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A BALANCED CROSS-SECTION THROUGH THE EASTERN NEPAL SIWALIK HILLS, BAGMATI RIVER REGION, IMPLICATIONS FOR THE STRUCTURE OF THE SOUTHERN HIMALAYA

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ABSTRACT

A balanced cross-section has been constructed across the eastern Nepal Siwalik Hills along the Bagmati River in order to determine the structural geometry of the Himalayan foreland fold- thrust belt and to estimate tectonic shortening. The Siwalik Hills are underlain by a basal detachment, the Main Detachment Fault, at a depth of about 6.9km to 8km. The Main Boundary Thrust, the Chaura- Marin Thrust and the Main Frontal Thrust are splay thrusts off the Main Detachment Fault which ramp directly up-section to the surface through 6.8 to 7.7km of Siwalik Sediments with no major intervening thrust flats; the Sub-Himalayan foreland fold thrust belt displays an emergent imbricate- fan geometry. Shortening across the Bagmati section of the Siwalik Hills has been 20km, or 40%, while thrusting along the Main Boundary Thrust has resulted in a minimum of another 25km of shortening.

INTRODUCTION

Throughout its length the Himalayan orogen can be divided into four tectonic zones (Gansser, 1964, 1981). From north to south, these tectonic zones are (a) the Tibetan- Tethys Himalaya, (b) the Higher Himalaya, (c) the lesser Himalaya, and (d) the Sub-Himalaya (Figure 1). The Tibetan Himalaya consists of Cambrian or Ordovician to Eocene platform to deep-sea sediments deposited in the Tethys Sea (Gansser, 1964, 1981; Stocklin, 1980; Le Fort, 1989). In eastern Nepal the sediments of the Tibetan Himalaya are exposed only on the summits of Mount Everest and Lhotse, and within the Kathmandu synform (Stocklin, 1980; Schelling, 1989). The Higher Himalaya, or the Higher Himalayan Crystallines, of eastern Nepal consists of medium to high grade metamorphics (Bordet, 1961; Hashimoto et. al., 1973; Brunel, 1986; Schelling, 1989), of Precambrian age, intruded by Cambro-Ordovician granites in the Kathmandu region (Le Fort et. al., 1983; Scharer and Allegre, 1983), and by the Miocene leucogranites in the Rolwaling, Everest and Makalu regions (Scharer and Allegre, 1986). The Higher Himalayan Crystallines have been thrust a minimum of 100km south-south westwards over the underlying Lesser Himalayan Metasediments along the Main Central Thrust (Schelling, 1989; Schelling and Arita, in press). The Lesser Himalaya, or the Lesser Himalayan Metasediments, lying under the MCT and north of the Main Boundary Thrust (MBT), consist of Precambrian to lower Paleozoic (?), very low to medium grade metasediments, and granitic augen gneiss intruded by occasional doleritic sills. The Sub- Himalaya, or the Siwalik Hills, lie between the Main Boundary Thrust (MBT) to the north and the Ganges Plain to the south, and consist of Miocene to Plio- Pleistocene mollasse sediments (Gansser, 1981; West and Munthe, 1981; Tokuoka et al., 1986), the Siwalik Group, deposited in the foreland basins of the Himalaya.

The Sub- Himalaya of eastern Nepal is a presently active foreland fold- thrust belt which is amenable to structural analysis using the techniques of balancing cross- sections (Dahlstrom, 1969; Hossack, 1979; Elliot, 1983; Cooper and Trayner, 1986). This paper discusses the structural geometry of the sub- Himalayan Siwalik Hills along the Bagmati River. A balanced cross- section through the region is presented and the amount of

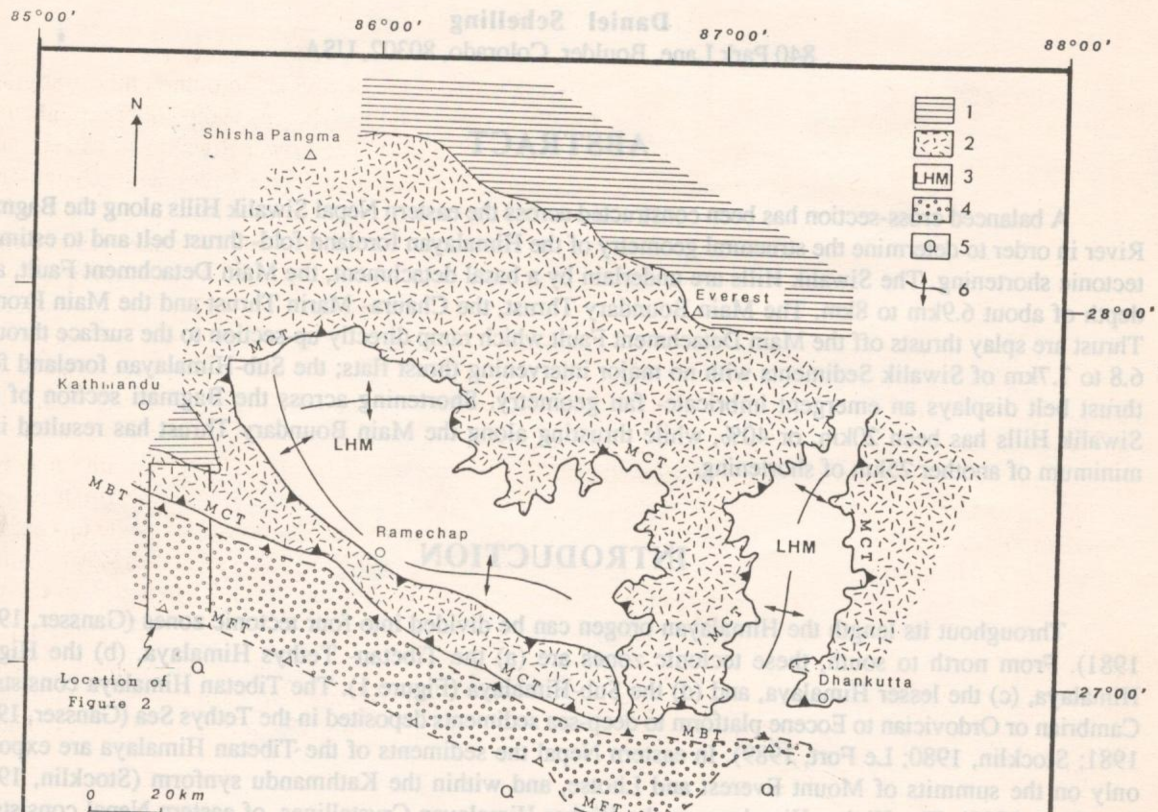

Figure 1. Tectonic map of the eastern Nepal Himalaya.

1 = Tibetan- Tethys Himalaya;
2 = Higher Himalayan Crystallines;
3 = Lesser Himalayan Metasediments;
4 = Sub-Himalaya;
5 = Quaternary alluvial sediments of the Ganges Basin: 6=antiform
MCT = Main Central Thrust; MBT = Main Boundary Thrust
MFT = Main Frontal Thrust. (Modified after Schelling, 1989).

shortening across the Siwalik Hills and along the Main Boundary Thrust has been calculated. The implications of the restored section for the structural geometry of the southern Himalaya of eastern Nepal are discussed.

THE SIWALIK GROUP

Throughout Nepal the Siwalik Group of the Sub- Himalaya can be divided into three lithostratigraphic units, the Lower Siwaliks, the Middle Siwaliks and the Upper Siwaliks (Hagen, 1969; Itihara et. al., 1972; West and Munthe, 1981; Herail et. al., 1986; Delcaillau et. al., 1987). The Lower Siwaliks of eastern Nepal consists primarily of gray, black, green and maroon mudstones and shales with minor white, beige or red sandstone beds. Along the Bagmati River the Lower Siwalik range in thickness from 2300m in the Main Frontal Thrust sheet to 3,100m in the Chaura-Marin Thrust sheet. The Middle Siwaliks consist predominantly of white and gray to beige, mica- rich sandstones and arkoses with minor, intercalated black, green, gray and beige mudstones. The cross- bedded sandstone sequences of the Middle Siwaliks are generally thicker than 10m and often up to tens of meters thick. Pebble- conglomerate beds are common in the upper sequences of the Middle Siwalik sandstones, the pebbles often of medium and high- grade metamorphic rocks and granites whose provenence lies within the Higher Himalayan Crystallines. The Middle Siwalik are 2900m thick along the Bagmati River. The Upper Siwaliks consist primarily of pebble and cobble conglomerates, along with minor sandstone and mudstone layers. The rounded and poorly sorted cobbles of the Upper Siwaliks may be up to 30cm in diameter. The Upper Siwalik sediments are more than 1,700m thick along the Bagmati River. In the Main Frontal Thrust sheet (in the southern Siwalik Hills) the Upper Siwalik sediments grade upwards into the sub- recent alluvial mudstones, sandstones and conglomerates of the Dun Valleys (eg. the Marin Dun near the Bagmati River, and in the Dabmai Dun Valley near Ilam in far- eastern Nepal). However, in the more internal thrust sheet of the Sub- Himalaya a sharp angular unconformity (of up to 90^{o}) is generally seen between the Upper Siwalik conglomerates and the sub- recent alluvial sediments The often non- horizontal disposition of recent and sub- recent alluvial sediments in the sub- Himalaya of eastern Nepal attests to the active nature of the Siwalik Hills (Williams, 1982; Herail et. al., 1986; Delcaillau et, al., 1987; Nakata, 1989)

The upward coarsening nature of the Siwalik Group in eastern Nepal, from the predominantly mudstone sequences of the Lower Siwaliks, through the sandstones of the Middle Siwaliks, to the primarily conglomeratic sequences of the Upper Siwaliks, records alluvial progradation in the Himalayan foreland basin during the southward migration of the Himalayan topographic front.

Magnetostratigraphic studies by Tokuoka et. al. (1986) in the Siwalik Group of the Arung Khola region of central Nepal (150km west of the Bagmati River) date the lowest exposed sequences of the Lower Siwaliks at approximately 15m.y. The Binai Khola Formation of Tokuoka et.al. (1986), which is the approximate equivalent of the Middle Siwalik sediments as defined in this paper, was deposited between about 8.5 m.y. and 2.5m.y., while the Chiwtan Formation of Tokuoka et. al. (1986), which is the approximate equivalent of the Upper Siwaliks of this paper, was deposited between about 2.5 and 1 m.y., (Tokuoka et. al.1986).

STRUCTURE OF THE BAGMATI RIVER REGION

South of the Mahabharat Lekh four major thrust faults are observed cutting the erosion surface (Figures 2 and 3a). The Main Central Thrust (MCT) is the fault which separates the overthrust Narayan Than biotite granites, of probable Cambro-Ordovician age (Le Fort, 1983; Scharer and Allegre, 1983), of the Higher

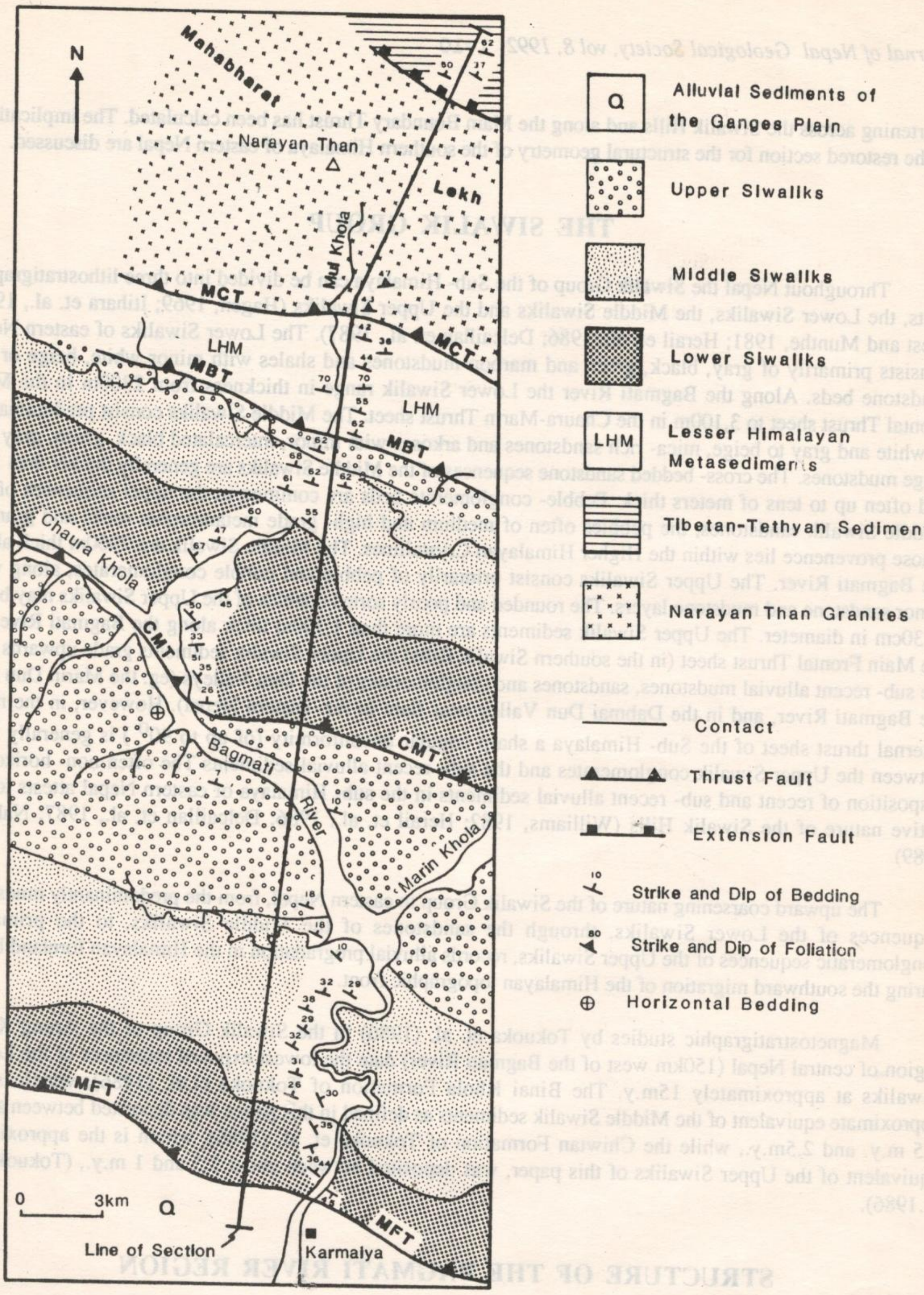

Figure 2. Geologic map of the Sub-Himalayan Siwalik Hills and the Mahabharat Lekh in the Bagmati- Mul Khola region of eastern Nepal.MCT = Main Central Thrust; MBT = Main Boundary Thrust; CMT = Chaura-Marin Thrust; MFT = Main Frontal Thrust.

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Himalayan Crystallines from the underlying Lesser Himalayan Metasediments. The north- northeast- dipping metaquartzites, phyllites and marbles of the Lesser Himalayan Metasediments have thrust over the Siwalik Group along the Main Boundary Thrust (MBT). Both the MCT and the MBT strike between N70^{o}W and N80^{o}W, sub- parallel to the bedding and foliation surfaces of the Siwalik Group. In the Mul Khola-Bagmati River region, Lesser Himalayan Metasediments have been thrust directly over Upper Siwaliks along the MBT (figures 2 and 3a).

South of the MBT lies the Chaura- Marin Thrust (the Main Dun Thrust of Herrail et. al., 1986, and Delcaillau et. al., 1987) along which the Lower Siwaliks of the hanging wall have been thrust over the Upper Siwaliks of the footwall. The Chaura- Marin Thrust cuts the erosion surface along the Chaura Khola and just north of the Marin Khola, with a general E-W trend. However, an oblique ramp in the footwall of Chaura - Marin Thrust has resulted in this thrust turning into a NW - SE orientation in the vicinity of, and along, the Bagmati River (Figure 2). The Chaura- Marin Thrust can be traced westwards, to the Hetaura region, where, it has been called the Hetaura Fault by Yoshida and Arita (1982), and eastwards, along the Marin Khola towards Dungrebans and Sindhuli Bazaar. Itihara et. al., 1972; Herail et. al., 1986; Delcaillau et. al., 1987 report the occurrence of Sub-Siwalik sedimentary rocks in the hanging wall of Chaura - Marin thrust east of the Bagmati Khola. The presence of these Sub- Siwalik rocks suggest that either (a) there is a lateral ramp in the hangingwall of the Chaura- Marin Thrust, or (b) that motion along the Chau-Marin has increase eastwards that along the Bagmati section Sub- Siwalik rocks are present in the hangingwall of the Chaura- Marin Thrust at depth.

The southernmost exposed thrust fault of the Himalayan orogen is the Main Frontal Thrust (MFT) which breaks the erosion surface at the topographic front of the Sub- Himalaya where the Siwalik Hills meet the Ganges Plain. Along the Bagmati River, in the vicinity of Karmaiya, Lower Siwaliks have been thrust over recent alluvial sediments of the Ganga Basin. The MFT trends roughly N70^{o} W in the vicinity of the Bagmati River.

North of the Mahabharat Lekh and Narayan Than a steeply north- dipping normal fault separates the Tibetan- Tethyan sedimentary rocks of the Kathmandu region in the hangingwall from the Narayan Than granites of the footwall (Figures 2 and 3). It is not clear whether motion along this normal fault predates or was coeval with thrusting along the MBT and within the Sub- Himalayan Siwalik Hills.

BALANCED CROSS SECTION

The balanced cross- section shown in Figure 3a displays the probable structural geometry of the Sub-Himalayan Siwalik Hills and the Mahabharat Lekh along the Bagmati River and Mul Khola.

Dips of bedding within the Main Frontal Thrust sheet are believed to define the dip of the underlying MFT, a hangingwall flat within, or at the base of the Lower Siwaliks probably being present along the MFT below the surface. The gradual flattening of dips to the north within the Main Frontal Thrust sheet suggest a listric- shaped MFT fault trajectory, and sub- horizontal bedding dips just south of the Chaura- Marin Thrust surface expose suggests that the MFT has approached reginal detachmen level and the Chaura-Marin. A thickness of 6,900m for the combined Lower, Middle and Upper Siwaliks in the Main Frontal Thrust sheet places the regional decollement, the Main Detachment Fault (MDF), at a depth of about 6.9 or 7km beneath the Chaura- Marin Thrust. A fold observed in the hangingwall of the MFT is interpreted as being a fault-propagation fold .

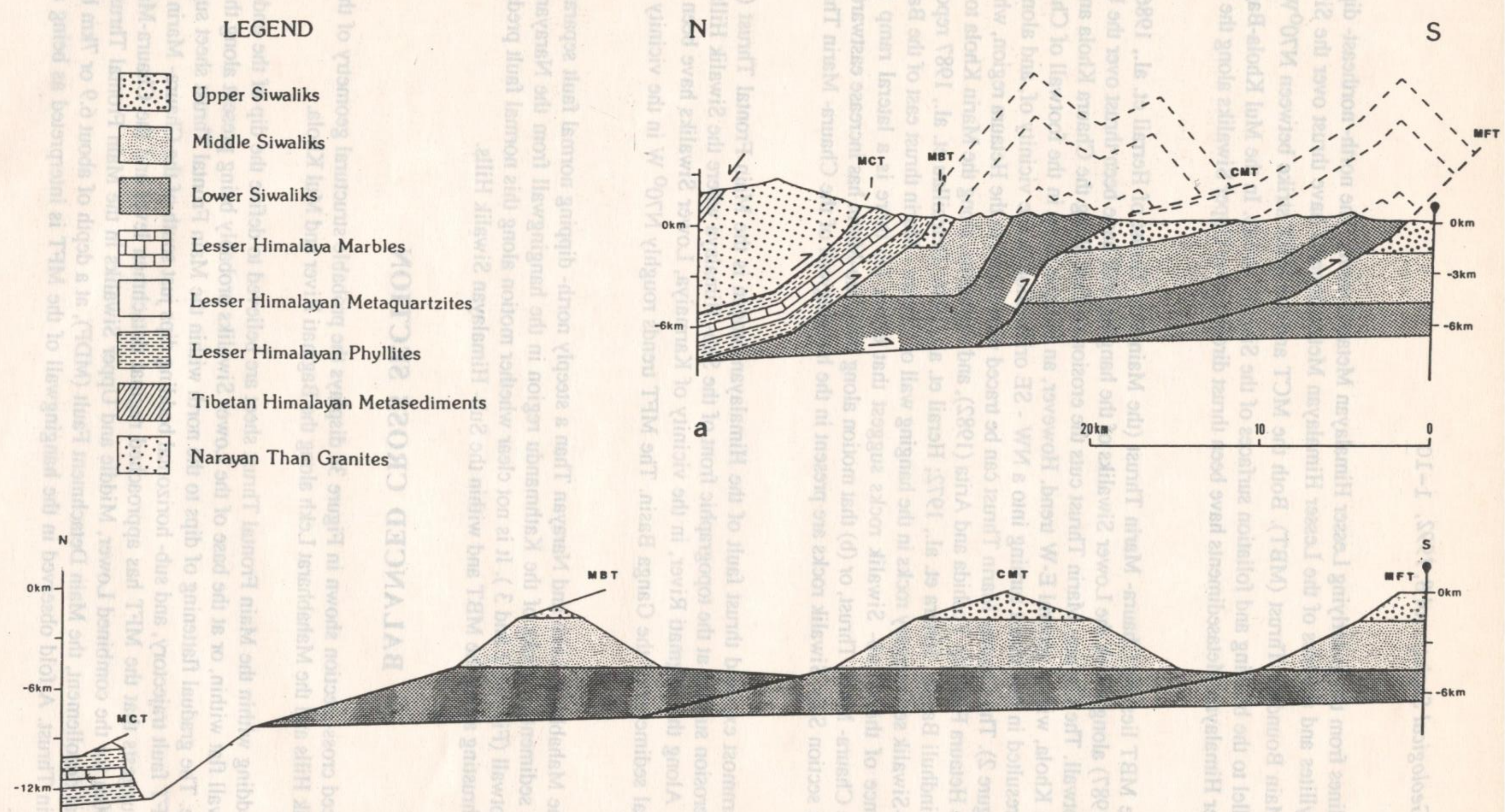

Figure 3. Balanced cross-section (3a) and restored cross- Section (3b) across the Mahabharat Lekh and the Siwalik Hills in the Bagmati River- Mul Khola region of eastern Nepal. No vertical exaggeration.

MCT = Main Central Thrust;
MBT = Main Boundary Thrust;
CMT = Chaura- Marin Thrust;
MFT = Main Frontal Thrust.

Steeply north- dipping bedding planes in the internal (northern) portions of the Chaura- Marin Thrust sheet reflect the steep dip of the underlying Chaura- Marin Thrust dipping 60^{o} or more to the N-NE. The anticline- syncline pair seen just north of the Chaura- Marin Thrust (Figure 3) is believed to have resulted from the flattening out of the Chaura- Marin Thrust within the Upper Siwaliks. Splay thrusts off the Chaura-Marin Thrust, within the haningwall, may be partly responsible for the complex structural geometry of the Lower Siwaliks within the Chaura- Marin Thrust sheet. The Siwalik Group in the hangingwall of the Chaura-Marin Thrust must flatten rapidly as it approaches its regional depth (approximately- 1,700m for the base of the Upper Siwaliks, and - 4,600m for the base of the Middle Siwaliks), and therefore the underlying Chaura-Marin Thrust must flatten rapidly as it approaches the MDF. A total thickness of Siwalik Group within the Marin- Chaura Thrust sheet of about 7,700m places the MDF at approximately 7.7km depth beneath the surface exposure of the MBT. The MDF thus lies between about 6.9km and 7.7km underneath the Sub-Himalayan Siwalik Hills of the Bagmati River region. The northward thickening of the Siwalik Group above the MDF, from 6,900m in the Main Frontal Thrust sheets to 7,700 m in the Chaura- Marin Thrust sheet, over a horizontal distance of 20km to 25 km as determined from the restored cross- section (Figure 3b) suggest a north-northeast dip of 1^{o} to 3^{o} for the MDF.

Bedding and foliation surfaces within the Lesser Himalayan Metasediments are believed to reflect the orientation of the underlying MBT, Which dips steeply (approximately 60^{o}) at the surface but flattens at depth. A hangingwall flat is shown within the phyllites of the Lesser Himalayan metasediments along the MBT; a footwall flat within Lesser Himalayan phyllites is shown along the MCT.

The Sub- Himalaya of eastern Nepal, in the Bagmati River region, thus displays an emergent imbricate- fan geometry, the MBT, Marin-Chaura Thrust and the MFT all ramping upwards to the erosion surface through 6.9km to 7.7 km. of Siwalik Group sedimentary section with no major intervening thrust flats.

Balancing of the Bagmati River cross- section (Figure 3), between the MBT and the MFT, shows that the Sub- Himalayan Siwalik Hills of this region have undergone 20km of shortening, or about 40% shortening. Motion along the MBT, which has thrust a 3,800 m thick section of Lesser Himalayan Metasediments over a 7,000 m thick package of Siwalik Group sedimentary rocks, has accomodated a minimum of another 25km of horizontal shortening. After section restoration the MBT is seen to lie 20 km north of it present position, and the MBT would not ramp steeply downwards into the Lesser Himalayan Metasediments in its footwall less than 65 km north of the Main Frontal Thrust (Figure 3b). The Main Detachment Fault, then, almost certainly remains at 7 to 8 km depth underneath the Mahabharat Lekh. A steep footwall frontal- ramp along the MBT, within the Lesser Himalayan Metasediments, if present, must lie north of the Mahabharat Lekh. A steep footwall ramp along the MBT (or the Main Detachment Fault) within the Lesser Himalayan Metasediments would result in an overlying, hangingwall fault- bend anticline, and such a ramp may therefore be responsible for one of the anticlines observed within the Ramechhap Window north of the Mahabharat Lekh (Figure 1)

Timing of thrusting within the Sub- Himalaya of eastern Nepal is difficult to constrain. The lack of any major unconformities within the Siwalik Group in both the Main Frontal Thrust sheet and the Chaura-Marin Thrust sheet suggests that extensive shortening along these two thrust faults post- dates Siwalik sedimentation. Magnetostratigraphy of Siwalik sediments in the Arung Khola region of central Nepal (Tokuoka et., al., 1986) places an upper age limit on the Upper Siwaliks in the Main Frontal Thrust sheet at approximately 1.5m.y if this date is accurate, then much of the 20 km of shortening observed in the Sub-Himalaya of the Bagmati region was accomplished during the last 1.5 m.y at a rate of 13mm to 14 mm per year.

CONCLUSION

A balanced cross- section constructed across the Siwalik Hills of eastern Nepal along the Bagmati River shows that the region is underlain by a basal detachment, the Main Detachment Fault, which lies at a depth of between 6.9 km and 8 km. The MBT, the Chaura- Marin Thrust and the MFT are splay thrusts off of the Main Detachment Fault, ramping directly upwards through the Siwalik Group sedimentary wedge to the erosion surface with no major intervening thrust-flats. The Sub- Himalayan foreland fold thrust belt of eastern Nepal has an emergent imbricate fan geometry. Total shortening across the Siwalik Hills, between the MBT, and the MFT, is on the order of 20 km, or 40%. Shortening within the Himalayan orogen, as a result of thrusting along the MBT has been a minimum of 25 km. The Mahabharat Lake is underlain by the main Detachment Fault, which probably dips gently to the north- northeast, and a footwall ramp along the MBT, within the Lesser Himalayan Metasediments, is thus believed to underlie the Ramechhap- Okhaldhungaa Window some 65 km or more north of the Himalayan topographic front .

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