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AN "EXPANDING MOUNTAIN FRONT" HYPOTHESIS FOR THE TECTONIC EVOLUTION OF THE SIWALIK ZONE, OUTER HIMALAYA

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ABSTRACT

The formation of the Siwalik Range at the southern fringe of the Himalaya is one of the latest geological events in the Himalaya. The rocks of the Siwalk Supergroup have recently been found to show extremely complicated structures in their internal domain, in contrast to the relatively simpler structures known so far. The bedding layers show duplex, imbricate fan systems, pop-up structures, snakehead anticlines and snakehead duplexes, fault-propagation folds, antiformal stacks, overstep thrust systems, and a variety of related strctures. These structures may be considered to be a direct result of the accommodation of the continued tectonic stresses under the collisional system that is neotectonically active, and suggest strong reactivation of layer anisotropies (bedding planes, faults, etc.) and consequent progressive deformation of the early-formed structures. The fractures (thrusts, faults etc.) drain water into the system which, in turn, increases the fluid pressure of the rocks, causes hydraulic weakening to the rocks and makes the rocks buoyant enough to facilitate motion along minor thrusts and faults under the deforming system. Development of the complicated structures and the thrust geometries in the internal domain may have caused a good deal of "structural thickening" of the original lithic pile of the Siwalik rocks. This, in turn, disturbs the critical taper of the Siwalik wedge. It seems quite possible that in order to maintain the critical taper, and to maintain the topography in an equilibrium state, the mountain must adjust the additional topography (caused due to structural thickening), by spreading or expanding the mountain front towards the craton, i.e. southwards. The Himalayan mountain front could thus be considered to be expanding southwards.

The proposed concept seems to have some far-reaching implications. For example, the Himalayan mountain front should then be a region of ground instability such as seismic activities, landslides, etc, and in fact, this is really so at present. Further, the spreading mountain front would cause a sympathetic instability to the modern adjoining foreland region (Indo-Gangetic Basin) also.

The Himalayan mountain front region could thus be considered to show an excellent example of Himalayan orogen-foreland interaction.

Key words : Expanding Mountain Siwalik zone, Thrust geometry, Outer Himalaya.

INTRODUCTION

The Himalaya constitutes an excellent example of continent-continent plate collision during the Eocene times. As a result of collision of the Indian plate against the Asian plate, untold amount of stresses were generated in the Himalayan region that resulted in the formation of the mountain chain. In front of the rising mountain front, a new basin was created during the Miocene times and it was rapidly filled up by fluvial deposits that later on formed the Siwalik Supergroup. Continued collisional stresses gave rise to the present-day structural architecture of the Siwalik rocks.

As yet, the Siwalik rocks are believed to show possibly the least structural complexities, at least in the exposed sections. The overall structural architecture, both on the megascopic and mesoscopic scales, have been described to be much simpler than those shown by the rocks of the other lithotectonic subdivisions of the Himalaya (viz. the Lesser, Greater and Tethys Himalayas). Author's detailed strctural studies have recently shown that the lithic layers of the Siwalik rocks show complex thrust geometries. In this paper, the wider implications for the complex structural geometries shown by the Siwalik rocks are discussed, and an "Expanding Mountain Front" Hypothesis for the Siwalik Zone of the Outer Himalaya is proposed.

STRUCTURAL SETTING

The Siwalik Supergroup constitutes the dominant lithotectonic unit of the Outer Himalaya (fig. 1) and it is one of the youngest stratigraphic units of the Himalaya. Lithologically, this unit is constituted of sandstone, shale and mudstone. Locally developed conglomerate horizons are occasionally noticed throughout the rock unit, but these are relatively common in the upper Siwalik rocks.

The northern boundary of the Siwalik unit is defined by a prominent tectonic plane, called the Main Boundary Fault (MBF) that brings the massive pile of calcargillaceous rocks of the Lesser Himalaya in tectonic contact with the Siwalik rocks. To the south, the Siwalik rocks are tectonically juxtaposed against the alluvium of the Gangetic plains, and the cotnact between the two is called the Hiamalayan Frontal Fault (HFF). Thus the Siwalik rocks occur as a tectonic slice sandwiched between the MBF and the HFF.

Megascopically, the Siwalik rocks show relatively simpler structures. In some sections, the strata show simple north-dipping structures (homocline). In other sections, the strata show open synclines and anticlines - the so called "Jura-type" folds. The strata are also affected by numerous normal faults of varying dimensions. The present work is mainly based on a detailed study of the Siwalik rocks of the

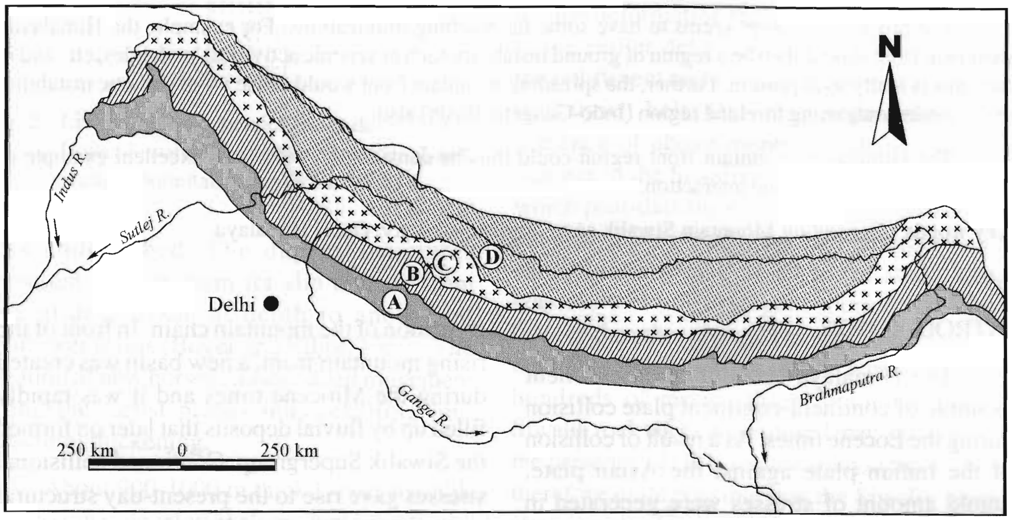

Fig. 1. Geological sketch map of the Himalaya showing the position of the Outer Hiamalya. The Siwalik zone constitutes a major part of the Outer Hiamalaya. A – Outer Himalaya, B – Lesser Himalaya, C – Greater Himalaya, D – Tethys Himalaya. (After Gansser, 1964).

Mohand area (south of Dehradun), and is supported by similar observations in a few other sections of the Siwalik zone, viz. Haridwar-Dehradun bye-pass, Chandi Devi-Chilla section (near Haridwar on the left bank of the Ganga river), west of Nainital, Baldiyakhan-Jeolikot section (south of Nainital) and Kotdwar section. In the Mohand section, Siwalik rocks are disposed as an anticline that has been modelled as a multi-bend fault-bend fold related to the Himalayan Frontal Fault HFF) (Mishra and Mukhopadhyaya, 2002).

Small scale folds are very rare in the entire pile of the strata, and these are in the form of gentle flexures to open folds. Prominent planar strctures include faults, joints and bedding planes. Most faults are steep to vertical and are mostly normal. Locally developed reverse faults are also occasionally noticed. The strata are also affected by numerous joints orineted in several directions. Most joints are steep to vertical, while bedding joints are also common. Linear structures are practically not well developed in the Siwalik rocks.

Some other structrural/tectonic aspects of the Siwalik rocks, especially in the regional framework, can be seen in the work of Yeats and Lillie, (1991), Yeats *et al.* (1992), Valdiya (1992), Raiverman *et al.* (1994), Thakur *et al.* (1995), Srivastava and John, (1999), Dubey *et al.* (2001).

STRUCTURES IN THE INTERNAL DOMAIN

In the light of recent structural studies of the author, the Siwalik rocks have been shown to exhibit complicated thrust geometries in their internal domain. (In this paper, the term "internal domain" has been used to include strcutrual features contained within the lithic layers or beds). A variety of strctures, such as duplex, imbricate fan system, thrust propagation strctures, pop-up structure, snakehead anticline, overstep thrust system, ramp-flat geometry, delta structure and the related structures have been noticed, most of these are described elsewhere (Bhattacharya and Agarwal, 2005). Some of these strctures are shown in fig. 2, while the sketches of some other types are shown in fig. 3.

The above metnioned structures have been observed in several sections exposing the Siwalik rocks as mentioned earlier. It is therefore quite possible that the entire sequence of Siwalik rocks is riddled with complex thrust geometries and the related minor strcutures within the lithic layers, i.e. in the internal domain, and this can, in general, be considered to be a characteristics feature of the Siwalik rocks.

THE DEFORMING WEDGE

In recent years, a good deal of information is available on the geometry of structures and the mechanisms of deformation in fold-and-thrust belts (e.g. Hubbert and Rubey, 1959; Elliot, 1976; Chapple, 1978; Boyer and Elliot, 1982; S. Mitra, 1986; G. Mitra and Boyer, 1986). In the light of recent work, it is commonly believed that it is impossible to push thin slabs of rocks larger distances without the slab breaking apart. Under compressional regime, the thrust continues to advance, thus forming a *wedge* towards the mountain front. Subsequent thrust wedges thus give rise to a *crustal taper* to the particular mountain chain. The surface slope of the thrust wedge is an important controlling factor to thrust movement, because the surface slope will impart the critical taper necessary for the movement of the turusts (cf. Chapple, 1978).

In the case of the Himalayan mountain front, the higher topographic elevation (average 1500 m) of the Himalayan fold-and-thrust belt promotes rapid erosion (by rivers, etc.). As erosion removes the material from the surface, more internal deformation is needed or more material must be added to the wedge to maintain the critical taper. This implies that the internal structural geometry of the Siwalik rocks (say,

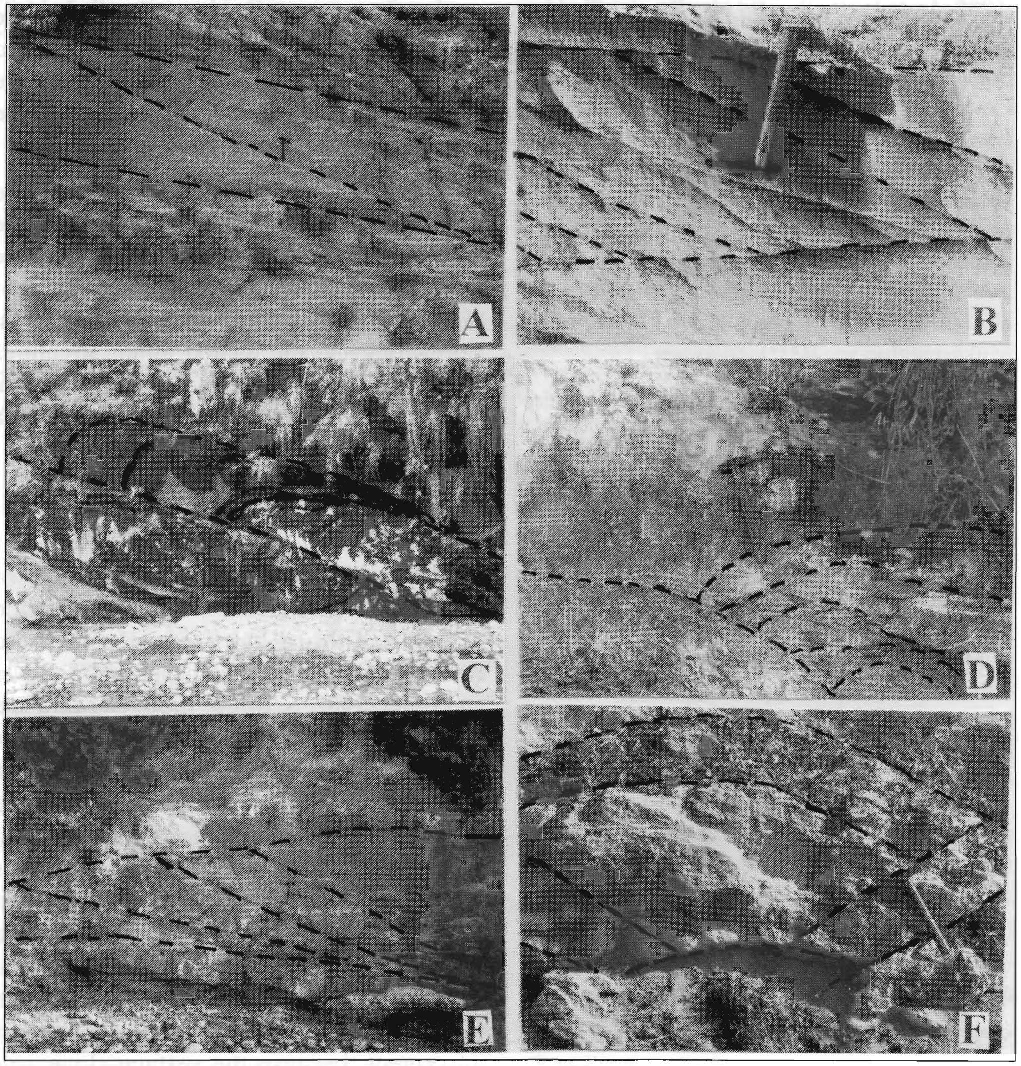

Fig. 2. Photographs of some common types of thrust geometries noticed in the lithic layers of the Siwalik rocks in the Mohand-Dehradun section. All the structures shown are developed in sandstone layers. A – Duplex structure, B – A duplex system showing the development of horses, C – Fault-bend fold, D – Snakehead anticline, E – Imbricate fans; the base of the individual horses become curved (tangential) and then become parallel to, or join, the lower bed, F – Pop-up structure.

the Outer Himalaya, in general) should not be that simple as assumed, viz. a more or less homoclinal slab to openly folded sequence with Jura-type folds. Quantitative tectonic strain shown by the Siwalik rocks is very low. Flattening values for the Siwalik folds, as estimated in three different sections of the Outer Himalaya have been found to be very low, up to 5% only, as compared to the relatively higher strain (up to 16%) shown by the adjoining rocks of the Krol Belt of the Lesser Himalaya (Bhattacharya, 1983, 1999).

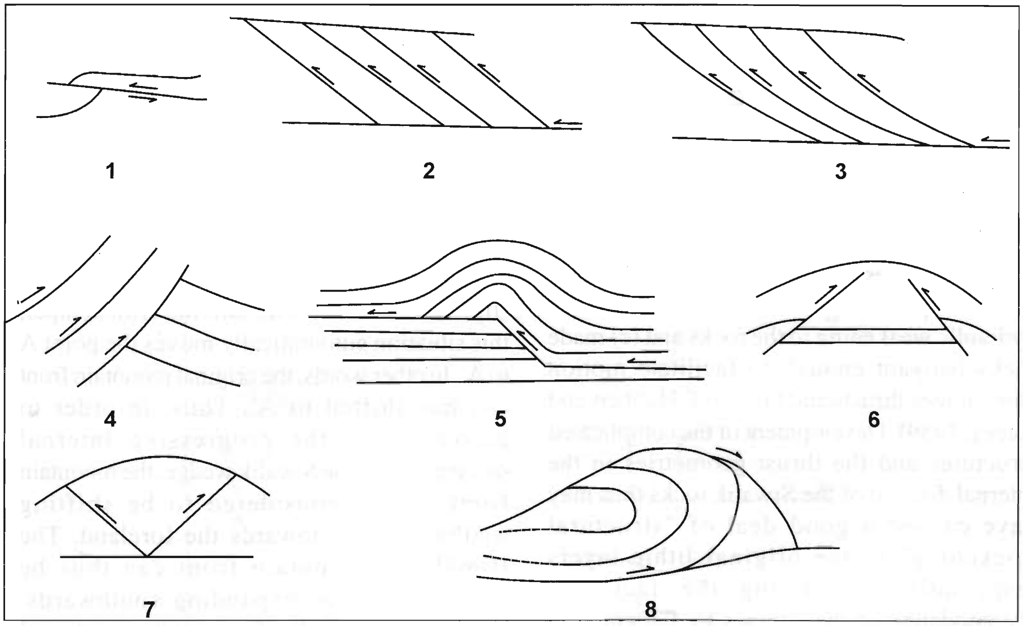

Fig. 3. Sketches of some common types of thrust geometries noticed in the lithic layers of the Siwalik zone. 1- spaly, 2- duplex, 3 - imbricate fan system, 4- overstep thrust sequence, 5- snakehead anticline, 6- delta structure, 7- pop-up stucture, 8- antiformal stack (rotated).

In addition to the development of internal structures, the deformational processes - as triggered and continuously maintained by the compressional stresses generated due to plate collison – also control the development of fabrics, textures and specific geometrical properties to the rocks (e.g. orientation of pore system, etc.) and the related features. In the case of the Siwalik rocks, most of these features are not so well developed or well marked. It is therefore quite possible that the Siwalik rocks, under the influence of continued collisional stresses, may have imparted, in addition to some others, the following features :

Deformation of the rock layers in the internal domain to accommoate the induced internal strain through (a) folding, (b) flattening of folds, (c) rotation/reorientation of folds and the early-formed structures, and (d) faulting.

- Reactivation of the layer anisotropies (bedding planes, faults, etc.). This commonly produces bedding-plane thrusts that may trigger/ facilitate ramp-flat structures and the related features.
- Progressive deformation, rotation and reorientation of the early-formed structures.
- Development of back-thrusts.

In the case of the Siwalik rocks, accommodation of compressive stresses through folding and flattening of folds may thus be considered to be very low to negligible. Fold development seems to be a rare phenomenon in the Siwalik rocks and the flattening strain shown by the minor folds is of very low amount (up to 5% only), as mentioned earlier. It therefore seems quite possible that most of the collisional stresses may have been accommodated in the development of fractures (thrusts, faults, etc.), and in reactivating the anisotropies such as bedding planes. The former (fractures) may have drained water into the rock masses which, in turn, (a) increased the fluid pressure of the rocks, (b) caused hydraulic weakening to the rocks and (c) made rocks buoyant enough to facilitate motion along minor thrusts and faults (cf. Hubbert and Rubey, 1959). Development of the complicated structures and the thrust geometries in the internal domian of the Siwalik rocks thus may have caused a good deal of "structural thickening" to the original lithic layers (especially considering the fact that accomodation of the stresses by flattening in folds is very low). This structural thickening, in turn, may have disturbed the "critical taper" of the Siwalik wedge.

The above situation has been diagrammatically explained in fig. 4 which represents the ideal Coulomb wedge for the Siwalik zone (assuming deformation in brittle regime). α is the dip of the basal thrust, β is the topographic slope angle, so that $(\alpha + \beta)$ is the

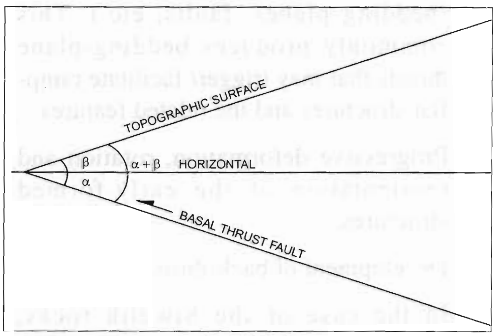

Fig.4. The ideal Coulomb wedge, assuming deformation in the brittle regime. α is the dip of the basal thrust, β is the topographic slope angle, so that $(\alpha + \beta)$ is the angle at the apex of the wedge (= the critical taper).

angle at the apex of the wedge (= the critical taper). With this setting, if A (fig. 5) represents the initial mountain front, then the material (rock masss) included between AB and AC constitutes the part of the Siwalik wedge that is undergoing structural thickening due to internal deformation. As the latter process (internal deformation) continues, the line AC moves up to take up a new position, say A' C' (fig. 5). In order to maintain the critical taper, this situation automatically moves the point A to A'. In other words, the original mountain front (A) has shifted to A'. Thus, in order to accommodate the progressive internal deformation in the Siwalik wedge, the mountain front can be considered to be shifting southwards, i.e. towards the foreland. The Himalayan mountain front can thus be considered to be expanding southwards. Further, as a result of progressive internal deformation in the Siwalik wedge, new thrusts must be forming at the mountain front and the early-formed blind thrusts are becoming emergent thrusts such as the HFF.

Further, the Siwalik wedge is tectonically bound by the HFF in the south and MBF in the north. Because of the northward motion of the Indian plate, this wedge is persistently getting squeezed. It therefore seems possible that the squeezed Siwalik terrain is currently undergoing internal deformation to accommodate the accumulated stress level. Thus, considering both the factors responsible for internal deformation of the Siwalik wedge - i.e. *external domain* due to compressional movement caused by plate motion as well as *internal domain* caused by reactivation of internal anisotropy planes and the various mesoscopic structures (as discussed in the paper) – the Siwalik terrain may be considered to be in a state of tectonic "expansion".

CONCLUSIONS

In the present work, it has been shown that the rocks of the Siwalik zone show complicated thrust geometries in their internal

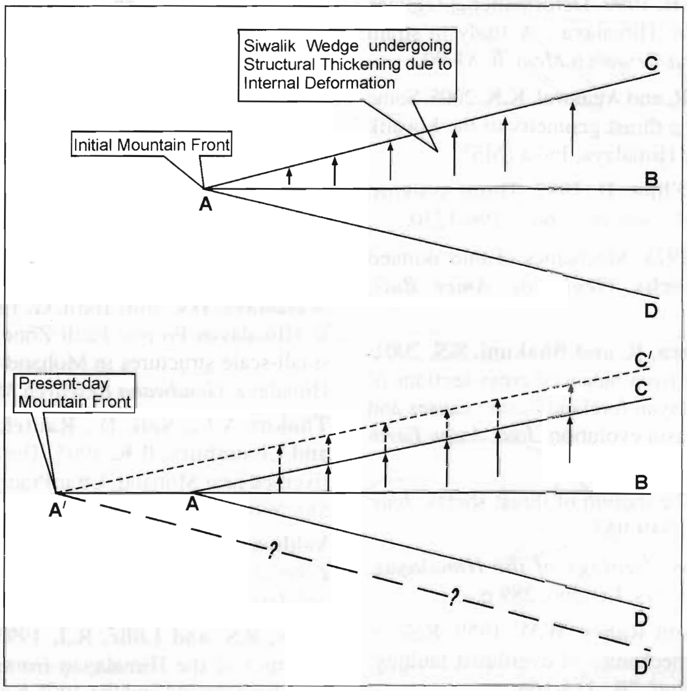

Fig.5. Diagrammatic representation of the Siwalik wedge (with reference to fig. 4). In the upper diagram, A representes the initial mountain front. The material (rock masses) included between AB and AC constitutes the part of the Siwalik wedge that is undergoing structural thickening (shown by upward arrows) due to internal deformation. With progressive deformation, the original mountain front, A, shifts to a new point, A' (lower diagram), implying that the mountain front is expanding southwards, i.e. towards the foreland.

domain which may have caused, and is still causing, "structural thickening" of the original lithic layers. Development of new thrusts, thrust packages, back-thrusts, piggy-back thrusts, folding, etc. is currently active. This disturbs the critical taper of the Siwalik wedge. In order to maintain the critical taper, the mountain front must be adjusting the additional topography (caused due to structural thickening) by spreading or expanding towards its free ends, i.e. southwards. The Himalayan mountain front thus seems to be expanding southwards, and consequently it can be considered to be a zone of active deformation in the internal domain. This, in turn, makes this region neotectonically active.

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