPS data from NE India and takes a closer look at the convergence rates in the region and addresses the following issues that pertain to the seismogenic potential of the region: (a) The variation in convergence in the Himalayan wedge in northeast India, (b) The nature of convergence accommodation in the Shillong Plateau, and (c) Deformation in the Indo-Burman range.

GPS Measurements and Data Analysis

Campaign mode as well as permanent station data (Table 1) was collected mostly during the period 2003-2006 to address the issues listed above. The data collected were converted into rinex observation files and quality check plots of all the GPS data were carefully examined and only the data that did not have cycle slips, was not affected by multi-path interference and measured over a time-period of > 12 hr was used for the analysis. Sampling interval of 30 seconds and satellite elevation cut off angle of 15° was used for collecting data. The data were processed together with International GNS (Global Navigation Satellite Sytems)

Table 1. Coordinates and ITRF 2000 Velocities of GPS Stations for the NE India

Station (^ Permanent IGS Station)	Latitude (º N)	Longitude (ºE)	Velocity (E) (mm/yr)	Velocity (N) (mm/yr)	Composite Velocity (mm/yr)	
IISc^	13.02	77.57	40.82±0.7	32.16±0.5	51.97±0.6;	N51.75±0.6E
Lhasa^	29.66	91.10	44.57±0.6	12.16±0.6	46.20±0.6;	N74.71±0.2E
Nim	27.00	88.68	36.83±0.8	31.41±0.6	48.41±0.8;	N49.54±0.9E
Mungpu	26.98	88.40	36.25±0.5	32.03±0.4	48.37±0.4;	N48.54±0.5E
Kanu	24.56	87.83	37.08±2.8	33.36±1.6	49.88±2.3;	N48.02±2.5E
Tura	25.53	90.21	35.30±0.5	37.50±0.6	51.50±0.6;	N46.73±0.6E
Mopen	25.23	91.44	37.20±0.8	30.70±0.6	48.23±0.7;	N50.47±0.8E
Silchar	24.89	92.59	39.87±3.3	30.43±1.7	50.15±2.8;	N52.65±2.8E
Guwahati	26.14	91.74	37.10±0.8	26.20±0.6	45.42±0.7;	N54.77±0.9E
Guwahait Univ.	26.15	91.66	37.00±0.4	28.80±0.4	46.89±0.4;	N52.10±0.5E
Tezpur	26.62	92.78	37.38±0.3	26.19±0.4	45.64±0.3;	N54.98±0.5E
Kanu	24.56	87.83	37.08±2.8	33.36±1.6	49.88±2.3;	N48.02±2.5E
Munn	25.41	91.84	37.70±0.8	28.50±0.6	47.26±0.7;	N52.91±0.8E
Lumami	26.22	94.48	32.60±0.5	18.55±0.4	37.51±0.5;	N60.36±0.6E
Imphal	24.75	93.93	26.54±0.6	18.63±0.4	32.43±0.5;	N54.93±0.8E
Aizawl	23.72	92.73	31.61±0.4	28.57±0.4	42.61±0.4;	N47.89±0.5E
Durgapur	23.53	87.31	35.90±2.3	34.15±1.2	49.55±1.9;	N46.43±2.1E

Service (IGS) station data using GAMIT/GLOBK software (King and Bock, 2000). In GAMIT, Zenith tropospheric delay for each station was estimated by incorporating a piecewise-linear model with stochastic constraints and then corrected for the signal delay due to troposphere. Ambiguity free and ambiguity fixed solutions were performed with ionosphere free linear combination to account for carrier phase ambiguities and signal delay due to ionosphere. The daily coordinates and velocities of all permanent and campaign sites were estimated in the ITRF 2000 reference frame (Altamimi et al. 2002) by constraining IGS reference station positions and velocities in the region to reported values in that frame with standard errors provided by IGS. Velocities of all campaign sites (Table 1; Figs.3 and 4) were obtained in the ITRF 2000 reference frame from three to four epochs of GPS data sets collected over 3 continuous days. Permanent station velocities were obtained in the same frame by processing 3 years of data from each site. Changes in baseline lengths (Table 2) over the measured time interval were computed to work out the shortening accommodated between each station pair.

Convergence in the Himalayan Wedge in Northeast India

A convergence of 12.32±1.16 mm/yr has been observed relative to Lhasa in the Darjiling-Sikkim Himalaya (Mukul et al. 2009). This is supported by the ~13 mm/yr shortening

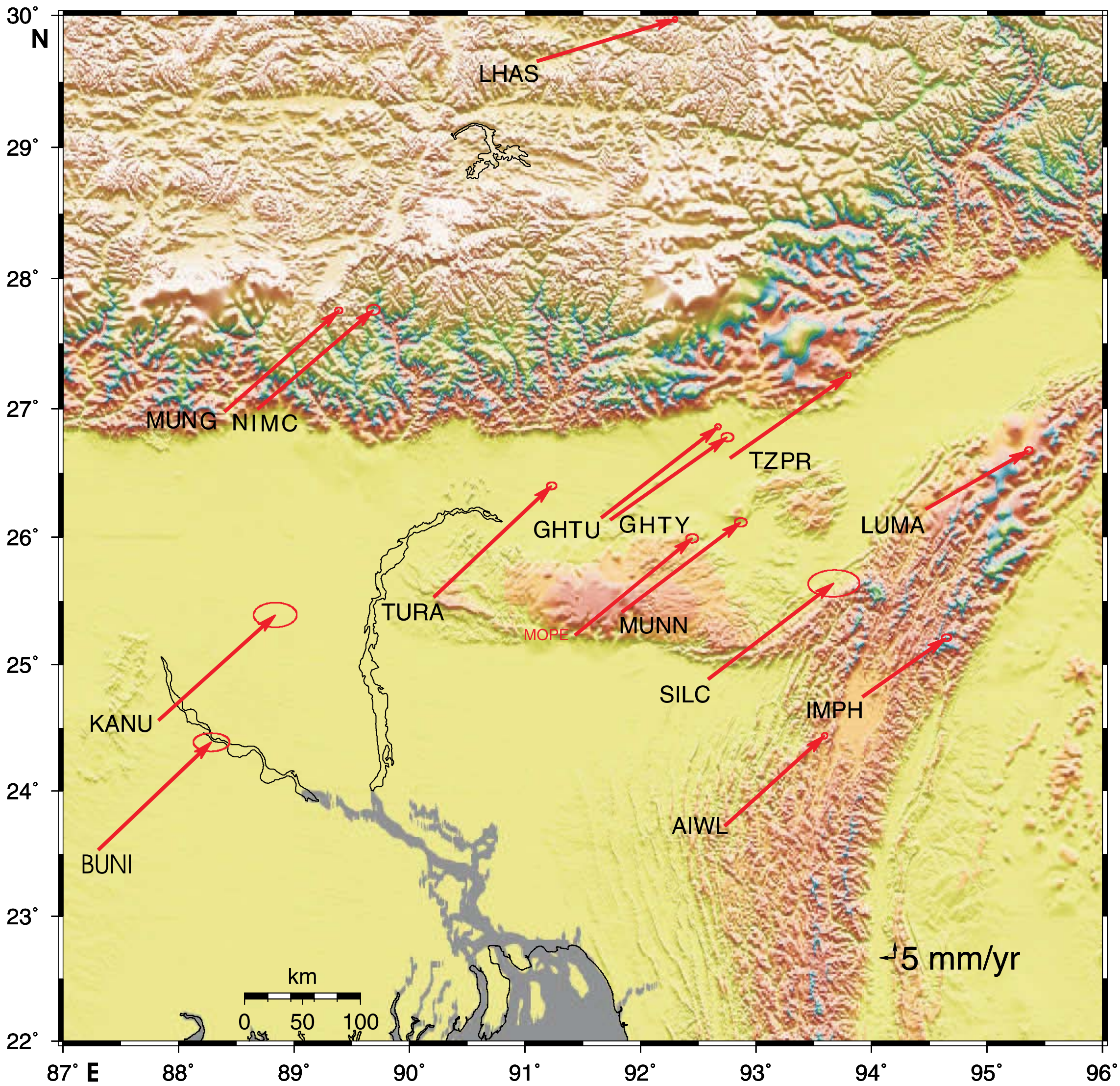

Fig.3. Northeast India GPS sites with ITRF 2000 (Altamimi et al. 2002) velocities with uncertainty ellipses. LHAS (Lhasa) is an IGS station. GHTU (Guwahati University), TZPR (Tezpur), LUMA (Lumami), IMPH (Imphal), and AIWL (Aizawl) are 24X7 permanent stations. MUNG (Mungpu), NIMC (Nim), KANU (Kanupur), BUNI (Durgapur), TURA (Tura), MOPE (Mopen), MUNN (Mun), GHTY (Guwahati) and SILC (Silchar) are campaign mode stations.

observed along the Kanu-Lhasa or IISc-Lhasa baselines as both Kanu and IISc stations are located south of the Himalaya. Similarly, Mungpu-Lhasa and Nim-Lhasa baseline changes are good proxies for the interseismic convergence accommodated in the Darjiling-Sikkim Himalayan wedge (Tables 1 and 2, Fig.5) as Mungpu and Nim are located very close to the Himalayan mountain front. The observed ~8.5-9 mm/yr convergence of the Mungpu-Lhasa and Nim-Lhasa baselines indicate that most of the ~13 mm/yr convergence is actually accommodated in the Darjiling-Sikkim Himalayan wedge. However, as discussed earlier, these convergence estimates are made from oblique baselines and represent only a component of the arc-perpendicular convergence, which was estimated to be about ~16 mm/yr. Therefore, arc-perpendicular measurements must be carried out in the Darjiling-Sikkim Himalaya to accurately compute the convergence in the Darjiling-Sikkim Himalayan wedge.

Farther east, in the Bhutan Himalaya, an arc-perpendicular convergence of ~20 mm/yr has been observed along the Tura-Lhasa baseline (Tables 1 and 2, Fig.6). This estimate includes convergence accommodated within the western part of Shillong Plateau. This indicates a jump in the amount of convergence east of 89°E longitude from ~16 mm/yr to ~20 mm/yr in the eastern Himalaya given that the campaign station Kanu (24.6° N) is located south of the Tura (25.5° N) station. Farther east of Tura, ~ 17 mm/yr of N-S arc-perpendicular convergence is observed in the central elevated part as well as the eastern part of the Shillong Plateau as evident from changes in the length of the baselines joining Lhasa and the southern most stations in the Shillong Plateau viz. Mopen and Silchar. Only ~1.5 to 3.5 mm/yr of

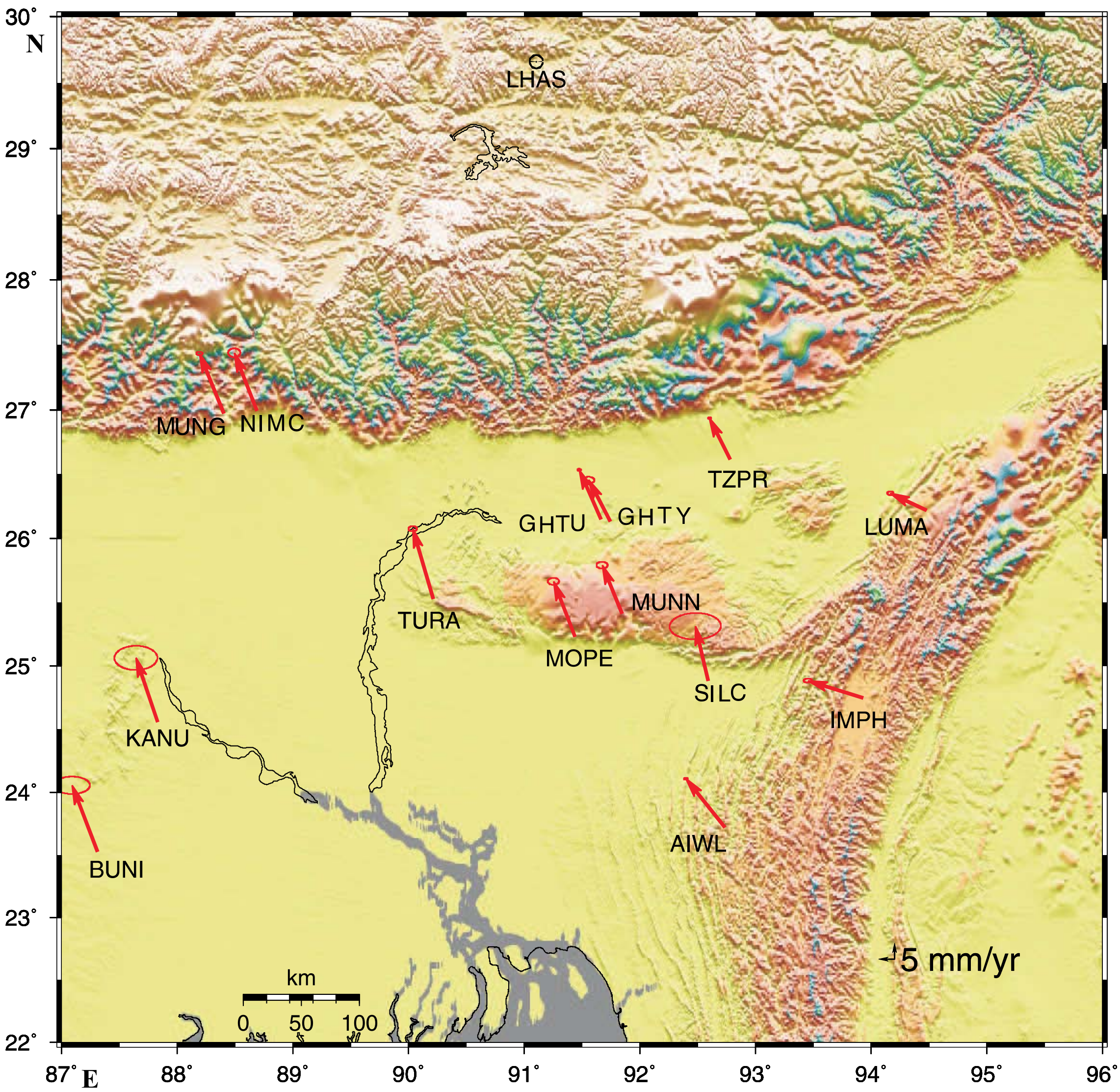

Fig.4. Northeast India GPS sites with LHAS (Lhasa) fixed velocities with uncertainty ellipses. Station codes same as in Fig.3.

Table 2. GPS convergence (shortening) rates in different parts of NE Himalaya

Baseline	Convergence mm/yr
GPS Convergence (Shortening) rates in the Darjiling-Sikkim Himalayan wedge	
IISc-Lhasa	12.97±0.11
Lhasa-Kanu	12.85±2.02
Lhasa-Mungpu	08.45±0.32
Lhasa-Nim	09.10±0.68
GPS Convergence (Shortening) rates in the Bhutan-Arunachal Himalayan wedge	
Lhasa-Tura	20.31±0.35
Lhasa-Mopen	17.76±0.46
Lhasa-Silchar	17.62±1.89
Lhasa-Tezpur	15.03±0.12
Guwahati Univ.-Mopen	01.74±0.48
Guwahati-Mopen	04.11±0.66
GPS Convergence (Shortening) rates in the Indo-Burman wedge	
Tezpur-Lumami	03.09±0.41
Mopen-Imphal	08.49±0.90
Munn-Imphal	07.81±0.87
Tura-Imphal	08.10±0.77
Munn- Tura	00.34±0.89
Mopen-Tura	00.59±0.90
Durgapur-Aizawl	05.55±2.36
Imphal-Aizawl	10.50±0.46

the ~17 mm/yr N-S convergences is presently being accommodated within the Shillong Plateau as evident from the changes in the lengths of the Guwahati-Mopen baselines. Also, ~15 mm/yr of convergence is accommodated within the Arunachal Himalaya as seen from the Tezpur-Lhasa baseline shortening (Table 2, Fig.6).

Accommodation of N-S convergence in the NE Himalayan wedge appears to be range bound (~15-20 mm/yr). The spatial variation of the convergence in the NE Himalayan wedge needs to be worked out in detail following these first-order studies as they will have important implications on the seismic potential of the region. The accommodation of N-S convergence needs to be understood together with the possible E-W convergence in the Indo-Burman ranges that is discussed below.

Convergence in the Indo-Burman Ranges in Northeast India

The Indo-Burman range defines a N-S trending fold-thrust belt with east-to-west transport of thrust sheets along east-dipping thrust faults. The frontal part of this Indo-Burman fold-thrust belt (IBFTB) exhibits salient-recess geometry (Macedo and Marshak, 1999; Jade et al. 2007). The fold-thrust belt is believed to be overprinted by strike-slip tectonics along the Saigang fault (e.g. Satyabala, 1998; Nandy, 2001; Cummins, 2007) implying no east-west compression and hence no active subduction. GPS measurements in Myanmar (e.g. Vigny et al. 2003), however, have suggested that only 60% of the relative plate motion between the Indian plate and southeast Asia is accommodated on the Sagaing fault. It has also been suggested that the rest 40% of the relative plate motion is accommodated by active convergence and thrusting west of the Saigang fault (Cummins, 2007).

GPS measurements in the frontal part of the IBFTB in north-east India indicate that E-W compression is active and varies from north to south along the length of the IBFTB. There is ~ 3mm/yr of E-W convergence between Tezpur and Lumami in the northern part of the IBFTB (Table 1 and 2, Fig.6). The convergence increases to ~8 mm/yr between Mopen-Imphal as well as Munn-Imphal near the central part of the IBFTB. Also, given that the Tura-Imphal baseline is also shortening at the rate of ~8 mm/yr, the eastern and central parts of the Shillong Plateau are accommodating both N-S as well as E-W convergence and the western part of the plateau is primarily accommodating N-S convergence. This is also evident from negligible E-W shortening along the Munn-Tura and Mopen-Tura baselines. In the southern part of the IBFTB in the Tripura salient, an E-W convergence of ~ 5 mm/yr is observed between Durgapur and Aizawl. N-S convergence of ~ 10 mm/yr between Aizawl-Imphal is also observed, which again, points to a variation in accommodation of shortening along the length of the IBFTB (Table 1 and 2, Fig.6). These results suggest that the deformation in the IBFTB is segmented into N-S blocks along E-W transverse zones exhibiting dextral slip between Imphal and Lumami and sinistral slip between Imphal and Aizawl (Jade et al. 2007). Several transverse faults (e.g. Mat fault, Gumti fault etc.) have been reported from the IBFTB (Nandy, 2001). The results presented above suggest active slip along some of these faults.

The above results, therefore, clearly indicate that the E-W convergence in the frontal part of the IBFTB is active. However, there is a variation in the amount of (a) convergence that is accommodated along the length of the IBFTB and (b) active slip along E-W transverse faults.

CONCLUSIONS

Deformation in mountain belts like the Himalaya is manifested over several different spatial and temporal scales. Collation of information across these scales is crucial to an integrated understanding of the overall deformation in the

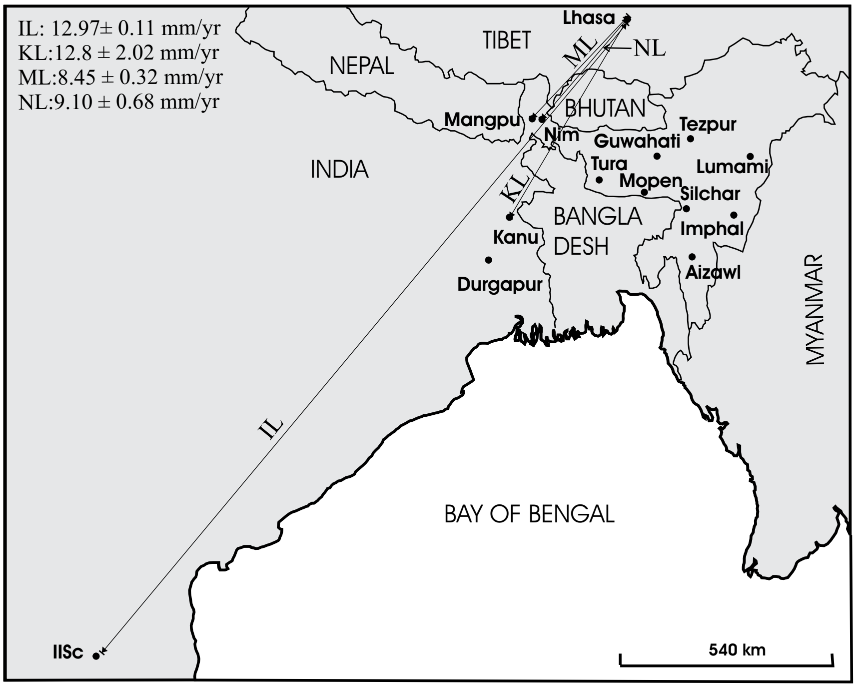

Fig.5. Convergence accommodation in the Darjiling-Sikkim-Tibet Himalayan wedge. About 9 mm/yr of interseismic convergence is being accommodated in the Darjiling-Sikkim-Tibet Himalayan wedge out of a maximum 13 mm/yr of convergence between Bangalore and Lhasa. However, these estimates are along baselines that are oblique to the Himalayan arc and are treated as components of the arc-perpendicular convergence that is estimated to be ~ 16 mm/yr.

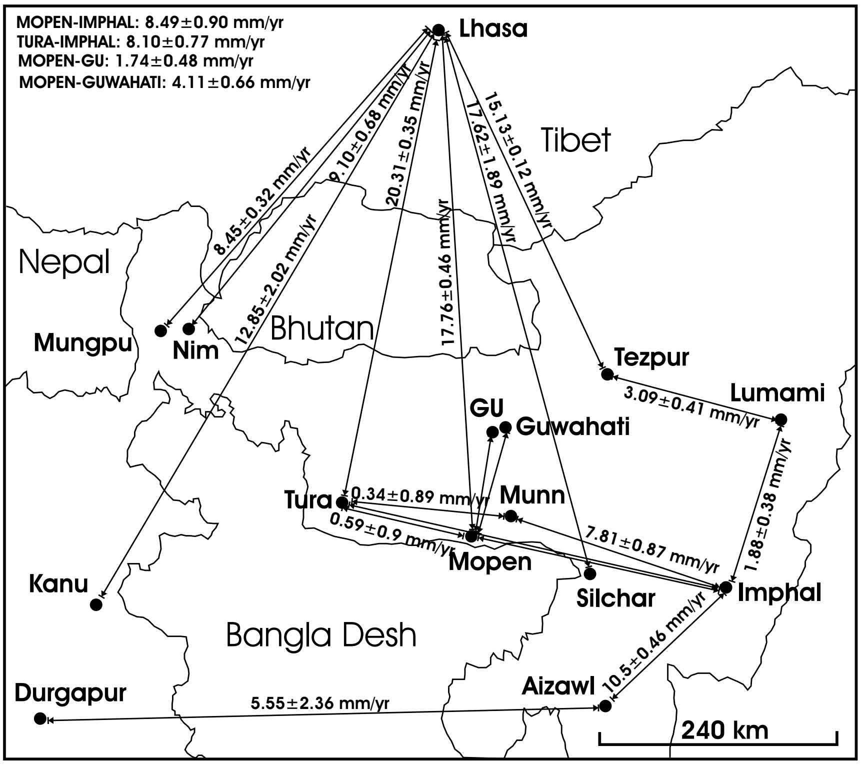

Fig.6. Convergence accommodation in the Bhutan and Arunachal Himalayan wedges, Shillong Plateau and Indo-Burman wedge. About 20 mm/yr of convergence is being accommodated north of 25º N just east of longitude 89º E in the Bhutan Himalayan wedge and Shillong Plateau. This decreases to ~17 mm/yr farther east. About 3-8 mm/yr of convergence is being accommodated in the frontal part of the Indo-Burman wedge.

mountain belt. Integration of geological shortening rates from retrodeformable balanced cross-sections and high-precision GPS based present-day convergence rates is one way of integrating information across time-scales. The results from GPS measurements carried out in NE India indicate that about 15-20 mm/yr of convergence is being accommodated in the NE Himalayan wedge. Balanced-cross sections indicate about 350-500 km of shortening has been accommodated in the NE Himalaya south of the South Tibet Detachment (STD). Geothermobarometric studies on rocks of the Bhutan Himalaya suggest that the rocks south of the STD deformed under peak metamorphic conditions at ~22 Ma (McQuarrie et al. 2008). This indicates a geological convergence rate of ~ 16-22 mm/yr which appears to be fairly consistent with the GPS derived convergence rates. Approximately 1.5 to 3.5 mm/yr (~10-20 %) of the present-day convergence in the NE Himalayan wedge is being accommodated in the Shillong Plateau. In addition, ~8-9 mm/yr of E-W convergence is observed in the eastern and central parts of the Shillong Plateau relative to Imphal located east of the Shillong Plateau in the Indo-Burman fold-thrust belt. This suggests that more detailed, higher resolution data need to be collected from NE India, especially from the Shillong Plateau in order to work out the present day deformation kinematics and understand the seismic hazard in the area.

The present study also highlights the importance of integrating geological and geophysical data to solve kinematic problems. The accommodation of present-day convergence in NE India needs to be understood in the context of geological balanced cross-sections that collectively address the kinematics of deformation in the NE Himalayan wedge, the frontal Indo-Burman wedge and the Shillong Plateau. Such integrated studies in the future will lead to more realistic quantitative models of deformation in NE India.

Acknowledgements: Financial support for this work was provided by Department of Science and Technology (DST), India through grants ESS/16/GPS/15/2001, DST/Seismo/GPS/05/2002, and ESS/23/VES/2001 to Malay Mukul and Sridevi Jade. We are grateful to Peter Molnar for his detailed and critical review that greatly improved the quality of this paper. We are also grateful to the volume editor, Manish Mamtani, for his comments as well as patience and support during the publication of this manuscript.

References

Altamimi, Z., Sillard, P. and Boucher, C. (2002) ITRF 2000: A new release of the International Terrestrial Reference frame for earth science applications. Jour. Geophys. Res. Solid Earth, v.107(B10), pp.2214.

Bendick, R. and Bilham, R. (2001) How perfect is the Himalayan arc? Geology, v.29(9), pp.791-794.

Bilham, R. and Gaur, V.K. (2000) Geodetic contributions to the study of seismotectonics in India. Curr. Sci., v.79(9), pp.1259-1269.

Boyer, S.E. and Elliott, D. (1982) Thrust systems. Amer. Assoc. Petrol. Geol., v.66, pp.1196-1230.

Cummins, P.R. (2007) The potential for giant tsunamigenic earthquakes in the northern Bay of Bengal. Nature, v.449, pp.75-78.

Dahlen, F.A. (1990) Critical taper model of fold-and-thrust belts and accretionary wedges. Annual Review of Earth and Planetary Sciences, v.18, pp.55.

Decelles, P.G. and Mitra, G. (1995) History of the Sevier orogenic wedge in terms of critical wedge models, north east Utah and south west Wyoming. Geol. Soc. Amer. Bull., v.107, pp.454-462.

Decelles, P.G., Gehrels, G.E., Quade, J. and Ojha, T. P. (1998) Eocene–early Miocene foreland basin development and the history of Himalayan thrusting, western and central Nepal. Tectonics, v.17, pp.741-765.

Decelles, P.G., Robinson, D.M., Quade, J., Ojha, T.P., Garzione, C.N., Copeland, P. and Upreti, B.N. (2001) Stratigraphy, structure and tectonic evolution of the Himalayan fold-thrust belt in western Nepal. Tectonics, v.20, pp.487-509.

Decelles, P.G., Robinson, D.M. and Zandt, G. (2002) Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau. Tectonics, v.21, No.6, pp.1062.

Hoffmann-Wellenhof, B., Lichtenegger, H. and Collins, J. (1997) GPS Theory and Practice. Springer-Verlag Wein, New York, 389p.

Jade, S., Mukul, M., Parvez, I.A., Ananda, M.B., Kumar, P.D. and Gaur, V.K. (2002) Estimates of Coseismic Displacement and Post-Seismic Deformation using Global Positioning System Geodesy for the Bhuj Earthquake of 26 January. Curr. Sci., v.82, pp.748-752.

Jade, S., Mukul, M., Parvez, I.A. , Ananda, M.B., Kumar, P.D., Gaur, V.K., Bendick,R., Bilham, R., Wallace, K., Abbasi,. I.A., Khan, M.A. and Ulhadi, S. (2003) Preseismic, coseismic and post-seismic displacements associated with the Bhuj 2001 Earthquake derived from Recent and Historic Geodetic Data. Proc. Indian Acad. Sci. (Earth Planet. Sci.), v.112, No.3, pp.1-14.

Jade, S., Mukul, M., Bhattacharyya, A.K., Vijayan, M.S.M., Saigeetha, J., Kumar, Ashok., Tiwari, R.P., Kumar, Arun, Kalita, S., Sahu, S.C., Krishna, A.P., Gupta, S.S., Murthy, M.V.R.L. and Gaur, V.K. (2007) Estimates of interseismic deformation in Northeast India from GPS Measurements. Earth

Planet. Sci. Lett., v.263, pp.221-234.

Klootwijk, C.T., Conaghan, P. J. and Powell, C. McA. (1985) The Himalayan arc: large scale continental subduction, oroclinal bending and back-arc spreading. Earth Planet. Sci. Lett., v.75, pp.167-183.

King, R.W. and Bock, Y. (2000) Documentation of the GAMIT GPS analysis software, Massachusetts Institute of Technology, Cambridge.

Macedo, J. and Marshak, S. (1999) The geometry of fold-thrust belt salients. Geol. Soc. Amer. Bull., v.111, pp.1808-1822.

Mccaffrey, R. and Nabelek, J. (1998) Role of oblique convergence in the active deformation of the Himalayas and southern Tibetan plateau. Geology, v.26, pp.691-694.

McNaught, M.A. and Mitra, G. (1993) A kinematic model for the origin of footwall synclines. Jour. Struct. Geol., v.15, pp.805-808.

McNaught, M. and Mitra, G. (1996) The use of finite strain data in constructing a retrodeformable cross-section of the Meade thrust sheet, southeastern Idaho. Jour. Struct. Geol., v.18, pp.573-583.

Mcquarrie, N., Robinson, D., Long, S., Tobgay, T., Grujic, D., Gehrels, G. and Ducea, M. (2008) Preliminary stratigraphic and structural architecture of Bhutan: Implications for the along strike architecture of the Himalayan system. Earth Planet. Sci. Lett., v.272, pp.105-117.

Mitra, G. (1994) Strain variation in thrust sheets of the Sevier fold-and-thrust belt, Idaho-Utah-Wyoming: Implications for section restoration and wedge taper evolution. Jour. Struct. Geol., v.16, pp.585-602.

Mitra, G. (1997) Evolution of salients in a fold-and-thrust belt: the effects of sedimentary basin geometry, strain distribution and critical taper. *In*: S. Sengupta (Eds.), Evolution of Geologic Structures from Macro- to Micro-scales. Chapman and Hall, London, pp.59-90.

Mitra, G., Bhattacharyya, K. and Mukul, M. (2010) The Lesser Himalayan Duplex in Sikkim: Implications for variations in Himalayan shortening. Jour. Geol. Soc. India, v.75, pp.289-301.

Mookerjee, M. and Mitra, G. (2008) Kinematics-Based Mathematical Model for Deforming Thrust Wedges. Mathematical Geosciences, v.40 (3), pp.249-275.

Molnar, P. and Lyon-Caen, H. (1989) Fault plane solutions of earthquakes and active tectonics of the Tibetan Plateau and its margins. Geophys. Jour. Internat., v.99, pp.123-153.

Mukul, M. (1998) A geostatistical approach to the quantification of finite strain variation in penetratively deformed thrust sheets: an example from the Sheeprock thrust sheet, Utah. Jour. Struct. Geol., v.20(4), pp.371-384.

Mukul, M. (1999) Strain variation in fold-and-thrust belts: Implications for construction of retrodeformable models. Proc. Indian Acad. Sci. (Earth Planet. Sci.), v.108, No.3, pp.207-221.

Mukul, M. (2000) The Geometry and Kinematics of the Main Boundary Thrust and related Neotectonics in the Darjiling Himalayan Fold-and-thrust belt, West Bengal. Jour. Struct. Geol., v.22 (9), pp.1261-1283.

Mukul, M. (2005) Continental deformation and Global Positioning System based Geodesy. Himalayan Geol., v.26(1), pp.193-198.

Mukul, M. and Mitra, G. (1998) Finite strain and Strain Variation Analysis in the Sheeprock Thrust Sheet: An internal Thrust Sheet in the Provo salient of the Sevier Fold-and-Thrust Belt, Central Utah. Jour. Struct. Geol., v.20 (4), pp.385-405.

Mukul, M., Jaiswal, M. and Singhvi, A.K. (2007) Timing of recent out-of-sequence active deformation in the frontal Himalayan wedge: Insights from the Darjiling sub-Himalaya, India. Geology, v.35(11), pp.999-1002.

Mukul, M., Jade, S. and Matin, A. (2009) Active Deformation in the Darjiling-Sikkim Himalaya based on 2000-2004 Geodetic Global Positioning System Measurements. *In*: P. Ghosh and S. Gangopadhyay (Eds.), Indian Statistical Institute Platinum Jubilee Volumes, Numerical Methods and Models in Earth Science, New India Publishing Agency, New Delhi, pp.1-28.

Mukul, M., Roy, D., Satpathy, S. and Anil Kumar, V. (2004) Bootstrapped Spatial Statistics: A More Robust Approach to the Analysis of Finite Strain Data. Jour. Struct. Geol., v.26(3), pp.595-600.

Nandy, D. R. (2001) Geodynamics of Northeastern India and the Adjoining Region. ACB publications, Lake Town, Calcutta, 209p.

Nelson, K.D. and Twenty Six Others (1996) Partially Molten Middle Crust Beneath Southern Tibet: Synthesis of Project INDEPTH Results. Science, v.274, pp.1684-1688.

Ni, J. and Barazangi, M. (1984) Seismotectonics of the Himalayan Collision Zone: Geometry of the underthrusting Indian plate beneath the Himalaya. Jour. Geophys. Res., v.89 (B2), pp.1147-1163.

Satyabala, S.P. (1998) Subduction in the Indo-Burma region: Is it still active? Geophys. Res. Lett., v.25, pp.3189-3192.

Srivastava, P. and Mitra, G. (1994) Thrust geometries and deep structure of the outer and lesser Himalaya, Kumaon and Garhwal (India): Implications for evolution of the Himalayan fold-and-thrust belt. Tectonics, v.13, pp.89-109.

Vigny, C., Socquet, A., Rangin, C., Chamot-Rooke, N., Pubellier, M., Boudin, M.-N., Bertrand, G. and Becker, M. (2003) Present-day crustal deformation around Sagaing fault, Myanmar. Jour. Geophys. Res., v.108 (B11), pp.2533, doi:10.1029/2002JB001999.

Wang, Q., Zhang, P-Z., Freymuller, J.T., Bilham, R., Larson, K.M., Lai, X., You, X., Niu, Z., Wu, J., Li, Y., Liu, J., Yang, Z. and Chen, Q. (2001) Present-Day Crustal Deformation in China constrained by Global Positioning System Measurements. Science, v.295, pp.574-577.

Wu, S. (1995) Fractal strain distribution and its implications for cross-section balancing. Jour. Struct. Geol., v.15, pp.1509-1512.

(Received: 4 January 2009; Revised form accepted: 29 April 2009)