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Some Observations on the Thrust Geometry of the Siwalik Rocks of the Outer Himalaya, India

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Abstract

The rocks of the Siwalik Supergroup of the Outer Himalaya have been found to show a complicated system of thrust geometry in their internal domain. The structures, which the lithic layers commonly show, include the following: duplex, imbricate fan system, thrust propagation structures, fault propagation folds, pop-up structures, antiformal stack, snakehead anticline, snakehead duplex, overstep thrust system and the related types. Occurrence of these structures suggests, amongst others, the active role, and/or reactivation, of the anisotropy planes of the rocks during deformation, and that the deformation was progressive in nature. Development of most of these structures may have involved addition of mass to the moving thrust complexes. Presence of the above structures possibly indicates that the Siwalik strata, in general, may have undergone structural thickening in their internal domain during the overall deformation of these rocks.

Introduction

The Himalayan mountain belt is an excellent example of collision of two continental plates during the Eocene times. The present-day tectonic setup and the structural architecture of this mountain chain is a direct reflection of the deformational processes that operated during and after the collision. The emerging Himalayan mountain belt and the thrust sheet loading caused flexural subsidence of the Indian lithosphere creating a foreland basin in front of it, in which the Siwalik sediments were deposited. Thus, the Siwalik sequence constitutes the outermost part of the Himalayan mountain chain, and extends almost all along the strike length, *i.e.* from Potwar Plateau in the west to Arunachal Pradesh in the east. Lithologically, the Siwalik unit is dominantly constituted of sandstone, siltstone, mudstone, and locally developed conglomerate horizons. This lithological assemblage represents typical foreland deposits. The Outer Lesser Himalaya in the vicinity of the Siwalik zone is dominantly constituted of a thick calcargillaceous sequence (Krol Group) of Proterozoic age.

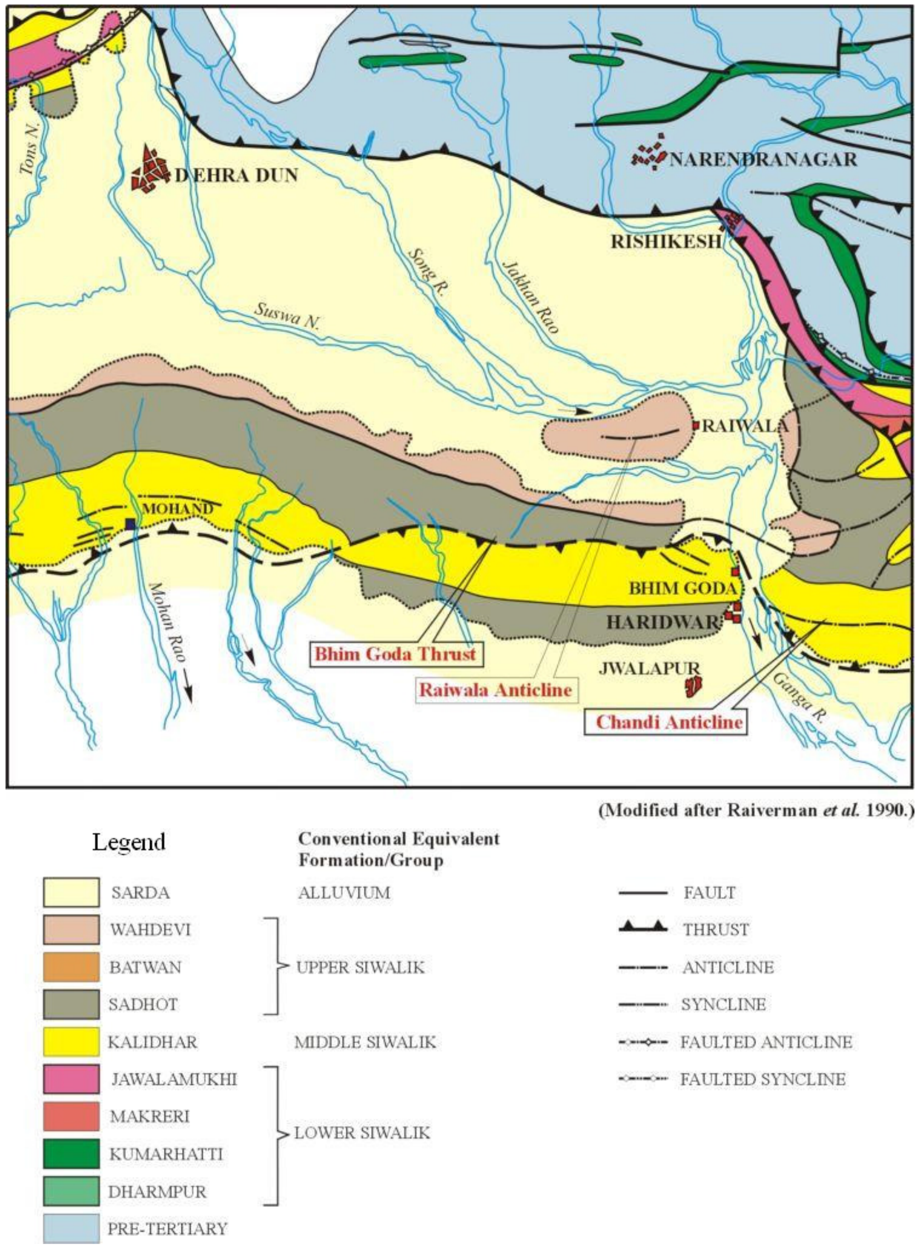

Fig. 1: Geological map of the Mohand area. The stratigraphic units of the area have been given in the legend (Modified after Raiverman *et al*., 1990)

The present study is based on detailed investigation of a typical Siwalik section as exposed in the Mohand area located south of Dehradun (Fig. 1). The geology of the area has been worked out in detail by Raiverman *et al.,* (1994). Burbank *et al.,* (1996) presented a regional tectonic framework of the foreland basin of the Himalaya. Srivastava and John (1999) studied deformation pattern in the Himalayan Frontal Fault zone of the adjoining Mohand-Khara area. Mishra and Mukhopadhyay (2002) worked out balanced structural cross-section of the Mohand Anticline and they modeled this structure as multi-bend fault-bend fold related to the Main Frontal Thrust. Bhattacharya (2005) proposed an "Expanding

Mountain Front Hypothesis" on the basis of the complicated thrust geometry of the Siwalik rocks in their internal domain. He suggested that in order to maintain the critical taper of the Siwalik wedge and to maintain the mountain topography in an equilibrium state, the Himalayan mountain front must adjust the additional topography (caused to structural thickening), by spreading or expanding the mountain front towards the foreland, *i.e.* southwards, as such, the Himalayan mountain front could be considered to be in a state of expanding southwards.

The present work incorporates a systematic study of the internal structures of the Siwalik rocks as mainly carried out along the Mohand-Dehradun traverse that closely follows the strike of the Siwalik lithounits.

Structure of the Siwalik Zone

The Siwalik Supergroup (Middle Miocene to Late Pleistocene) constitutes the most dominant lithostratigraphic unit of the Outer Himalaya. This unit is delimited to the north by a prominent tectonic plane, called the Main Boundary Fault (MBF), against the Outer Sedimentary Belt of the Lesser Himalaya, and is juxtaposed against the alluvium of the Ganga plain to the south, also with a tectonic contact named as Himalayan Frontal Fault (HFF). The Siwalik unit can, thus, be considered as a tectonic slice sandwiched between the MBF and the HFF. Megascopically, the Siwalik zone appears to show a relatively simple structural architecture. In some sections, it shows a rather simple north-dipping structure, while in other sections, the strata show open synclines and anticlines – so called Jura-type folds. The strata are also affected by a number of normal faults of varying dimensions.

In the light of our detailed investigation, a complicated system of thrust geometry has been observed in the internal domain of the Siwalik unit. Report of similar type of structures is scantly to almost negligible (see Bhattacharya, 2005). In the paper, the various types of structural geometries have been identified and their implications for the structure of the Outer Himalaya have been highlighted.

Internal structures and thrust geometry

Duplex:

Duplex seems to be the most common type of structure of the Siwalik rocks in the internal domain. In its most general form, the structure shows two parallel thrust faults (the roof and floor thrusts), and the intervening area shows a few parallel to sub- parallel faults. The latter commonly occur in imbricate fashion and are known as horses (Boyer and Elliott, 1982; Mitra and Boyer, 1986). The individual subsidiary faults (horses) commonly occur as planar units with straight sides (Fig. 2 A, B). The beds above and below the duplex, are more or less undisturbed.

The duplex structures in the area have significant bearing on the structure of the Siwalik rocks in the internal domain. According to Boyer and Elliott (1982), duplexes represent a mechanism for slip transfer from one glide horizon at depth to another at shallower levels. This slip transfer and creation of new horses cause structural thickening, duplex growth, and addition of mass to the moving thrust complex. It is therefore, quite possible that the Siwalik strata showing duplex structures have undergone structural thickening in their internal domain.

Imbricate Fan System:

Occasionally, a few faults join up together so as to give a branching array. Thus, a lower common thrust – sole thrust – can be identified. From the sole thrust, a few thrust slices spread upward such that they are asymmetrically shaped downward, thus giving rise to an imbricate fan system. Dip of individual thrust is in the same direction and increases from the sole thrust upward, and thus the structure looks like roof tiles in which the individual horses take up a more or less triangular shape. At some later stage, the thrusts are tangential to both the roof and sole thrusts (Fig. 2C). All these suggest progressive deformation and development of foreland directed thrusts (cf. Boyer and Elliot, 1982).

With the development of the above geometries, the imbricate structures appear to have caused thickening of the lithic units in which they are developed. The adjacent members of the lithic unit, where imbricate fan structure is not developed, however, do not show thickening. Development of the imbricate fan systems, as described here, can thus be considered to constitute a mechanism of thickening and shortening of the lithologic sequence of the Siwalik Supergroup.

Fault-Bend Folds:

At places, an antiform is formed due to riding of a thrust slice above a ramp. Occasionally, this gives rise to the development of a flat-topped anticline on the hanging wall, and an antiform–synform structure is also developed above a ramp. Formation of such folds – also called fault-bend-folds – has been commonly observed in relatively thin layers (upto few cm) of the Siwalik rocks (Fig. 2 D). With progressive deformation, the early-formed structure (antiform, in this case) continued to deform to give rise to more complicated structures. The structure in its present form has been described here as a fault propagation fold.

Antiformal Stack:

The antiformal stack (Fig. 2E) seems to be a common structure developed in the Siwalik rocks. It contains an anticline, which possibly have developed by curving up or up arching of the sole thrust. This appears to be a case when an early-formed duplex has undergone relatively larger displacement.

Presence of the antiformal stacks in the Siwalik rocks possibly indicates that the formation of the thrusts progressed in time downward and toward the foreland. As a result, most duplexes appear to have been folded by displacement on later faults/thrusts resulting in culminations in the earlier thrusts (cf. Twiss and Moores, 1992, p. 105).

Snakehead Anticline:

The snakehead anticline (Fig. 2F) is also a common type of structure in the Siwalik rocks. The structure is in the form of an anticline that rests over a ramp. Apparently, the anticline has not moved very far past the ramp. The limbs of the anticline show the development of a set of contraction faults oriented perpendicular to the layering. These faults may have developed during the formation of the snakehead anticline. The structure in the present form also looks like a domed unit that encloses another unit with a few curved duplex. Thus, the snakehead anticline shows an anticline resting over a ramp. But the presence of internal duplex system below the domed unit (or anticline) and above an apparently undisturbed bed seems to be quite typical, as such, this structure can also be designated here as a snakehead duplex.

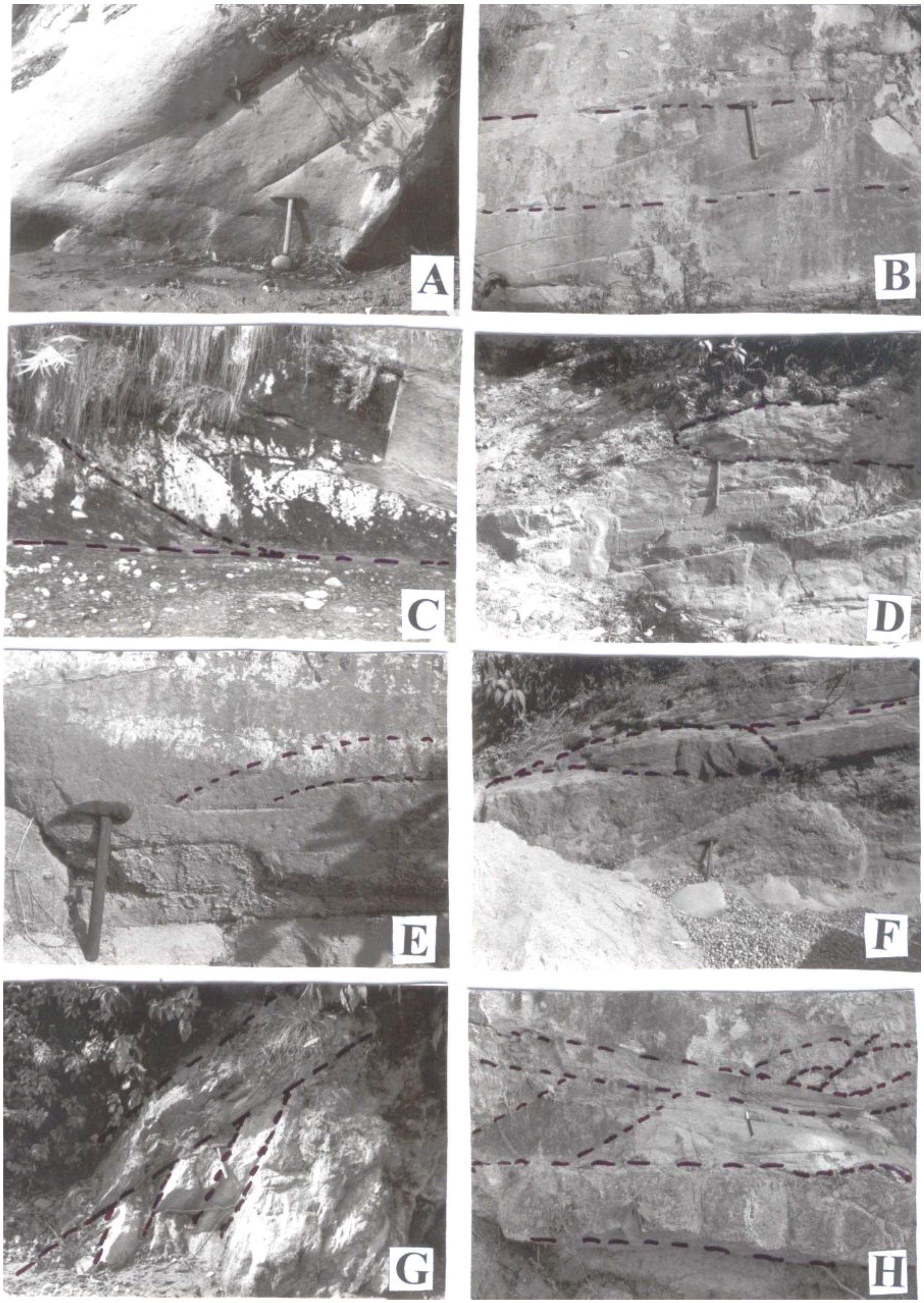
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Fig. 2: Field photographs of the structures/thrust geometries observed in the Siwalik rocks of the Mohand-Dehradun section. A – A thick sandstone layers showing *duplex* structure. B – *Duplex* structure in sandstone layers showing the horses within the lithic layers. C - *Imbricate fan system* in which the thrusts within a sandstone layer taper tangentially at the sole thrust below. D – A *Fault bend fold* is developed (central right side of the photograph) when a sub-horizontal fault is obstructed during its movement. E - *Antiformal stack* in the moderately bedded sandstone layers. F – *Snakehead anticline* in the moderately dipping sandstone beds. G – *Overstep thrust system* in the thickly bedded sandstone layers. A number of near-vertical thrusts are abruptly truncated against a moderately dipping (to the left) thrust. H – *Composite structure* developed due to progressive deformation and rotation of an initial lithic layers; the structure is characterized by the presence of more than one type of structure, *e.g.* a partly developed pop-up structure (upper right) enclosed within an open synform (central right), *duplex* with *horses,* etc.

Overstep Thrust System:

Occasionally, a few layers of low-dipping beds get abruptly truncated by another unit, which contains few parallel and steep faults dipping in the opposite directions (Fig. 2G). As a result, new thrusts appear to have developed in the hanging wall and the individual horses are disposed steeply. The structure, thus developed, has been designated here as a overstep thrust system.

Composite Structures:

In addition to the above, a few other types of structures are also developed in the Siwalik rocks. These structures appear to occur in a combination of a few structures. Since the authors have not seen any report of such structures in the literature, no specific nomenclature has been assigned to these structures in the present work. Instead, these have simply been grouped here as composite structures. A partly developed pop-up structure is seen enclosed within an open synform (Fig. 2H). The whole structure appears to have developed in a few stages. Initially, a pop-up structure may have developed as described above. At a later stage, the strata may have undergone gentle synformal folding. Some lower layers show duplex structures with horses within the bedding layers. Formation of such a (composite) structure clearly indicates considerable progressive deformation that may have caused quite a good deal of shortening in the associate lithologic units.

Discussion

Presence of a variety of structures and thrust systems in the internal domain of the Siwalik strata, as described in the paper, suggest a complicated structural history of these rocks. The geometry of the individual structures indicates progressive deformation of the early-formed structures. It is quite possible that initiation of deformation may have taken place by the reactivation of the anisotropies existing in the rock layers, mainly bedding planes. This may have given rise to the formation of bedding-plane thrusts. The latter, with progressive deformation, may have formed a series/variety of structures depending upon the local stress field and rheological factors, thus giving rise to ramps, horses etc. The progressive deformation also induced progressive reorientation of structures, thus leading to local reversal of directions of the early-formed minor thrusts giving rise to backthrusts, reversed horses, etc. At some advanced stages of deformation, reversal of the original thrusts, horses, etc. may have also taken place mainly due to space problem and to accommodate the additional stresses in the compressional regime. All this ultimately gave rise to a complicated system of structures and thrust geometries to the Siwalik rocks.

Most of the structures thus appear to have caused local thickening of the original lithologic layers by progressive and persistent internal deformation. If this is visualized on a regional scale, the entire Siwalik succession appears to have undergone thickening of its original lithologic layers to accommodate the additional and persisting stresses. Thus, the present-day Siwalik sequence may be described to occur in a structurally thickened state.

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