Journal of Nepal Geological Society, 2011, Vol. 43 (Special Issue), pp. 83–101

Lithostratigraphy of the Siwalik Group, Karnali River section, far-west Nepal Himalaya

***Ashok Sigdel[1], Tetsuya Sakai[1], Prakash D. Ulak[2], Ananta P. Gajurel[2] and Bishal N. Upreti[2]**
[1]*Department of Geoscience, Shimane University, Matsue 690-8504, Japan*
[2]*Department of Geology, Tri-Chandra Campus, Tribhuvan University, Ghantaghar, Kathmandu, Nepal*
*(*Email: ashoksigdel7@yahoo.com)*

ABSTRACT

The Siwalik Group (4,000 – 6,500 m thick) lying in the southern flank of the Himalaya represents ancient Gangetic plain deposits. The Siwalik Group along the Karnali River section is the target of this stratigraphic study. Stratigraphically, the Karnali River section is divided into the Chisapani Formation (equivalent to the Lower Siwaliks, 2045 m in thickness), Baka Formation (equivalent to the Middle Siwaliks, 2740 m), and the Kuine and Panikhola Gaun Formations (equivalent to the Upper Siwaliks, 1500 m), in ascending order. The Chisapani Formation is composed of red mudstones and fine- to medium-grained sandstones. The Baka Formation is composed of medium- to coarse-grained sandstones and pebbly sandstones, interbedded with greenish-grey mudstones. The Kuine Formation consists of clast-supported and imbricated pebble to cobble conglomerates, whereas the Panikhola Gaun Formation consists of thick matrix-supported pebble, cobble and boulder conglomerates. The stratigraphy of the Karnali River section and its correlation with other Siwalik sections shows that deposits filling the Himalaya foreland basin vary greatly in both space and time. The lithostratigraphic boundaries of the Lower - Middle and the Middle - Upper Siwaliks are diachronous, with age ranges of roughly one and two Myr, respectively. Earlier appearance of coarse 'salt and pepper' sandstones marking the base of the Middle Siwaliks, indicating sediment supply from the Higher Himalayas, shows that the paleo-Karnali River had a larger drainage basin system that cut back into the Higher Himalaya earlier than in other areas. The age of the Middle - Upper Siwaliks boundary, estimated to be at ~3.9 Ma, suggests earlier progradation of the alluvial fan system than in other areas, and more voluminous sediment supply than in other Nepalese Siwalik sections. Local climatic effects should be minimal in large drainage basins, and hence basins of this size should be most suitable for reconstruction of paleoclimatic history in the Siwalik Group. The Karnali River succession is thus a key sedimentary succession, well-suited for future detailed analysis of paleoclimate related to the uplift of the Nepal Himalayas.

Keywords: Lithostratigraphy, correlation, diachronous boundary, Karnali River, Siwalik Group

Received: 15 December 2010 **revision accepted:** 15 July 2011

INTRODUCTION

The Siwalik Group was deposited in the Himalayan foreland basin system during the Middle Miocene to Early Pleistocene, and now occupies the southern frontal part of the Himalayan fold thrust belt (Gansser 1964, Johnson et al. 1983, Tokuoka et al. 1986, Burbank et al. 1996, DeCelles et al. 1998, Robinson et al. 2006). It consists of a 4-6 km thickness of fluvial sediments laid down in the paleo-foreland basin situated above the downwardly flexured Indian plate, in a basin formed by the rising Himalaya (Prakash et al. 1980, Mugnier et al. 1999). The Siwalik Group is bounded to the north by the Main Boundary Thrust (MBT) and to the south by the Main Frontal Thrust (MFT), which overthrusts Quaternary deposits (Nakata 1989, DeCelles et al. 1998) (Fig. 1). The Main Dun Thrust (MDT) (Hérail and Mascle 1980) is another primary thrust which constitutes a series of relayed thrusts propagating westward as ramp folds (Mugnier et al. 1998). The Siwalik Group has been the focus of numerous lithostratigraphic, sedimentologic and chronostratigraphic studies because of its great potential for elucidating the tectonic, climatic and erosional histories of the Himalaya and the surrounding area (Auden 1935, Hagen 1969, Glennie and Ziegler 1964, Opdyke et al. 1982, Tokuoka et al. 1986, Willis 1993, Corvinus and Nanda 1994, Sah et al. 1994, Zaleha 1997, Nakayama and Ulak 1999).

The earliest lithological and paleontological studies of the Siwaliks were made in the Potwar Basin of Pakistan, where a tripartite subdivision based on lithology and six fold faunal zones was first established. The faunal zones correspond to lithofacies. The tripartite division consists of the Lower Siwaliks (Kamlial and Chinji Formations), Middle Siwaliks (Nagri and Dhok Pathan Formations), and the Upper Siwaliks (Tatrot and Pinjor Formations) (Piligram 1913, Lewis 1937, Auden 1935, Opdyke et al. 1982, Barry et al. 1982, 1985). Other work established a lithostratigraphy based on proportions of mudstone, sandstone and conglomerate and defined the Kamlial, Chinji, Nagri, Dhok Pathan, Tatrot, Pinjor and Boulder Conglomerate Formations, along with

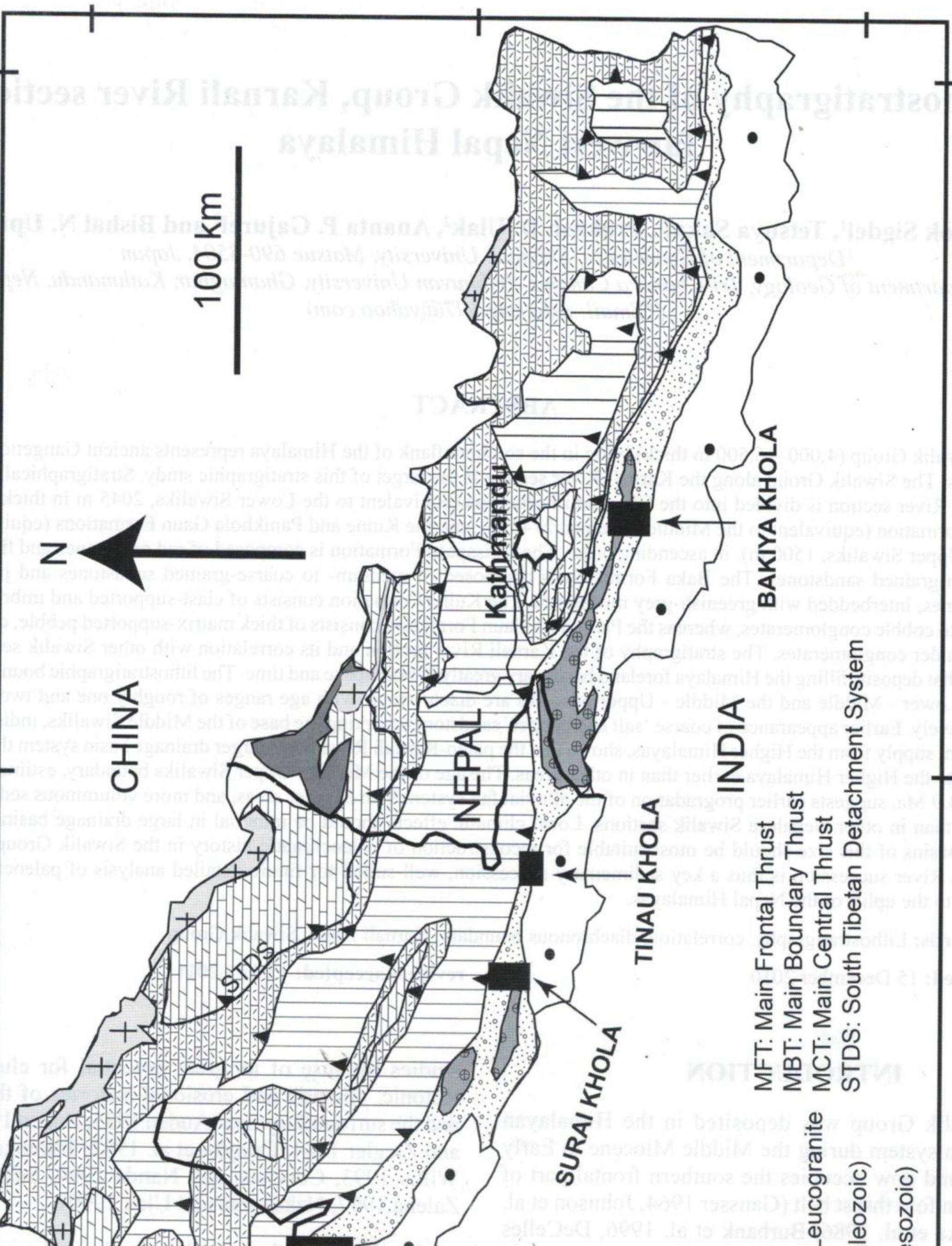

Fig. 1: Generalized geological map of Nepal Himalaya (modified from Amatya and Jnawali 1994). Open rectangle indicates the location of the study area.

several magnetostratigraphic studies (Fatmi 1973, Shah 1977, Johnson et al. 1982, 1985, Tauxe and Opdyke 1982, Raza 1983, Willis 1993, Zaleha 1997). These divisions are now used as the standard stratigraphic nomenclature in Pakistan.

In India, the classification from the Potwar Basin has been broadly applied (Johnson et al. 1983, Tandon et al. 1984, Sangode et al. 1996, Kumarvel et al. 2005). Several studies have, however, defined different stratigraphy for some areas of the Indian Siwaliks (Gupta and Verma 1988, Ranga Rao et al. 1988, Kumar 1997, Gupta 1997, 2000).

Since the earliest geological studies of the Siwalik Group in Nepal Himalaya, stratigraphic classifications have been proposed using the classical tripartite nomenclature (Lower, Middle and Upper Siwaliks) or using local stratigraphic names (Auden 1935, Glennie and Ziegler 1964, Hagen 1969, Sharma 1977, Yoshida and Arita 1982, Tokuoka et al. 1986, DMG 1987,2003, Corvinus and Nanda 1994, Sah et al. 1994, Dhital et al. 1995, DeCelles et al. 1998, Ulak and Nakayama 1998, Ojha et al. 2000, Gautam and Fujiwara 2000, Robinson et al. 2006), as in the Hetauda-Bakiya Khola in central Nepal, the Arung Khola -Tinau Khola area in central western Nepal, the Surai Khola area in western Nepal and in the Khutia Khola and Karnali River areas in far western Nepal (Table 1).

The classical tripartite classification (Lower, Middle and Upper Siwaliks) was mainly based on lithofacies and biostratigraphy in limited areas where vertebrate fossils were available. Unfortunately, the Nepalese Siwaliks are generally poor in vertebrate fossils, and in some areas none have been found. Studies in the last 30 years have shown that large lithological variations occur in the Nepalese Siwaliks. Tokuoka et al. (1986, 1990) established a four-fold classification in the Arung-Tinau Khola area of west central Nepal. They divided the succession into the Arung Khola, Binai Khola, Chitwan, and Deorali Formations, in ascending order. The Upper Siwalik was divided into two formations, where the debris-flow deposit-dominated interval in the uppermost part of the Upper Siwalik was identified as a separate stratigraphic unit (Deorali Formation). The same four-fold classification was applied in the Hetauda-Bakiya Khola area in central and eastern Nepal (Sah et al. 1994, Ulak and Nakayama 1998). Corvinus and Nanda (1994) subsequently established the traditional stratigraphy in the Surai Khola area of western Nepal. Their classification and correlation was based on both lithology and fossils. Dhital et al. (1995) retained the stratigraphy of the Surai Khola area and defined five formations, together with description of sedimentary structures and the petrography of sandstones.

Table 1: Classification of the Siwalik Group of the Nepal Himalaya

Auden (1935)	Glennie & Ziegler (1964)	Hagen (1969)	Sharma (1973)	Yoshida & Arita (1982)	Tokuoka et al. (1986, 1988)	Sah et al. (1994), Ulak and Nakayama (1998)	Corvinus & Nanda, (1994) and Dhital et al. (1995)	DMG(1987, 2003) Ojha et al.(2000), Gautam and Fujiwara (2000), Robinson et al. (2006),	Present study
1	2	3	4	5	6	7	8	9	10
Upper Siwalik	Conglomerate facies	Upper Siwalik	Upper Churia Group	Upper Siwalik	Deorali Formation	Churia Mai Formation	Dhan Khola Formation	Upper Siwalik	Panikhola Gaun Formation
					Chitwan Formation	Churia Khola Formation	Dobata Formation		Kuine Formation
Middle Siwalik		Middle Siwalik		Middle Siwalik	Binai Khola Formation	Amlekhganj Formation	Surai Khola Formation	Middle Siwalik	Baka Formation
	Sandstone facies		Lower Churia Group				Chor Khola Formation		
Lower Siwalik		Lower Siwalik		Lower Siwalik	Arung Khola Formation	Rapti Formation	Bankas Formation	Lower Siwalik	Chisapani Formation

1) Udaipur Garhi-Anraha and Amlekhganj-Sanotar areas; 2) Kali Ganga, Sarda river, Taptakunda, Koilabas, Butwal, Kaligandaki, Amlekhganj, Hetauda and Saptakoshi areas; 3) Various parts of Nepalese Siwaliks; 4) Dang, Koilabas, Butwal, Amlekhganj, Trijuga and Kankai River areas; 5) Surai Khola, Patharkot, Banganga, Butwal, Narayani River and Hetauda areas; 6) Arung Khola, Tinau Khola, Binai Khola areas; 7) Amlekhganj, Hetauda, Bakiya Khola areas; 8) Surai Khola; 9) Far western Nepal around the Khutia Khola and Karnali River 10) Karnali River

The Karnali River section of westernmost Nepal has been the locus of a variety of studies (Gautam and Fujiwara 2000, Huyghe et al. 2005, Szulc et al. 2006, Van der Beek et. al. 2006, Bernet et al. 2006). These studies focused on petrography, isotopes and age dating. DMG (1987, 2003) examined the area on a broad scale and divided it into the Lower, Middle, and Upper Siwaliks. Gautam and Fujiwara (2000) studied the magnetostratigraphy and some lithological characteristics of the sediments, and defined the Lower and Middle Siwaliks based on age and grain size. That study simply adapted the criteria followed by Rosler et al. (1997) and Mugnier et al. (1998). However, they did not examine lithofacies characteristics at meter-scale and also did not define the exact Middle - Upper Siwalik boundary, and a large part of the Upper Siwalik remains unstudied and undated. Their study was thus incomplete, being focused on age, and not on lithology. To define the lithostratigraphy, the typical characteristics (type locality, lithofacies, fossils, marker beds) of particular sections need to be assessed individually, rather than simply being based on comparison with adjacent areas, and following the divisions made at those sites. Consequently, previous stratigraphic work in the Karnali River section does not adequately follow the international stratigraphic nomenclature. Furthermore, those studies did not address detailed meter-scale variations of lithology and grain size in the area, which is required for the future work on paleoclimate and tectonic evolution. It is thus difficult to correlate with other sections of the Siwalik Group in Nepal where four or five-fold classifications (along with several subdivisions) have been adopted (Table 1). This study aims to build a new lithostratigraphy of the area, to permit comparison and correlation among the different sections of the Siwalik Group of the Nepal Himalayas, and with the Potwar Basin in Pakistan. This will establish a template for future research on the tectonic evolution and paleoclimate of the Himalaya and surrounding regions.

GEOLOGICAL SETTING

The tripartite lithological division (Lower, Middle and Upper) has previously been applied to the Siwalik Group in the Karnali area (DMG 1987, 2003, Mugnier et al. 1998, 1999). The age range up to the Middle Siwalik (15.8 to 5.2 Ma) was obtained by a paleomagnetic study (Gautam and Fujiwara 2000). Structurally, this section consists of two large belts separated by the MDT, which is an extensive and major and intra-Siwalik thrust (Mugnier et al. 1999) (Figs 2, 3). The southern belt is about 12 km wide, north to south. The previous work indicated that this belt contained all three lithologic units (Lower, Middle and Upper Siwaliks), and had a total thickness of 4-6 km (Mugnier et al. 1998). The northern belt is about 6 km in width. This study focuses on the southern belt, because of the presence of good exposures from the lowermost to the uppermost part of the Siwalik Group, between Chisapani Bazaar in the south, and Panikhola Gaun Village in the north (Fig. 3). The northern belt is mostly covered by forest, and exposure is poor. It is thus excluded from this study.

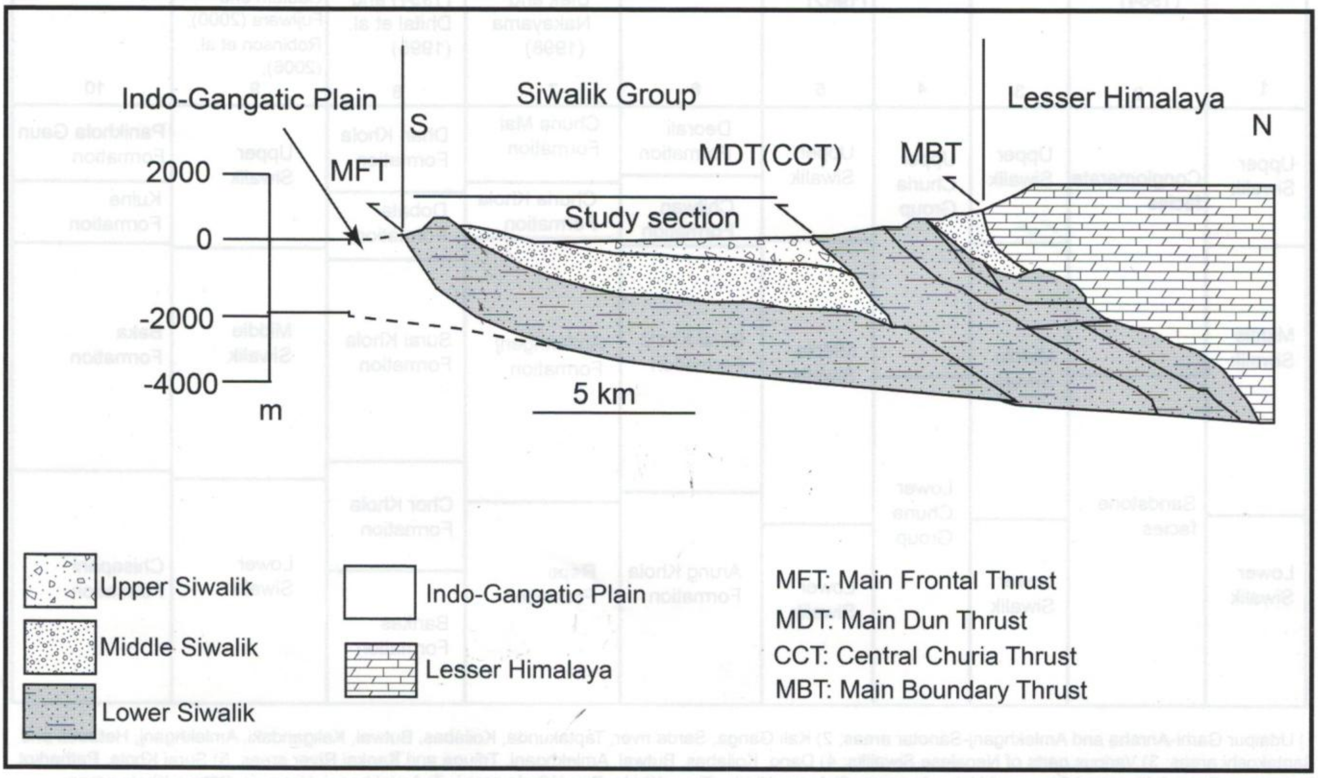

Fig. 2: Cross-section along the Karnali River section showing several geotectonic zones (modified from Mugnier et al. 1999).

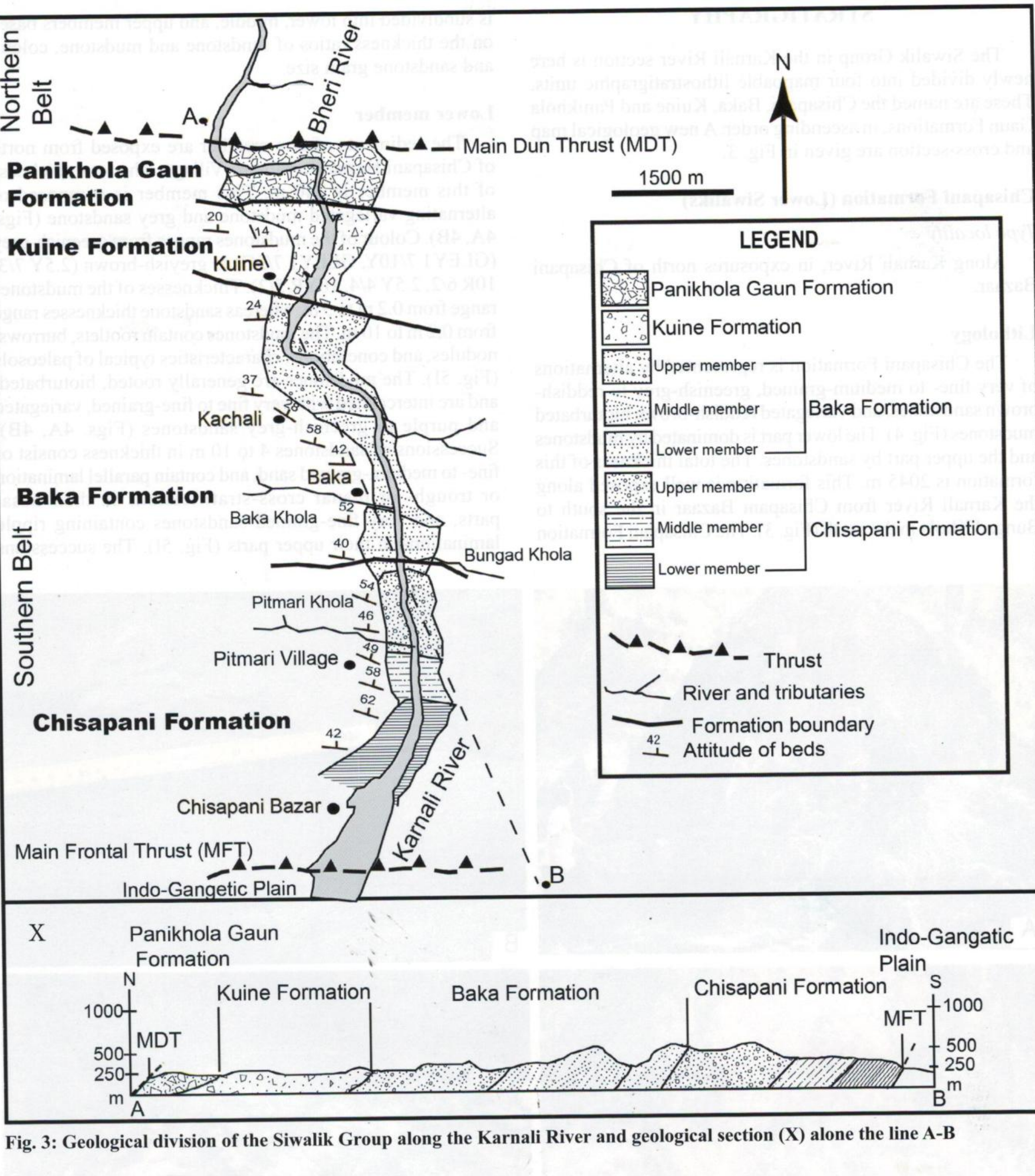

Fig. 3: Geological division of the Siwalik Group along the Karnali River and geological section (X) alone the line A-B

METHOD

This study is based on geological traverses only along the river sections. Survey could not be expanded to nearby areas because restricted access areas of the Bardiya National Park extend to the east, and dense forest covers most of the area to the west. Classification of the rock units into formations and members was made based on grain size, color, and thicknesses of sandstone, mudstone and conglomerate beds. The thicknesses of the individual beds, colour (Munsell colour chart), and grain size changes within the beds were measured in detail, and the data compiled as columnar sections. Existing paleomagnetic data (Gautam and Fujiwara 2000) permits regional correlation with other Nepalese Siwalik sections.

STRATIGRAPHY

The Siwalik Group in the Karnali River section is here newly divided into four mappable lithostratigraphic units. These are named the Chisapani, Baka, Kuine and Panikhola Gaun Formations, in ascending order. A new geological map and cross-section are given in Fig. 3.

Chisapani Formation (Lower Siwaliks)

Type locality

Along Karnali River, in exposures north of Chisapani Bazaar.

Lithology

The Chisapani Formation is represented by alternations of very fine- to medium-grained, greenish-grey to reddish-brown sandstones, and variegated reddish-brown bioturbated mudstones (Fig. 4). The lower part is dominated by mudstones and the upper part by sandstones. The total thickness of this formation is 2045 m. This formation is well exposed along the Karnali River from Chisapani Bazaar in the south to Bungad Khola in the north (Fig. 3). The Chisapani Formation is subdivided into lower, middle, and upper members based on the thickness ratios of sandstone and mudstone, colour, and sandstone grain size.

Lower member

The sediments of this member are exposed from north of Chisapani Bazaar to Pitmari Village. The total thickness of this member is 340 m. This member is composed of alternating variegated mudstone and grey sandstone (Figs. 4A, 4B). Colour of the mudstones ranges from greenish-grey (GLEY1 7/10Y, GLEY1 7/5G) to greyish-brown (2.5Y 7/3, 10R 6/2, 2.5Y 4/4, 10YR 5/2). Thicknesses of the mudstones range from 0.2 m to 5 m, whereas sandstone thicknesses range from 0.2 m to 10 m. The mudstones contain rootlets, burrows, nodules, and concretions, characteristics typical of paleosols (Fig. 5I). The mudstones are generally rooted, bioturbated, and are intercalated with very fine to fine-grained, variegated and purple to greenish-grey sandstones (Figs. 4A, 4B). Successions of sandstones 4 to 10 m in thickness consist of fine- to medium-grained sand, and contain parallel lamination or trough- or planar cross-stratifications in their basal parts, and very fine-grained sandstones containing ripple laminations in their upper parts (Fig. 5I). The successions

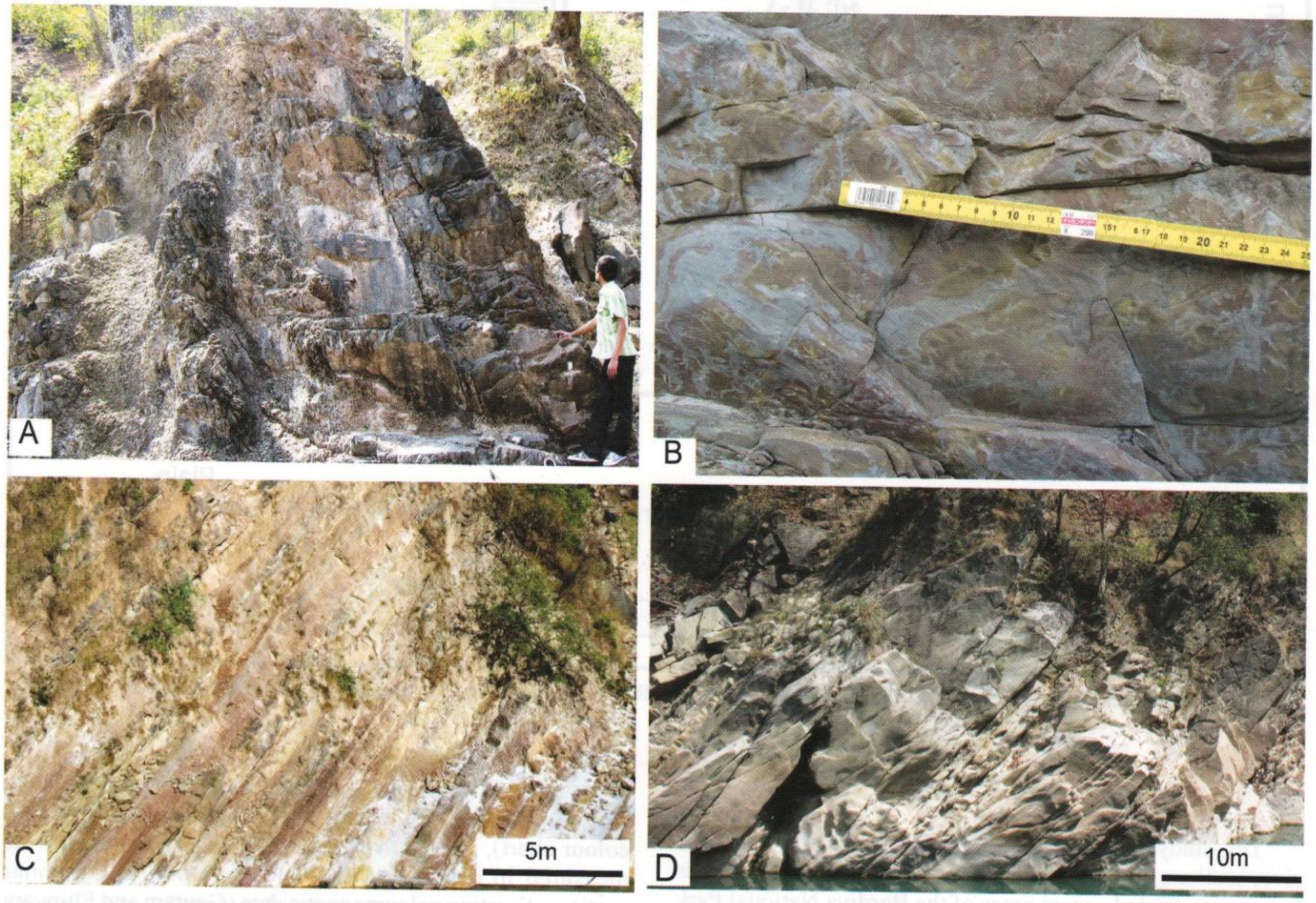

Fig. 4: Outcrop photographs of the Chisapani Formation A) Mudstone-dominated interval in the lower member. Person for scale (1.7 m). B) Variegated, rooted and bioturbated mudstone in the lower member. The scale is 25 cm long. C) Red mudstone - dominated interval in the middle member. D) Thicker sandstones in the upper member.

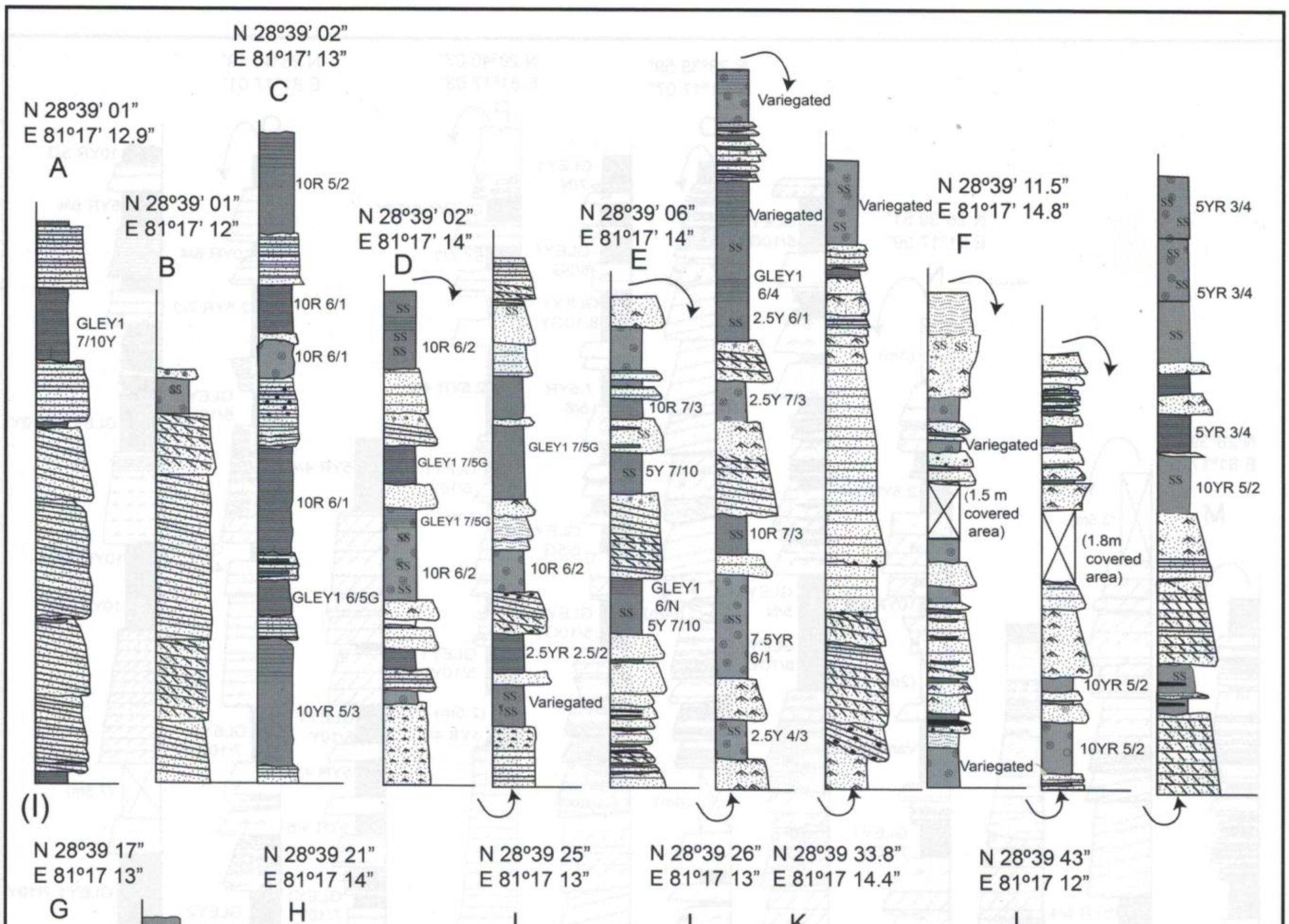

Fig. 5: Typical columnar sections of the Chisapani Formation. I) Lower member II) Middle member. Letters A, B, C… Q (with latitude and longitude) at the top of each column indicate the locations of the measured sections.

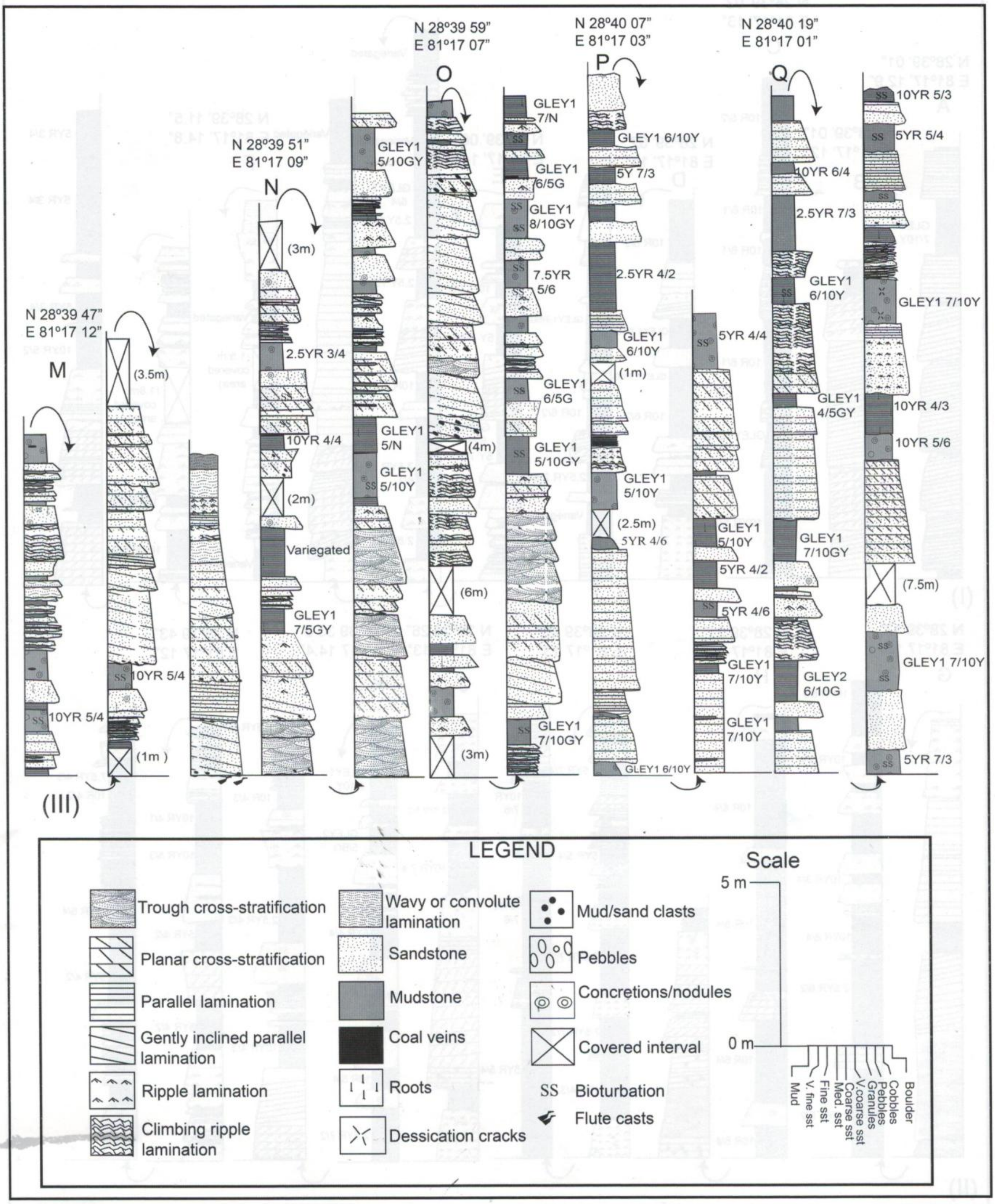

Fig. 5 (Contd.): Typical columnar sections of the Chisapani Formation. III) Upper member. Letters A, B, C… Q (with latitude and longitude) at the top of each column indicate the locations of the measured sections.

show fining-upward trends. The bases of the fining-upward successions are marked by erosional surfaces, upon which mud clasts are scattered. The frequency of thicker sandstone successions tends to increase up-section in this member.

Middle member

The middle member has a total thickness of about 580 m, and is well exposed around Pitmari Village. It is characterized by fine- to coarse-grained sandstones and bioturbated, reddish-brown (5YR5/4, 5YR 5/3) to brown (7.5YR 5/3) or grey mudstones (GLEY 1 7/10Y). The red mudstones (10YR 4/6, 2.5YR 5/4, 7.5YR 5/4, 7YR 5/3, 5YR 5/3, 5YR 3/2) contain rootlets, burrows, nodules, and concretions typical of paleosols, and are frequently interbedded among the sandstones in this member (Figs. 4C, 5II). The nodules within the red mudstones consist mostly of calcium carbonate and iron oxides (Fig. 5II). The sandstone beds are thin (0.5-1m) and interbedded with red mudstones. These sandstones exhibit parallel and ripple lamination (Fig. 5II). The thicknesses of the individual sandstone and mudstone beds range from 0.2 to 12 m. The ratio of sandstone and mudstone is roughly equal in the lower half of this member, but the proportion of sandstone increases up-section. Medium- to coarse-grained sandstones first appear in the upper half of this member. This type of sandstone is referred to as "salt and pepper" sandstone, because it contains significant amounts of a black mineral (biotite) interspersed with white minerals such as quartz and feldspar (Nakayama and Ulak 1999). Generally, sets of sandstones form fining-upward successions. The thickness of the fining-upward successions ranges from 6 to 12 m. The fining-upward successions contain trough and planar cross-stratification, with parallel lamination in the lower part and ripple laminations in the upper part, grading upward into mudstones. The bases of the successions are almost flat, or feature shallow erosional depressions up to 0.5 m in relief.

Upper member

The upper member is well exposed between Pitamari Khola and Bungad Khola along the Karnali River and road sections. Total thickness is about 1125 m. The upper member consists mainly of medium- to coarse-grained, thick bedded, grey sandstones and laminated mudstone interbeds. The laminated mudstones range from greenish-grey (GLEY1 5/10Y, GLEY1 5/10GY, GLEY1 5/N)) to yellowish-brown (10YR 5/3, 10YR 5/4, 2.5YR 4/2), and contain rootlets, burrows, nodules and concretions characteristic of paleosols. Thicknesses of the sandstone and mudstone beds range from 0.5 to 15 m and 0.1 m to 4 m, respectively. The reddish-brown mudstones are less frequent than in the lower and middle members. Sets of sandstone beds (up to 15 m thick) show fining-upward trends more commonly than the lower and middle members (Fig. 4D). The basal parts of the successions are dominated by trough cross-stratifications or parallel laminations which are followed by planar cross-stratifications and ripple laminations (Fig. 5III, locs. M, N, O). The thinly-bedded, fine-grained sandstones (0.5 to 1 m) contain parallel laminations and ripple lamination or climbing ripples. Some of these thinly-bedded sandstones are massive and grade upward into the overlying mudstones (Fig 5III, loc. Q). The bed bases in the lower part of the fining-upward successions are erosional, and mud clasts are scattered upon them. Coarse-grained sandstones ("salt and pepper") also occur at the base of this member, and are interbedded at 300 m intervals in the lower part. The mudstone-dominated intervals contain thin sandstones and have sheet-like geometry. These mudstones are about 4 m thick, whereas thickness of the sandstone interbeds ranges from 0.2 to 1 m. The sandstone interbeds feature parallel lamination and ripple and climbing-ripple lamination, mostly in the upper half of the member.

Age

The age of this formation ranges from 15.8 to 9.6 Ma, based on magnetic polarity (Gautam and Fujiwara 2000). The ages of the lower, middle and upper members are 15.8 - 15.2 Ma, 15.2 - 13.2 Ma and 13.2 - 9.6 Ma, respectively.

Stratigraphic relationship

Chisapani Formation almost corresponds to the Lower Siwalik as proposed by Gautam and Fujiwara (2000), but differs from that by DMG (1987, 2003). DMG placed the boundary between the Lower and Middle Siwalik near Pitmari Khola. However, this is actually the boundary between the lower and middle members of the Chisapani Formation (Lower Siwalik) based on our present study. We also confirmed that the boundary between the Lower and Middle Siwalik is situated near Bungad Khola, where first appearance of continuous thick "salt and pepper" sandstones is found. The appearance of the interval dominated by red mudstone is defined as the boundary between the lower and the middle members, and the first appearance of "salt and pepper" sandstones is defined as the boundary between the middle and upper members. The Main Frontal Thrust (MFT) forms the lower limit of this formation. The upper boundary is conformable with the overlying Baka Formation (Fig. 3).

Baka Formation (Middle Siwaliks)

Type Locality

The type locality of this formation is around Baka Village.

Lithology

The Baka Formation is distributed between Baka Village in the south and Satbaseri-Kuine Villages in the north. Total thickness is about 2740 m. Baka Formation is composed of thickly bedded, medium- to very coarse-grained sandstones and pebbly sandstones, along with mudstone interbeds (Fig. 6). All of the sandstones contain abundant biotite, quartz, and feldspar, and hence exhibit "salt and pepper" characteristics. These sandstones are interbedded with greenish-grey, olive-brown to grey laminated mudstones (GLEY1 7/10Y, GLEY1 6/5GY, GLEY1 7/5GY, 5Y 5/6, 2.5Y 4/3, GLEY1 4/N, GLEY2 5/10G). The Baka Formation is also subdivided into lower, middle and upper members.

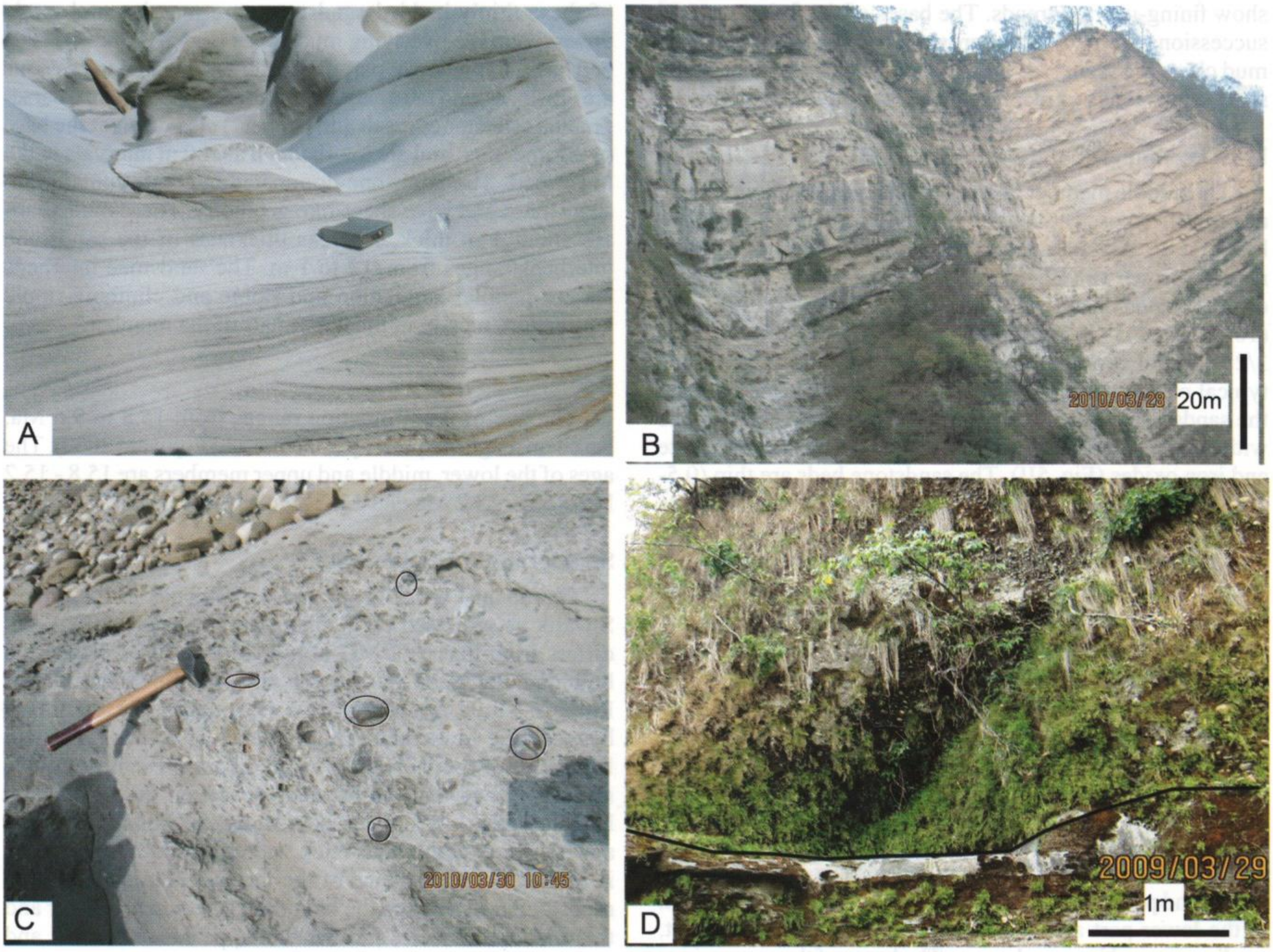

Fig. 6: Outcrop photographs of the Baka Formation. A) A "salt and pepper" sandstone, in which white grains are quartz and feldspar and black grains are mica. The compass is 7 cm long. B) Thick amalgamated sandstone in the middle member. C) Pebbly sandstones in the upper member. The hammer is 30 cm long. D) Boundary (black line) between the Baka and Kuine Formations.

Lower member

The main exposures of this member are distributed from Bungad Khola to Baka Village (Fig. 3). Total thickness of this member is about 540 m. It is characterized by thick medium- to coarse-grained "salt and pepper" sandstones. Thickness of individual sandstone successions ranges from 3 to 17 m, whereas mudstone intervals range from 0.2 to 2 m in thickness. Individual sets of thick sandstone successions overlying mudstone beds show fining-upward trend (Fig. 7I). The bases of these successions are erosional, with mud clasts scattered on these surfaces. The basal parts of the thick sandstone successions generally feature trough and planar cross-stratification, followed by ripple laminated beds, and massive beds in the upper parts of the successions (Figs. 6A, 7I, locs. R, S, T). Thinner sandstone beds (0.5 to 3 m) contain either parallel or ripple and climbing ripple laminations. The mudstones are laminated and are greenish-grey (GLEY1 7/10Y, GLEY1 6/5GY, GLEY1 7/5GY) to greenish-brown (2.5Y 6/4). Olive brown (2.5Y 5/6 2.5Y 4/3) mudstones containing rootlets, concretions and nodules characteristic of paleosols occur frequently in this member (Fig. 7I).

Middle member

The middle member of the Baka Formation is distributed between Baka Village and Kachali Village, reaching about 650 m in thickness. This member is composed of thickly bedded, coarse- to very coarse-grained sandstone and mudstone interbeds. The sandstone beds are commonly trough and planar cross-stratified (Fig. 6B). The interbedded mudstone are greenish-grey (GLEY1 7/10GY, GLEY1 6/10GY, GLEY1 7/5GY, GLEY1 4/N) to olive grey (5Y 6/2, 5Y 4/2, 5Y 6/4), to olive brown (2.5YR 5/3, 2.5YR 6/2) (Fig. 7II). The thickness of individual sandstone successions reaches 25 m, showing upward-fining trend, whereas mudstone beds typically 0.3 to 2 m thick. Abundant mud and sand clasts are scattered within the sandstone beds, and pebbles of pre-Siwalik or Lesser Himalayan rocks also occur in places (Fig. 7II). In some places, 0.5 m thick coal seams are interbedded within the mudstones (Fig. 7II, locs. V, X).

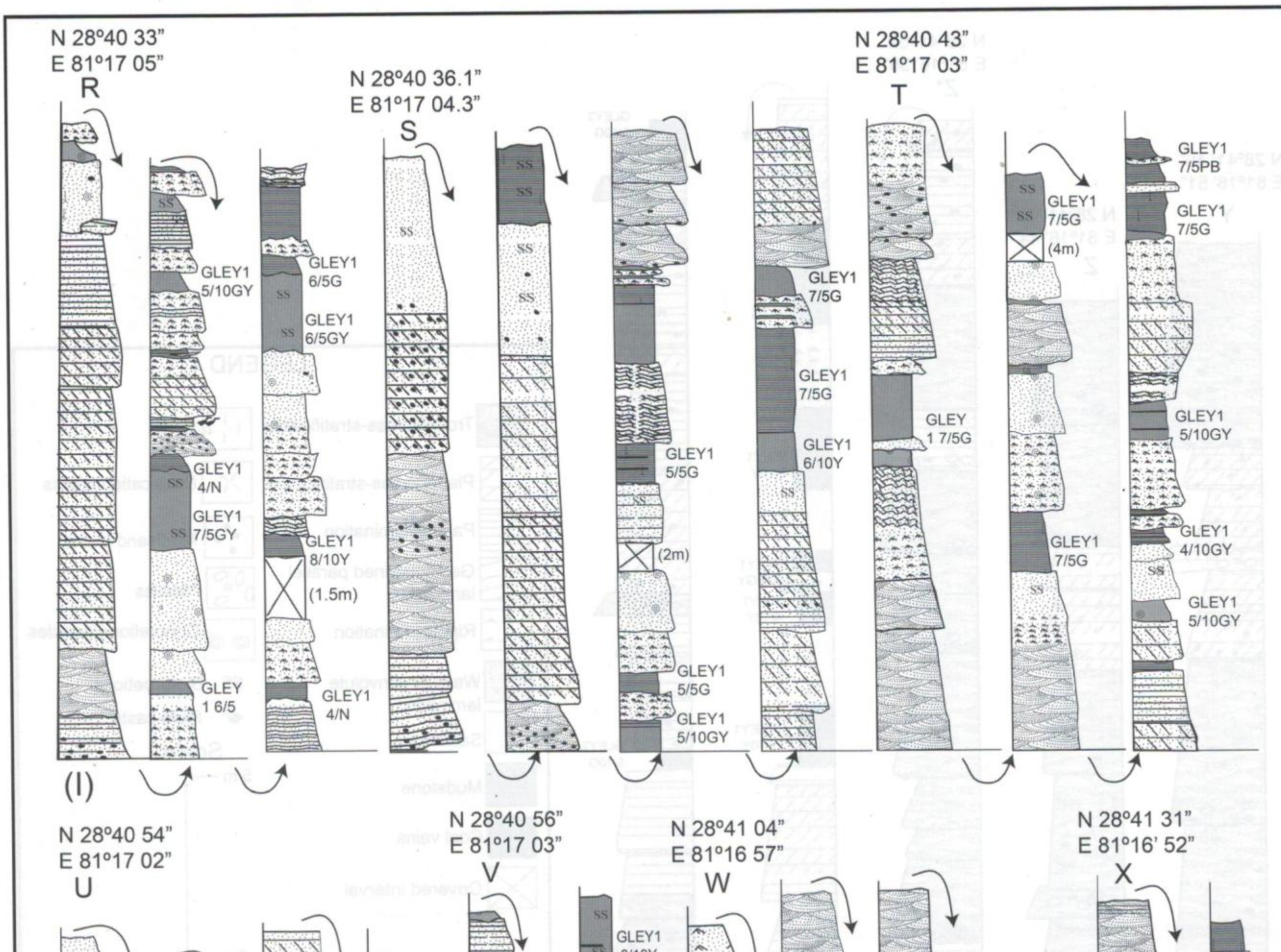

Fig. 7: Typical columnar sections of the Baka Formation. I) Lower member, II) Middle member, Letters R, S, T… Z* (with latitude and longitude) at the top of each column indicate the locations of measured sections.

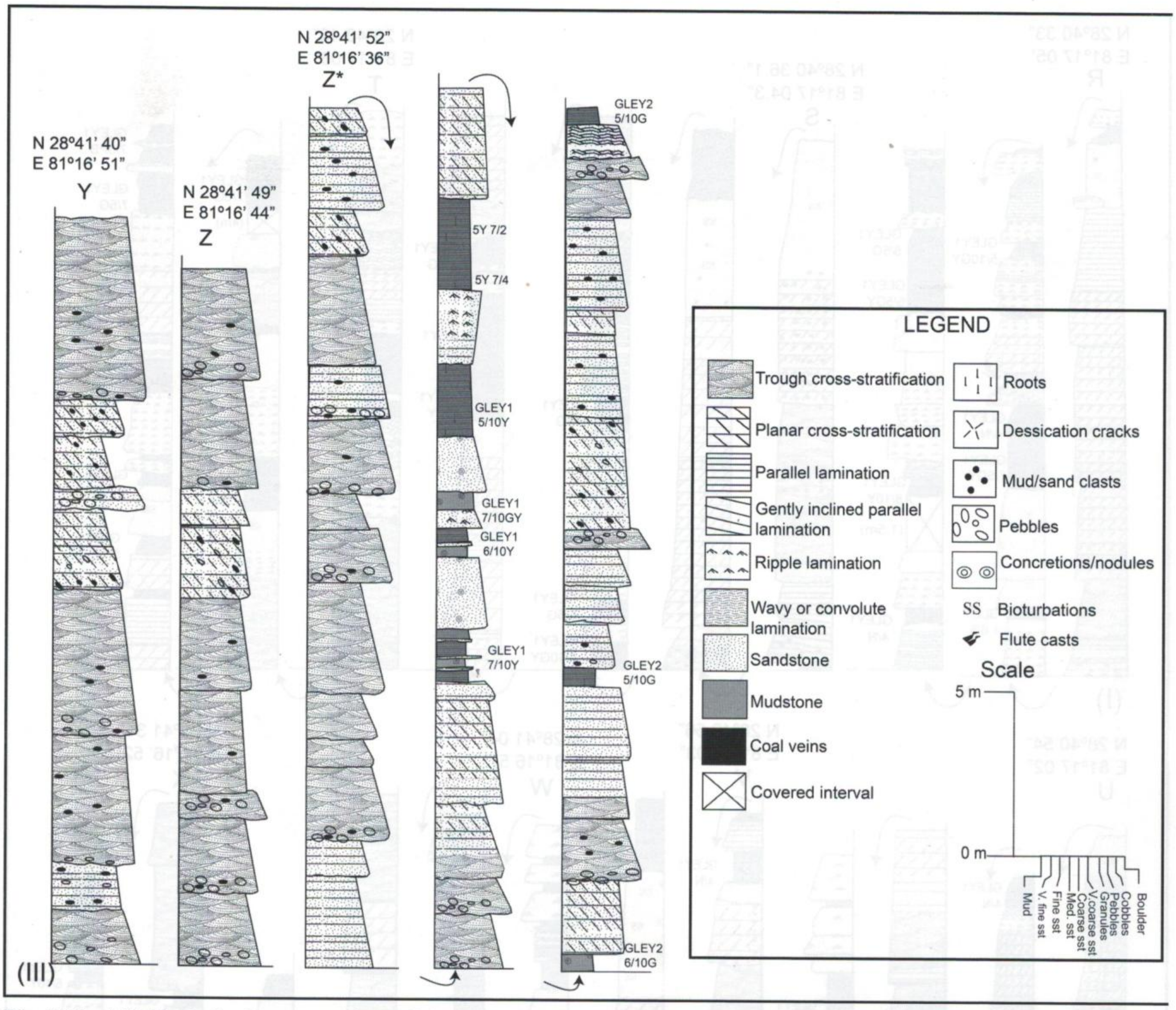

Fig. 7 (Contd.): Typical columnar sections of the Baka Formation. III) Upper member. Letters R, S, T… Z* (with latitude and longitude) at the top of each column indicate the locations of measured sections.

Upper member

This member is well exposed around Kachali Village. Total thickness is about 1550 m. The upper member consists of coarse- to very coarse-grained, pebbly sandstones and thin mudstone interbeds (Figs 6C, 7III). The long axes of the pebbles have lengths ranging from 1 to 8 cm. The pebbles are mainly quartzite. The sandstones display trough and planar cross-stratification, and thickness of individual sandstone successions reaches 25 m (Fig. 7III, locs. Z, Z*). Sandstone successions in this member show a faint fining-upward trend, starting from trough cross-stratification at the base, followed by planar cross-stratification, succeeded by rare mudstones beds at the top. These successions are bounded by major erosional surfaces that are laterally continuous in large outcrops (Fig. 7III). Pebbles and mud clasts are scattered throughout the sandstone beds. The mudstones are thinly laminated, with colour ranging from greenish-black (GLEY1 4/N, GLEY2 5/10G) to greenish-grey (GLEY 1 7/10Y, GLEY 1 6/10Y). Thicknesses of the mudstone intervals range from 0.5 to 2 m.

Age

The age of the Baka Formation has been established by Gautam and Fujiwara (2000), up to the lower half of the upper member. Although the specific age of the uppermost boundary has not been yet been obtained, it is expected to be around 3.9 Ma, based on calculated sedimentation rate. The age ranges of the individual members are 9.6-8.6 Ma, 8.6-6.0 Ma and 6.0-~3.9 Ma (lower, middle, and upper, respectively).

Stratigraphic relationship

The upper stratigraphic position of the formation is the same as that proposed by DMG (2003) for the Middle Siwaliks. Gautam and Fujiwara (2000) did not precisely define the Middle - Upper Siwalik boundary, but expected it to be slightly younger than 5.2 Ma. The first appearances of the thick coarse-grained "salt and pepper" sandstones mark the boundary between the Chisapani Formation and the lower member of the Baka Formation. The appearance of coarse- to very coarse-grained sandstones containing abundant mud and sand clasts mark the boundary between the lower and middle members. The pebbly sandstone distinguishes the boundary between the middle and upper members of this formation. The Baka Formation is conformably overlain by the Kuine Formation (Fig. 6D).

Kuine Formation (Upper Siwaliks)

Type locality

The type locality of this formation is defined in riverside exposures in the Karnali River near Kuine Village.

Lithology

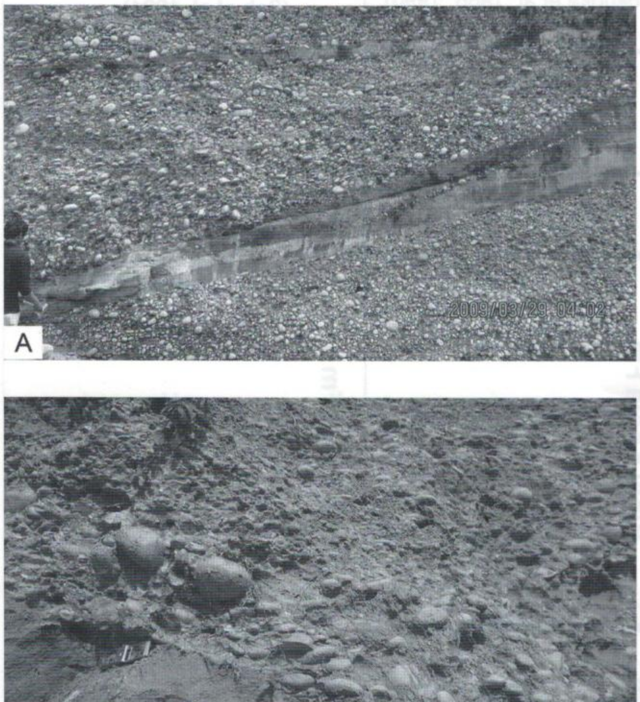

Fig. 8: Outcrop photographs of the Upper Siwalik conglomerates. (A) A well-sorted imbricated pebble to cobble conglomerate of the Kuine Formation. Person for scale (1.7 m). (B) Poorly-sorted, matrix-supported boulder conglomerate of the Panikhola Gaun Formation. The scale (compass) at lower left is 15 cm long.

The Kuine Formation is well exposed from Kuine Village in the south to Panikhola Gaun Village in the north (Fig. 3). Total thickness is about 1000 m. The Kuine Formation consists of thick-bedded, imbricated, well-sorted, clast-supported, cobble- and pebble-sized conglomerates (Fig. 8A). The gravels consist mainly of quartzite and carbonate rocks with some metamorphic rocks. Clasts range from 1 to 10 cm in diameter. Sandstones and mudstones are interbedded as lenses within the conglomerate beds. The conglomerate beds are 5 to 30 m thick, whereas thicknesses of the sandstone and mudstone lenses range from 0.5 to 3 m.

Age

This formation has not been dated.

Stratigraphic relationship

The sudden appearance of thick conglomerate beds marks the boundary between the Baka and Kuine Formations. The stratigraphic relationship between the Baka and Kuine Formations is the same as that between the Middle and Upper Siwaliks, as proposed by DMG (2003) near Kuine Village. Gautam and Fujiwara (2000) did not define the exact boundary position, thickness and characteristics of the Upper Siwalik in this section. The Kuine Formation conformably underlies the Panikhola Gaun Formation.

Panikhola Gaun Formation (Upper Siwaliks)

Type locality

Exposures near Panikhola Gaun village are defined as the type locality of the formation.

Lithology

This formation is well exposed around Panikhola Gaun and Karawa Gaun villages, where it reaches about 500 m in total thickness. The Panikhola Gaun Formation consists of matrix-supported pebble, cobble, to boulder conglomerates, and coarse- to very coarse-grained sandstone and mudstone interbeds. Gravels are mostly angular to sub-rounded, and are composed of quartzite and occasional Siwalik Group sandstone clasts (Fig. 8B). The gravels are 1 to 10 cm (pebbles/cobbles) and 25 to 30 cm (boulder) in diameter. The conglomerate beds range from 8 to 30 m in thickness, whereas individual sandstone and mudstone interbeds range from 1 to 2 m thick.

Age

The formation has not yet been dated.

Stratigraphic relationship

The boundary between the Kuine and Panikhola Gaun Formations was not delineated by Gautam and Fujiwara (2000). The boundary between US, US1 and US2 defined by DMG (1987, 2003) which is very similar to the Kuine and Panikhola Gaun boundary defined in our present study. Based on our study, the first appearance of boulder sized-conglomerates bed marks the boundary between the Kuine and Panikhola Gaun Formations. The Panikhola Gaun Formation is truncated at its top by the Main Dun Thrust (MDT) (Fig. 3).

DISCUSSIONS

Ages of the Lower - Middle and Middle - Upper Siwalik boundaries

Previous lithostratigrapic studies of sections from the Hetauda-Bakiya Khola area (Harrison et al. 1993, Sah et al. 1994), Arung Khola-Tinau Khola (Tokuoka et al. 1986, 1990, Gautam and Appel 1994), Surai Khola (Corvinus and Nanda 1994, Dhital et al. 1995, Appel and Rosler 1994) and our new lithostratigraphic work in the Karnali River permit regional correlation in the Siwalik Group across Nepal Himalaya. Basically, the stratigraphy of these areas differs. The traditional tripartite (Lower, Middle and Upper Siwaliks) stratigraphic boundaries are used here to discuss the stratigraphic patterns and their age. Several previous studies have already indicated that there are discrepancies in the ages of these boundaries between locations (Tables 1 and 2).

The Lower–Middle Siwalik boundary is defined as the top of the Rapti Formation in the Hetauda-Bakiya Khola area (ca. 9.5 Ma), the top of the Arung Khola Formation in the Arung Khola–Tinau Khola area (ca. 8.5 Ma), and the top of the Chor Khola Formation in the Surai Khola (ca. 8.3 Ma). The top of the Chisapani Formation in the Karnali River section is dated around 9.6 Ma, only slightly older than the age in the Hetauda–Bakiya Khola area (Table 2).

Table 2: Lithostratigraphic classification of the Siwalik Group in the Nepal Himalaya and its correlation. The bold lines indicate that the boundaries between the Lower-Middle and Middle-Upper Siwaliks. Black part indicates the no deposition. Fm: Formation, mbr: member

Age (Ma)	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15
Karnali River (Present Study)	Panikhola Gaun Fm; Kuine Fm; Baka Fm (Upper mbr, Middle mbr, Lower mbr); Chisapani Fm (Upper mbr, Middle mbr, Lower mbr)
Surai Khola (Dhital et al. 1995)	Dhan Khola Fm; Dobata Fm; Surai Khola Fm (Upper mbr, Middle mbr, Lower mbr); Chor Khola Fm (Shivgarhi mbr, Jungali Khola mbr); Bankas Fm
Arung Khola-Tinau Khola (Tokuoka et al. 1986, 1990)	Deorali Fm; Chitwan Fm; Binai Khola Fm (Upper mbr, Middle mbr, Lower mbr); Arung Khola Fm (Upper mbr, Middle mbr, Lower mbr)
Hetauda-Bakiya Khola (Sah et al. 1994), (Nakayama and Ulak 1999)	Churia Mai Fm; Churia Khola Fm; Amlekhganj Fm (Upper mbr, Middle mbr, Lower mbr); Rapti Fm (Upper mbr, Middle mbr, Lower mbr)

The Lower and Middle Siwalik boundary is defined based on the grain-size and increasing thickness of sandstone beds, together with the appearance of distinctive "salt and pepper sandstone". These sandstone beds contain more mica grains than underlying sandstone intervals, suggestive of derivation from the Higher Himalayan Belt. The fining-upward successions that characterize these sandstones may represent channel fill deposits (Miall 1996). The thickening trend of such succession implies that river size increased through time. In the present day Himalayan river systems, the channels become deeper downstream from the upstream braided region to the downstream meandering region; bed-thickness also increases in the same direction, hence recording increased water discharge and sediment supply through time (Zaleha 1997).

The appearance of the "salt and pepper" sandstones indicate not only that the drainage basins of the river systems had reached the Higher Himalayan belt, but also that they had deeply incised the Higher Himalayan rocks. The earlier appearance of such sandstones in the Karnali River section indicates that its drainage basin spread into the Higher Himalayas earlier than in other areas. The appearance of such sandstones also coincides with the increase in uplift rate of the Himalaya in western Nepal at about 12-9 Ma (DeCelles 1998, Robinson et al. 2001, Huyghe et al. 2005). Therefore, the timing of the Lower – Middle Siwalik boundary in the Karnali River section is consistent with the timing of the uplift.

The Middle and Upper Siwalik boundaries also show variations in ages. In the Hetauda-Bakiya Khola area it is dated at around 3.0 Ma, compared to ~2.5 Ma in the Arung Khola – Tinau Khola and ~4.0 Ma in the Surai Khola. Although the specific age of the boundary has not yet been obtained in the Karnali River section, it is expected to be around 3.9 Ma, based on calculated sedimentation rate (Gautam and Fujiwara 2000). Corvinus and Nanda (1994) and Dhital et al. (1995) reported that the Dobata Formation, which forms the lower part of the Upper Siwaliks in the Surai Khola; Nakayama and Ulak (1999), considered that it had an anastomosed river origin. In contrast, in other areas the Upper Siwaliks is represented by a conglomeratic facies (alluvial fan deposits). The onset of "normal" Upper Siwalik deposition around the Surai Khola area should thus be recognized as the base of the first conglomeratic deposits in the Dhan Khola Formation (around 2.3Ma).

The Middle – Upper Siwaliks boundary is marked by a change from sandy to gravelly facies (Nakayama and Ulak 1999). These facies are closely related to the progradation of alluvial fans; these were developed by the southward-flowing transverse drainage pattern created by the activity of thrusts (DeCelles et al. 1988, Heller and Poala 1992, Kumar et al. 2003). This thrust activity is manifested by the trapping of coarse detritus sediment in the proximity of the thrust front, and transportation of finer-grained material toward distal environments (Heller and Paola 1992). The progradation rate of alluvial fans along the vicinity of the MFT is consistent with the diachronous boundaries between the Middle and Upper Siwaliks (Burbank 1992, Brozovic and Burbank 2000). In the modern environment, activity of thrust splays in the footwall of the Main Frontal Thrust (MFT) has caused large-scale progradation of alluvial fans (gravel fans near the foot of the Siwalik Hills) toward the present Indo-Gangatic plain (Pati et al. 2011). However, the Surai Khola section experienced a different environmental change, marked by the appearance of anastomosed river deposits. This clearly suggests that the environment of the Surai Khola area changed temporarily to become an inter-alluvial fan region. Because the distribution of coarse-grained river deposits is limited to the places where the rivers crossed the Himalayan Frontal Thrusts at their time of deposition, the diachronity of this boundary should be expected to be larger than that of the Lower and Middle Siwaliks.

Based on comparison with the Siwalik deposits in the Nepal Himalaya, the Siwalik Group sediments along the Karnali River were deposited from rivers with larger drainage systems than in other areas. In large river systems, local climate (i.e. local precipitation) has minimal effect on the fluvial channel style, which can change only by regional or basin-wide precipitation. Previous paleoclimatolotical studies from the Siwalik Group of Nepal Himalayas have less focused on the paleodrainage systems into account. The Karnali River section is thus a sedimentary succession which is suitable for the analysis of paleoclimate related to the uplift of the Himalayas in the future.

Correlation with the Potwar Basin

Direct lithological correlations of Nepalese Siwalik sections with the Siwalik sections in the Potwar Basin of Pakistan are difficult, due to the prominent lithological variations within the alluvial sediments and the diachronous nature of the boundaries, even within Pakistan (Barry et al. 1982, Willis 1993, Zaleha 1997). Consequently, the correlation is based mainly on magnetic polarity patterns, and to a lesser extent on lithological units (Johnson et al. 1982). The long normal magneto-polarity zone (C5n.2n or Chron 9) is a strong tool for correlation with the Potwar Basin of Pakistan, and where it appears in the Nagri Formation (Barry et al. 1982). The same polarity (C5n.2n) zone was also used to correlate between the Nepalese Siwalik sections (Tokuoka et al. 1986, Gautam and Rosler 1999, Ojha et al. 2009). This long normal polarity episode appears in the upper half of the upper member of the Chisapani Formation (Gautam and Fujiwara 2000) (Fig. 9). The lower and middle members and the lower half of the upper member of the Chisapani Formation are thus correlated with the Chinji Formation. Similarly, the Baka Formation is correlated with the Dhok Pathan and Tatrot Formations. The appearance of conglomerates in the Kuine and Panikhola Gaun Formations are correlated with the Pinjor and Boulder Conglomerate (Upper Siwaliks) Formations, respectively (Fig. 9).

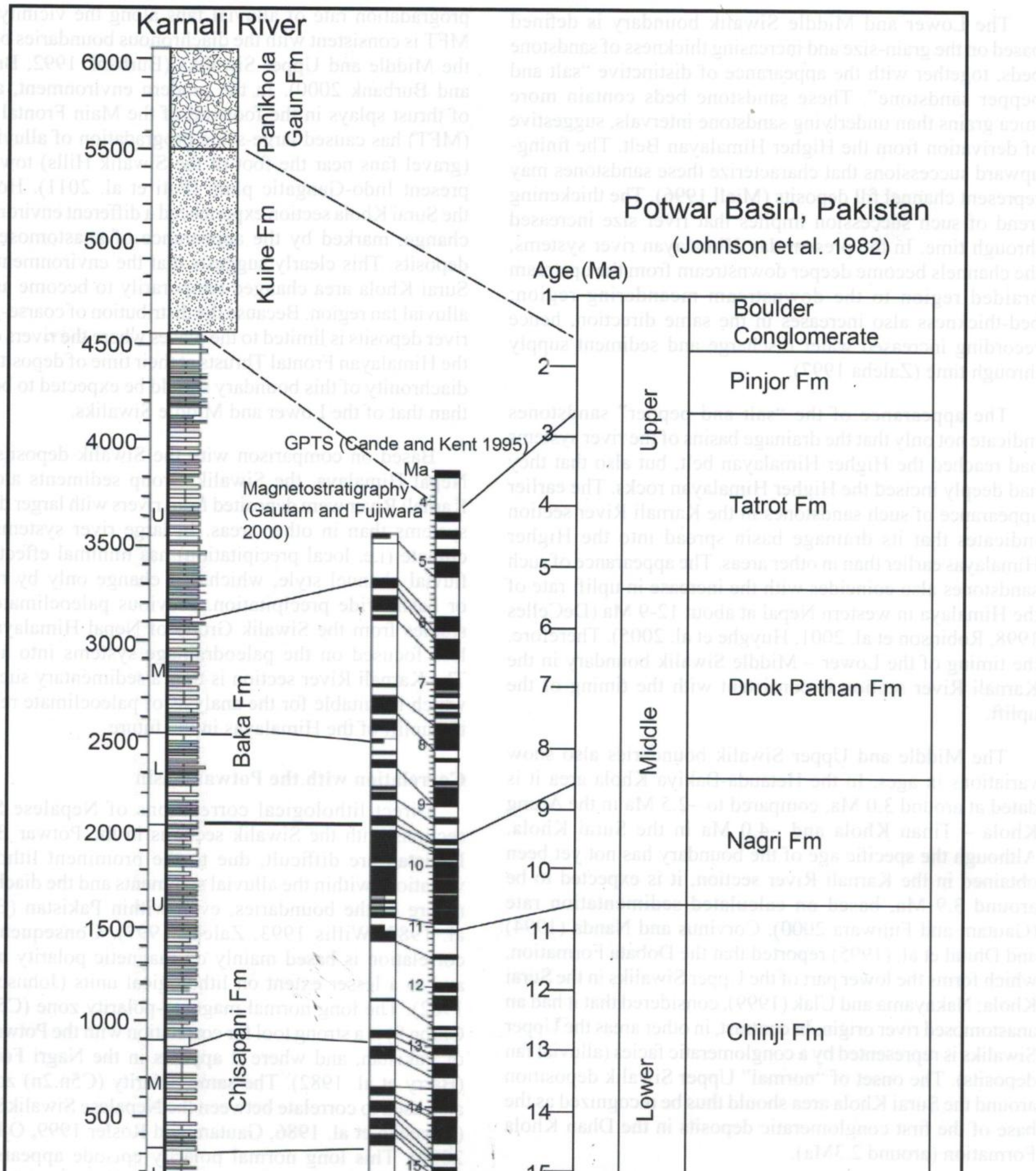

Fig. 9: Magnetostratigraphy and lithostratigraphy divisions of the Siwalik Group along the Karnali River section (modified from Gautam and Fujiwara, 2000) and its correlation with the Potwar Basin, Pakistan (Johnson et al. 1982). The dashed lines indicate the tentative correlation of the Kuine and Panikhola Gaun Formations (undated).

The correlation with the Potwar Basin shows that the appearance of thick coarse- to very coarse-grained sandstones in the Middle Siwalik (Nagri Formation) at about 11.0 Ma records the increasing river size and discharge over that in the lower Chinji Formation (Willis 1993, Zaleha 1997). Similar thick, coarse-grained "salt and pepper sandstones" are observed in the Nepalese Siwaliks (Middle Siwaliks) at about 9-10 Ma. These sediments were derived from the Higher Himalaya, as indicated by petrographic analysis (Tokuoka et al. 1986, Zaleha 1997, Kumar 2003, Szulc 2006). The changes in fluvial architecture and sediment grain size are due either to uplift of the source area or increase in rainfall, which increase the size of the catchment basin or discharge of the river, respectively (Damanti 1993, Horton and DeCelles 2001). The Middle Siwalik sediments were th erefore deposited by a large river system, comparable to large modern rivers such as the Koshi and Ganga River deposits (Willis 1993, Zaleha 1997). The diachronous evolution of such large drainage systems may thus be helpful to understand the stratigraphic depositional pattern in the Siwalik foreland basin in relation to the tectonic, climate and paleo-drainage system in the Himalaya region during the Middle Miocene to Early Pleistocene.

CONCLUSIONS

The stratigraphy of an almost complete succession of the Siwalik Group was studied in the Karnali River section. The Siwalik Group in this section consists of the Chisapani, Baka, Kuine, and Panikhola Gaun Formations, in ascending order, all newly defined in this study. The Chisapani Formation is equivalent to the Lower Siwalik, and is dominated by mudstone. It is here subdivided into lower, middle, and upper members. The Baka Formation corresponds to the Middle Siwalik, and is characterized by "salt and pepper" sandstone. The Baka Formation is also subdivided into lower, middle, and upper members. The Kuine and Panikhola Gaun Formations together correspond to the Upper Siwaliks. The Kuine Formation is characterized by well-sorted and imbricated pebble to cobble conglomerates, whereas the overlying Panikhola Gaun Formation consists of poorly-sorted, matrix-supported boulder conglomerates.

Paleomagnetic dating by Gautam and Fujiwara (2000) and newly defined the lithostratigraphic division in this study have led to fruitful correlation with the stratigraphy of the Surai Khola, Tinau Khola, and Hetauda Bakiya Khola sections in Nepal and in the Potwar Basin in Pakistan. This correlation confirms that the boundary between the Lower and Middle Siwaliks is diachronous, as previously reported, over an age range of ~1 Myr. The top of the Chisapani Formation (Lower-Middle Siwalik boundary) is dated at about 9.6 Ma, slightly older than the age of equivalent horizons in the other sections. The earlier appearance of sediments originated from the Higher Himalaya can be recognized in the Karnali drainage basin, which cut back into the Higher Himalayas earlier than in other areas. Similarly, the boundary between Middle and Upper Siwaliks is also highly diachronous, with ages of 3.9 Ma (Karnali River) and 4.0 Ma (Surai Khola), and 2.5 Ma (Tinau Khola) and 3.0 Ma (Hetauda-Bakiya Khola). These boundaries are strongly linked to the progradation of alluvial fans, and hence could be related to the propagation of major southern thrust systems (MBT and MFT) in the Himalaya. The lithological and chronological variations of the sediments between the Karnali River section and the Potwar Basin in Pakistan which could be related to the timing of drainage basin expansion deep into the Higher Himalaya.

AKNOWLEDGEMENTS

We thank the Ministry of Education, Culture, Science and Technology of Japan for providing a Monbukagakusho scholarship for study to the first author. We would also like to thank Dr. B.P. Roser for his critical reviewing and helpful comments on early version of the manuscript. We are also indebted to Biraj Gautam and Basanta R. Adhikari for their assistance during our fieldwork.

REFERENCES

Amatya, K.M. and Jnawali, B.M., 1994, Geological map of Nepal (Scale 1:1000, 000). Department of Mines and Geology (DMG) Kathmandu, Nepal.

Appel, E. and Rosler, W., 1994, Magnetic polarity stratigraphy of the Neogene Surai Khola section (Siwalik, SW Nepal). Himal. Geol., v. 15, pp. 63-68.

Auden, J.B., 1935, Traverses in the Himalaya. Rec. Geol. Surv. India, v. 69, pp. 123-167.

Barry, J.C., Lindsay, Jacob E.H. and L.L., 1982, A biostratigraphy zonation of the Middle and Upper Siwaliks of the Potwar Plateau of northern Pakistan. Palaeogeogr., Palaeoclimatol., Palaeoecol., v. 37, pp. 95-130.

Barry, J.C., Johnson, N.M., Raza, S.M. and Jacob, L.L., 1985, Neogene mammalian faunal change in southern Asia: Correlations with climatic, tectonic, and eustatic events. Geology, v.13, pp. 637-640.

Bernet, M., Van Der Beek, P., Pik, R., Huyghe, P., Mugnier, J.L., Labrin, E., and Szulc, A.G. 2006, Miocene to recent exhumation of central Himalaya determined from combined detrital zircon fission-track and U/Pb analysis of Siwalik sediments, western Nepal. Basin Res. v. 18, pp. 393-412.

Brozovic, N. and Burbank, D.W., 2000, Dynamic fluvial systems and gravel progradation in the Himalayan foreland. Geol. Soc. Am. Bull, v. 112, pp. 394–412.

Burbank, D.W., 1992, Cause of recent Himalayan uplift deduce from deposited pattern in the Ganga basin. Nat., v. 357, pp. 680–683.

Burbank, D.W., Beck, R.A. and Mulder, T., 1996, The Himalayan Foreland: Asian Tectonics. Cambridge Univ. Press, pp. 149-188.

Cande, S.C. and Kent, D.V., 1995, Revised calibration of the geomagnetic polarity time scale for the late Cretaceous and Cenozoic. Jour. Geophys. Res., v. 100(B4), pp. 6093-6095.

Corvinus, G. and Nanda, A.C., 1994, Stratigraphy and paleontology of the Siwalik Group of Surai Khola and Rato Khola in Nepal. N. Jb. Geol. Palaeont. Abh., v. 191, pp. 25-68.

Damanti, J.F., 1993, Geomorphic and structural controls on facies patterns and sediment composition in a modern foreland basin. In: Alluvial Sedimentation (ed. by M. Marzo & C. PuigdefaÁbregas), Spec. Publ. Int. Ass. Sedimentology, v. 17, pp. 221-233.

Dhital, M.R., Gajurel, A.P., Pathak, D., Paudel, L.P. and Kizaki, K. 1995, Geology and structure of the Siwaliks and Lesser Himalaya in the Surai Khola-Bardanda area, mid-western Nepal. Bull. Dept. Geol. Tribhuvan Univ., v. 4, pp. 1-70.

Department of Mines and Geology (DMG/HMGN), 1987, Geological Map of Far Western Nepal, 1:250,000.

Department of Mines and Geology (DMG/HMGN), 2003, Geological Map of Petroleum Exploration Block-2, Karnali, Far Western Nepal, 1:250,000

DeCelles, P.G., Gehrels, G.E., Quade, J., Ojha, T.P., Kapp, P.A. and Upreti, B. N., 1998, Neogene foreland basin deposits, erosional unroofing, and the kinematic history of the Himalayan fold-thrust belt, western Nepal. Geol. Soc. Am. Bull. v. 110, pp. 2-21.

Fatmi, A.N., 1973, Lithostratigraphic units of the Kohart-Potwar Province, Indus Basin, Pakistan. Mem. Geol. Surv. Pak., v. 10, pp. 1-80.

Gansser, A., 1964, *Geology of the Himalayas*. Interscience, London, 289 p.

Gautam, P. and Appel, E., 1994, Magnetic polarity stratigraphy of the Siwalik Group sediments of the Tinau Khola section in west central Nepal, revisited. Geophys. J. Int., v. 117, pp. 223-234.

Gautam, P. and Fujiwara, Y., 2000, Magnetic polarity stratigraphy of Siwalik Group sediments of the Karnali River section in western Nepal. Geophys. J. Int., v. 142, pp. 812-824.

Glennie, K.W. and Ziegler, M.A., 1964, The Siwalik Formations of Nepal. Int. Geol. Congr., 22, Delhi, v. 25, pp. 82-95.

Gupta, S.S. and Verma, B.C., 1988, Stratigraphy and vertebrate fauna of the Siwalik Jammu District Group, Mansar Uttarbani section, J & K. J. Palaeontol Soc. India, v. 33, pp. 117-124.

Gupta, S.S., 1997, Study and documentation of vertebrate fossils from the Siwalik Group of Jammu Sub Himalayan foot hills. Rec. Geol. Surv. India, v. 129 (8), pp. 5-7.

Gupta, S.S., 2000, Lithostratigraphy and structure of the Siwalik succession and its relationship with the Murree succession around Ramnagar area, Udhampur district, Jammu and Kashmir. Himal. Geol., v. 21, pp. 53-61.

Hagen, T., 1969, *Report on the Geological Survey of Nepal: Preliminary Reconnaissance*. Denkschr. Naturw. Ges. v. 86, 185 p.

Harrison, T.M., Copeland, P., Hall, S.A., Quade, J., Burner, S., Ojha, T.P. and Kidd, W.S.F., 1993, Isotopic preservation of Himalayan/ Tibetan uplift, denudation and climatic histories in two molasses deposits. Jour. Geol., v. 101, pp. 157-175.

Heller, P.L. and Paola, C., 1992, The large scale dynamics of grain-size variation in alluvial basins, 2: Application to syntectonic conglomerate. Basin Res., v. 4, pp. 91-102.

Hérail, G. and Mascle, G. 1980, Les Siwalik du Népal central: structure et géomorphologie d'un péimont en cours de déformation. Bull. Ass. Geog. Fr., v. 471, pp. 259-267.

Horton, B. K. and DeCelles P. G., 2001, Modern and ancient fluvial megafans in the foreland basin system of the central Andes, southern Bolivia: implications for drainage network evolution in fold-thrust belts. Basin Res., v. 13, pp. 43-63.

Huyghe, P., Mugnier, J.L., Gajurel, A.P. and Decaillau, B., 2005, Tectonic and climatic control of the changes in the sedimentary record of the Karnali river section (Siwaliks of western Nepal). The Island Arc, v. 14, pp. 311-327.

Johnson, N.M., Opdyke, N.D., Johnson, G.D., Lindsay, E.H. and Tahirkheli, R.A.K., 1982, Magnetic polarity stratigraphy and age of the Siwalik group rocks of Potwar plateau, Pakistan. Palaeogeogr., palaeoclimatol. Palaeoecol., v. 37, pp. 17-42.

Johnson, G. D., Opdyke, N.D., Tandon, S. K. and Nanda, A. C., 1983, The magnetic polarity stratigraphy of the Siwalik Group at Haritalyangar (India) and a new last appearance datum for Ramapithecus and Sivapithecus in Asia. Palaeogeogr., palaeoclimatol. Palaeoecol., v. 44, pp. 223-249.

Johnson, N.M., Stix, J., Tauxe, L., Cerveny, P.F. and Tahirkheli, R.A.K., 1985, Paleomagnetic chronology, fluvial processes and tectonic implication of the Siwalik deposits near Chinji village, Pakistan. Jour. Geol., v. 93, pp. 203-226.

Kumar, G. 1997, *Geology of Arunachal Pradesh. Bangalore*: Geol Soc. India, 217 p.

Kumar, R., Ghosh, S.K. and Sangode, S.J., 2003, Mio–Pliocene sedimentation history in the northwestern part of the Himalayan foreland basin, India. Curr. Sci. v. 84 (8) pp. 1006–1013.

Kumaravel, V., Sangode, S.J., Kumar, R. and Siva Siddaiah, N., 2005, Magnetic polarity stratigraphy of Plio–Pleistocene Pinjor Formation (type locality), Siwalik Group, NW Himalaya, India. Curr. sci, v. 88, pp. 1453-1461.

Lewis, G.E., 1937, A new Siwalik correlation. Am. Jour. Sci., v. 33, pp. 191-204.

Miall, A.D., 1996, *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology*. Springer-Verlag, New York. 582 p.

Mugnier, J.L., Delcaillau, B., Huyghe, P. and Leturmy, P., 1998, The break-back thrust splay of the Main Dun Thrust (Himalayas of western Nepal): evidence of an intermediate displacement scale between earthquake slip and finite geometry of thrust systems. Jour. Struct. Geol. v. 20, pp. 857-864.

Mugnier, J.L., Leturmy, P., Mascle, G., Huygle, P., Chalaron, E., Vidal, G., Husson, L. and Delcaillau, B., 1999, The Siwalik of Western Nepal: I. geometry and kinematics. Jour. Asian Earth Sci., v. 17, pp. 629-642.

Nakata, T., 1989, Active faults of the Himalaya of India and Nepal. Geol. Soc. Am. Sp. Pap., v. 232, pp. 243-264.

Nakayama, K. and Ulak, P.D., 1999, Evolution of fluvial style in the Siwalik Group in the foothills of the Nepal Himalaya. Sediment. Geol., v. 125, pp. 205-224.

Ojha, T.P., Butler R.F., Quade, J., DeCelles, P.G., Richards, D. and Upreti, B.N., 2000, Magnetic polarity stratigraphy of the Neogene Siwalik Group at Khutia Khola, far western Nepal. Jour. Geol. Soc. Am. Bull., v. 112, pp. 424-434.

Ojha, T.P., Butler R.F., DeCelles, P.G. and Quade, J., 2009, Magnetic polarity stratigraphy of the Neogene foreland basin deposits of Nepal. Basin Res., v. 21, pp. 61-90.

Opdyke, N.D., Johnson, N.M., Johnson, G.D., Lindsay, E.H. and Tahirkheli, R.A.K., 1982, Plaeomagnetism of the Middle Siwalik formations of Northern Pakistan and Rotation of the Salt Range Decollement and age of the Siwalik group rocks of Potwar plateau, Pakistan. Palaeogeogr. palaeoclimatol. Palaeoecol., v. 37, pp. 1-15.

Pati, P., Prakash B., Awasthi, A.K. and Acharya, V., 2011, Holocene tectono-geomorphic evolution of parts of the Upper and Middle Gangetic plains, India. Geomorphology, v. 128, pp. 148-170.

Piligram, G.E., 1913, The correlation of the Siwaliks with mammal horizons of Europe. Rec. Geol. Surv. India, v. 43 (4), pp. 264-326.

Prakash, B., Sharma, R.P. and Roy, A.K., 1980, The Siwalik Group (molasse) sediments shed by collision of continental plates. Sediment. Geol., v. 25, pp. 127-159

Ranga Rao, A., Agarwal, R.P., Sharma, U.N., Bhalla, M.S. and Nanda, A.C., 1988, Magnetic polarity stratigraphy and vertebrate palaeontology of the Upper Siwalik Subgroup of Jammu Hills, India. Jour. Geol. Soc. India, v. 31 (4), pp. 361-385.

Raza, S. M., 1983, *Taphonomy and paleoecology of Middle Miocene vertebrate assemblages, southern Potwar Plateau, Pakistan.* Unpublished Ph.D. Dissertation, Yale University, New Haven, Connecticut, 414 p.

Robinson, D.M., DeCelles, P. G., Patchett, P.J. and Garzione, C.N. 2001, The kinematic evolution of the Nepalese Himalaya interpreted from Nd isotopes. Earth and Planet. Sci. Lett., v. 192, pp. 507-521

Robinson, D.M., DeCelles, P. G. and Copeland, P. 2006, Tectonic evolution of the Himalaya thrust belt in western Nepal: Implication for channel flow models. Geol. Soc. Am. Bull., v. 118, pp. 868-885.

Rosler, W.,Metzler, W. and Appel, E., 1997, Neogene magnetic polarity stratigraphy of some fluviatile Siwalik sections, Nepal. Geophys. J. Int., v. 130, pp. 89-111.

Sah, R.B. Ulak, P.D., Gajurel, A.P. and Rimal, L.N., 1994, Lithostratigraphy of the Siwalik sediments of the Amlekhganj-Hetauda area, sub-Himalaya of Nepal. Himal. Geol. v. 15, pp. 37-48.

Sangode, S.J., Kumar, R. and Ghosh, S.K., 1996, Magnetic polarity stratigraphy of the Siwalik sequence of Haripur area, NW Himalaya. Jour. Geol. Soc. India., v.47. pp. 683-704.

Shah, S.M.I., 1977, *Stratigraphy of Pakistan.* Published by the Director General, Geological Survey of Pakistan, Quetta., 175 p.

Sharma, C.K., 1977, *Geology of Nepal.* Educational Enterprises, Kathmandu, 164 p.

Szulc, A.G., Najman, Y., Sinclair, H., Pringle, M., Bickle, M., Chapman, H., Garzanti, E., Ando, S., Huyghe, P., Mugnier, J.L., Ojha, T.P. and DeCelles, P.G. 2006, Tectonic evolution of the Himalaya constrained by detrital 40Ar-39Ar, Sm-Nd and petrographic data from the Siwalik foreland basin succession, SW Nepal. Basin Res., v. 18, pp. 375-391.

Tauxe, L. and Opdyke, N.D., 1982, A time framework based on magnetostratigraphy for Siwalik sediments of Khaur area, northern Pakistan. Paleogeog. Paleoclimatol. Palaeoecol., v. 37, pp. 43-63.

Tandon, S. K. and Kumar, R., 1984, Discovery of tuffaceous mudstones in the Pinjor formation of Punjab sub-Himalaya, India. Curr. Sci., v. 53, pp. 982-984.

Tokuoka, T., Takayasu, K., Yoshida, M. and Hisatomi, K., 1986, The Churia (Siwalik) Group of Arungg Khola area, west-central Nepal. Mem. Fac. Sci. Shimane Univ., v. 22, pp. 135-210.

Tokuoka, T., Takayasu, K., Hisatomi, K., Yamasaki, H., Tanaka, S., Konomatu, M., Sah, R.B., and Roy, S.M., 1990, The Churia (Siwalik) Group of Tinau Khola-Binai Khola area, west-central Nepal. Mem. Fac. Sci. Shimane Univ., v. 24, pp. 71-88.

Piligram, G.E., 1913, The correlation of the Siwaliks with mammal horizons of Europe. Rec. Geol. Surv. India, v. 43 (4), pp. 264-326.

Ulak, P. D. and Nakayama, K., 1998, Lithostratigraphy and evolution of the fluvial style in the Siwalik Group in the Hetauda-Bakiya Khola area, Central Nepal. Bull. Dept. Geol. Tribhuvan Univ., v. 6, pp. 1–14.

Van Der Beek, P., Robert, X., Mugnier, J.L., Bernet, M., Huyghe, P. and Labrin, E. 2006, Late Miocene-Recent exhumation of central Himalaya and recycling in the foreland basin assessed by apatite fission tract thermochronology of Siwalik Sediments, Nepal. Basin Res., v. 18, pp. 413-434.

Willis, B.J., 1993a, Ancient river systems in the Himalayan foredeep, Chinji village area, northern Pakistan. Sediment. Geol., v. 88, pp. 1-76.

Willis, B.J., 1993b, Evolution of Miocene fluvial systems in the Himalayan foredeep through a two kilometer-thick succession in northern Pakistan. Sediment. Geol., v. 88, pp. 77–121.

Yoshida, M. and Arita, K., 1982, On the Siwaliks observed along some routes in Central Nepal. Jour. Nepal. Geol. Soc., v. 2, Spec. Issue, pp. 51-58.

Zaleha, M.J., 1997, Intra-and extrabasinal controls on fluvial deposition in the Miocene Indo Gangatic foreland basin, northern Pakistan. Sedimentology, v. 44, pp. 369-390.