2.1 Continental Deformation Ahead of the Striding Indian Plate: A Study of the Trans-Himalayan Kinematics in Ladakh, India

Re-measurement at the Global Positioning System (GPS) stations in Ladakh Himalaya on both the wings of Karakoram fault were carried out for a period of five consecutive days in July, 1999. The aim of this experiment was to constrain the slip rate along the dextral Karakoram fault, keeping in mind the objective of modeling the intracontinental deformation between the Himalaya and South Tibet. The two existing models of continental deformation in the convergence zones are, (a) homogeneous crustal thickening model (deformation of a thin viscous sheet) and, (b) concentration of deformation in localized shear zones, allowing intervening region to move out as coherent blocks (plasticine models).

The long Karakoram fault stretching over 1000 km from Pamir to Manasarovar in Tibet is a right lateral strike slip fault and a major feature of continental deformation north of the Himalaya. Ten sites on both the wings of Karakoram fault have been monitored using GPS receivers, each for a period of five consecutive days, in each of the years of 1997-1999. The GPS site at Leh is continuously running for the last three years and the site at Hanleh was kept running during the period when the ten sites were being monitored. The results of this experiment are in the form of GPS derived absolute velocities (Fig. 2.1.1) for all the GPS sites in Ladakh Himalaya along with the International GPS Service for Geodynamics (IGS) stations at IISc, Lhasa, Kitab and Pol. The convergence rates (Fig. 2.1.2) between these sites on the Karakoram fault, Leh and Hanleh and the IGS station at IISc, Bangalore were also obtained. From this experiment, the major points of significance that have emerged are as follows. Convergence between the southern tip of India and Himalaya is within the error bar of 5 mm/yr, confirming the near rigidity of Indian continental plate. Most of the convergence takes place in the northern part of Himalayan belt whereas the southern Himalaya is locked to the Indian plate. The convergence rates in the Himalayan belt varies from 10 to 20 mm/yr in the west (Ladakh) to 15 mm/yr in central Himalaya (Almora). The trans-Himalayan region apparently undergoes little or no convergence in the N-S direction. However, there is E-W extension between Lhasa and sites of S-W limb of Karakoram fault at the rate of 20 mm/yr. Deformation model in the trans-Himalaya is perhaps nearer to the strain-softening model.

To substantiate the above results with much more

Fig. 2.1.1. GPS derived absolute velocities of the sites in Ladakh Himalaya.

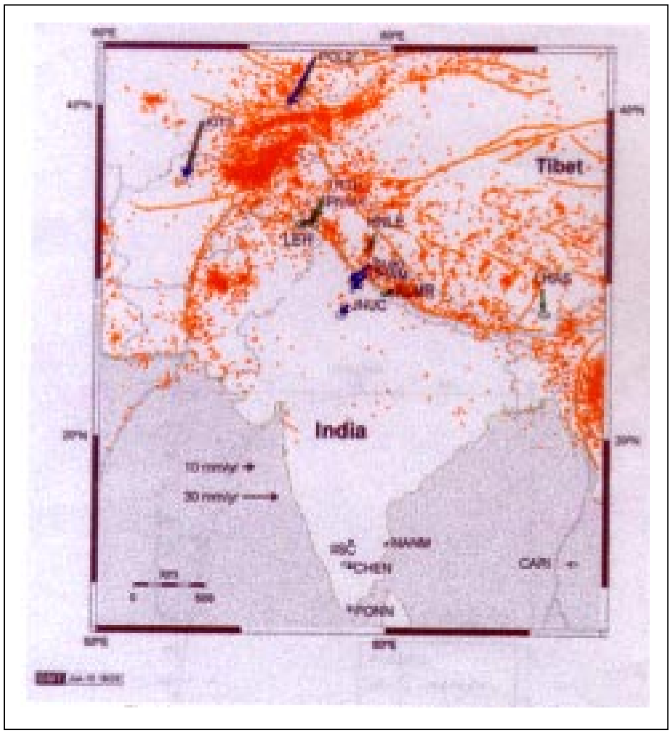
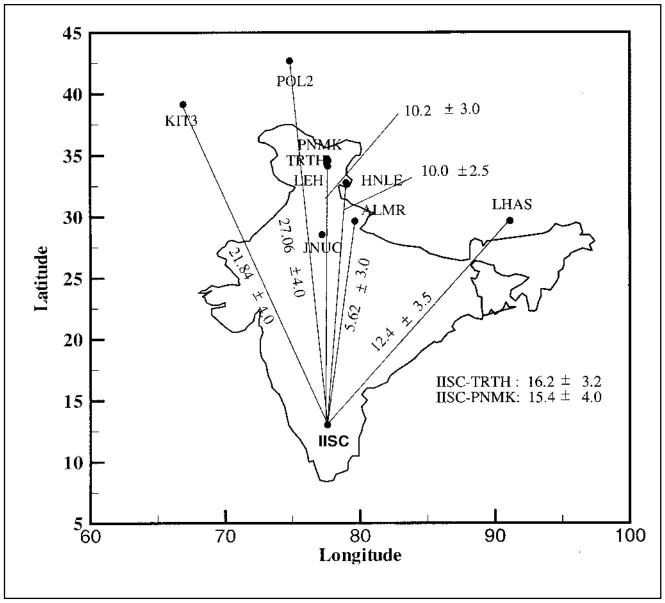


Fig. 2.1.2. Rates of baseline shortening in mm/yr.



confidence, measurements at the ten GPS sites need to be carried out in the year 2000 for a period of minimum five consecutive days at each site. The results of this strain measurement experiment in Ladakh Himalaya are to be looked at with a new perspective based on the knowledge of the geology of the area to arrive at best constrained slip rates along the fault and also accurate convergence rates between the GPS sites in Himalaya and the IGS station in Bangalore. These GPS derived slip rates can be used to model the continental deformation in the Karakoram fault region so as to decide on one of the two deformation models as the end result.

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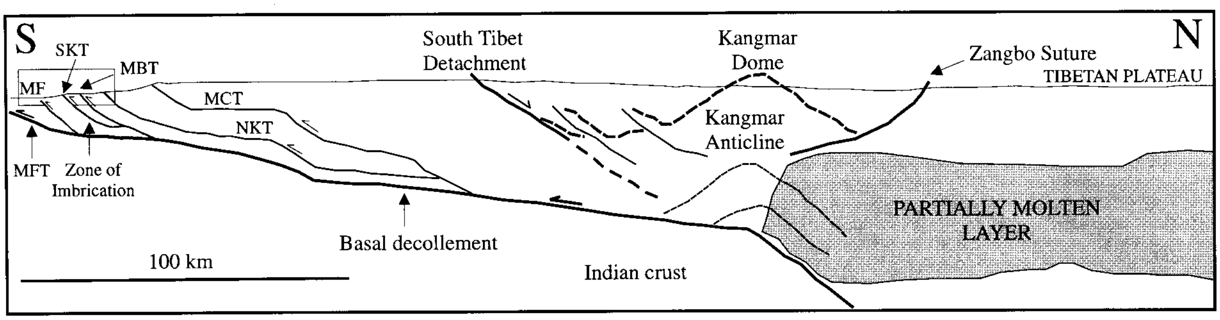
2.2 Deformation in the Darjiling-Sikkim-Tibet Himalayan Wedge

A lot of work has been done over the years to understand the mechanics of deformation in the Himalayan mountain belt. In the late 1990s, some French scientists have attempted to understand the deformation in the Nepal Himalayas in the light of the *critical wedge taper theory* that has been applied to the Sevier fold-and-thrust belt in the western United States and which has, subsequently, evolved as the contemporary paradigm for understanding deformation in sedimentary wedges that evolve into a mountain belt in a compressive regime. However, efforts to apply the critical wedge theory to the Himalayas have been severely constrained by the fact that the hinterland (or the back-end of the wedge) structure over most of the Himalayas is unknown. As hinterland structures are the first-formed structures in the kinematics of deforming wedges in compressive regimes, they control the subsequent tectonic evolution of the mountain belt and should, therefore, be well-understood. Project INDEPTH (Cornell University, USA, 1996) has provided the first insight into the hinterland structure of the Himalayan wedge in Tibet, directly north of the state of Sikkim, India.

C-MMACS has initiated work towards understanding the deformation in the Himalayan wedge and the initial work has been directed towards understanding the qualitative nature of the Darjiling-Sikkim-Tibet (DaSiT) wedge on the basis of published data and preliminary fieldwork followed by identification of questions that need to be addressed by non-linear finite-element modelling.

Project INDEPTH imaged a ramp in the basal detachment of the Himalayan fold-and-thrust belt; the fault-bend-fold or the ramp anticline (Kangmar anticline) associated with this has an amplitude of almost 35 km (Fig. 2.2.1). What would be the implications of such a structure in the hinterland of the DaSiT Himalayan fold-and-thrust belt on the subsequent tectonic evolution of the mountain belt ? Critical wedge theory indicates that a ramp anticline of 35 km amplitude will result in an initial supercritical wedge which must subsequently reduce its taper to attain mechanical equilibrium. The known taper reducing mechanisms are frontal imbrication (in-sequence growth and propagation of several thrust faults in the front of the supercritical wedge) and hinterland collapse (by extensional normal faulting). The INDEPTH profile images extensional faults in the hinterland but does not extend into the frontal part of the wedge which is in India. However, our mapping of the frontal part of the wedge shows

Fig. 2.2.1. Large scale structure of the DaSiT Himalayan wedge. The Kangmar Dome is the surface expression of the large-scale, basement-cored, ramp anticline that developed over a ramp in the basal detachment of the wedge at about 70 km depth. The formation of the Kangmar structure resulted in an initial supercritical taper and caused the Kangmar anticline to be the initial dominant hinterland structure that drove the frontal folding and thrusting in the wedge. Supercritical taper was also probably reduced by hinterland collapse by normal faulting along the South Tibetan Detachment (STD) system. Abbreviations: MFT- Main Frontal Fault; MF - Mountain Front; SKT- South Kalijhora Thrust; MBT- Main Boundary Thrust; NKT - North Kalijhora Thrust; MCT - Main Central Thrust.



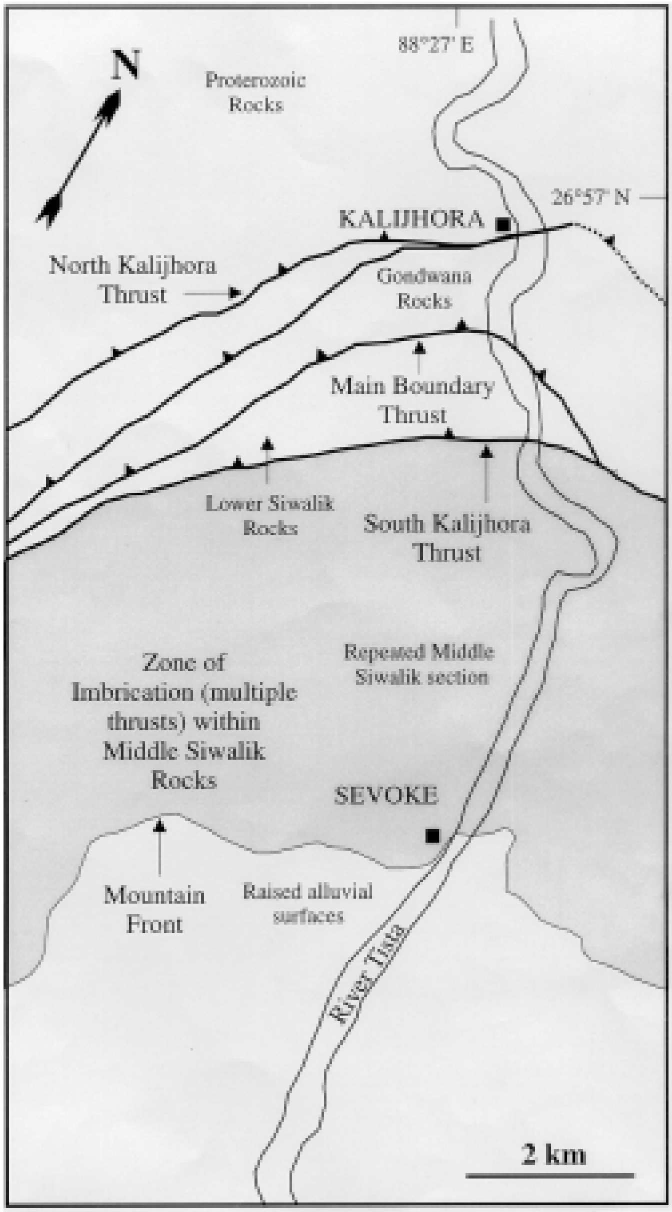


Fig. 2.2.2. Frontal imbrication in the DaSiT Himalayan wedge south of the MCT. At least three major imbricate thrust faults and a zone of imbrication in the Middle Siwalik section exists in the frontal part of the wedge which points to the probable existence of supercritical taper at the back-end of the wedge that was created by the formation of the Kangmar structure. The Main Frontal Thrust (MFT) is blind in the region as evident from uplifted alluvial surfaces south of the mountain front.

extensive imbrication (Fig. 2.2.2); these results indicate that the initial Himalayan wedge was supercritical. Nevertheless, the details of the formation of the Kangmar anticline remains an open question. Such high amplitude ramp anticlines have not been reported from anywhere else and thus the kinematics of its formation is an important question that is currently being investigated by non-linear finite element modelling of the wedge.

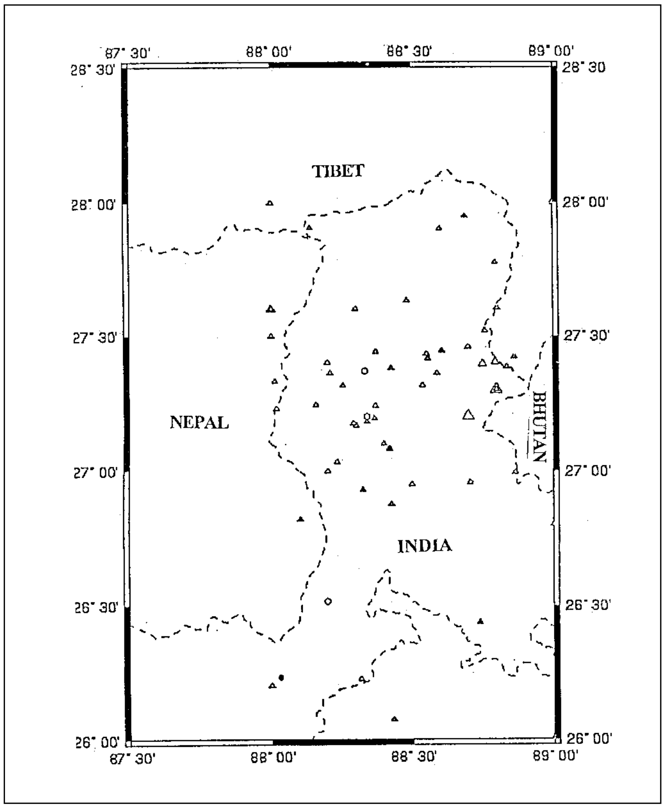


Fig. 2.2.3. Map of earthquake epicentres from the DaSiT area in India. Epicentres form an E-W band between the latitudes 27° and 27.5° indicating the central part of the DaSiT wedge is active.

The other important question about the Himalayan wedge is the location of the earthquakes in it. In the DaSiT Himalayan wedge, compilation of earthquake data (Fig. 2.2.3) reveals that the middle part of the wedge is active. This is supported by geological evidence such as the formation of uplifted strath terraces (Fig. 2.2.4) along the river Tista and formation of duplex structures (Fig. 2.2.5). In a growing mountain belt, neotectonic activity is generally expected in the front of the deforming wedge where new thrust faults break and propagate to the foreland. Thus, earthquake (neotectonic) activity in the centre of the deforming DaSiT Himalayan wedge is an intriguing question and is the subject of current study. These earthquakes (and the supporting geological evidence) point to the fact that the central part of the wedge has somehow become sub-critical and is deforming to restore wedge-taper and continue the southward extension of the Himalayan mountain front. What has caused the wedge to become sub-critical in the centre ? One possible explanation is that, with the onset of the monsoon in the late Miocene, and increased rates of erosion, the critically deforming wedge probably became subcritical and stalled over time. The high taper and strength of the back-end of the wedge was no longer

Fig. 2.2.4. Raised asymmetric, strath river terraces on the west bank of River Tista. Three of the five terraces seen in the area are shown by arrows. Gravel that was part of the earlier bedload of the Tista, and which has been left behind by the river as it adjusted to the uplift of the terrain, is also seen.

sufficient to support further frontal imbrication especially because the middle part of the wedge which consisted of sheets carrying lower-strength sedimentary rocks, was excessively eroded. The wedge needed to restore critical taper, particularly in the middle part of the wedge where there is a drop in the material strength (basement to meta-sedimentary rocks), in order to advance into the Gangetic plain. Evidence of neotectonic activity within the exposed mountain front probably reflects deformation directed towards achieving this because duplex formation is one of the mechanisms for building taper in stalled, subcritical wedges. This hypothesis is being currently examined by construction of non-linear finite element models of the wedge.

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2.3 Flow Modelling of Mountain Glaciers

Glaciers are made up of fallen snow that is compressed into a large, thickened mass of ice over many years. Presently, glaciers occupy about 10% of the world's total land area and most of them are located in polar regions like Antarctica (85%) and Greenland (12%); the remaining 3% of the glaciers occur in mountain regions such as the Himalaya, Arctic Canada, Alaska and Andes. Improved understanding of the deformation and flow within mountain glaciers is essential for estimation of glacial hazards and

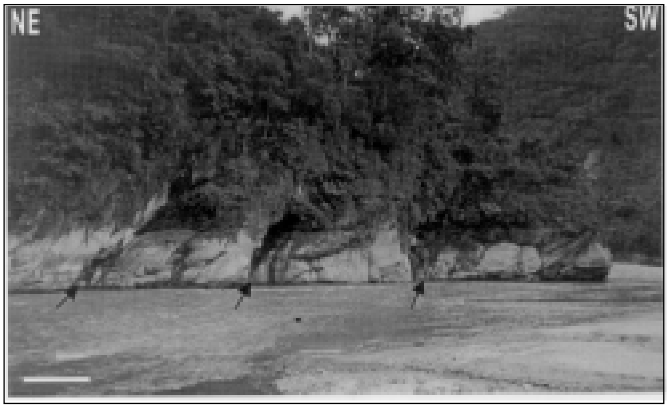

Fig. 2.2.5. Horses in the central part of the DaSiT Himalayan wedge defining a duplex. The fault planes (indicated by arrows) in the horses occur along shale horizons within the Middle Siwalik Geabdat sandstones. Scale bar = 15 m.

reduction in loss of human life and property. Roughly 25% of the world's population, who live in the mountains, are in Himalaya and thus, the mountain glaciers there are of critical importance to India. Given this importance of Himalayan glaciers, the Department of Science and Technology (DST) has initiated a nationwide effort to promote research effort in mathematical modelling of mountain glaciers.

As the first step towards mathematical modelling of mountain glaciers, literature on the concepts involved in modelling of flow in idealized glaciers is being reviewed. Simple analytical models have been reviewed to explore some of the important parameters related to glacier flow which can form the basis for more realistic modelling. Flow in valley or mountain glaciers is essentially two-dimensional and is considered to occur in the *x*-*z* plane. The simple models reviewed, reveal that stresses σ_{zx} and σ_{zz} vary linearly with depth and, longitudinal stresses are extending in accumulation areas and compressive in ablation areas, although the magnitude of the longitudinal stresses are not constrained. We also found that vertical velocities vary linearly with depth for idealized glaciers whereas horizontal velocities decrease nonlinearly with depth. However, when more realistic and complicated glacier flow models are considered, governing differential equations are nonlinear and numerical solutions are the norm.

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