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Evolution of fluvial system in Siwalik Group of Chatara–Barahakshetra area, east Nepal Himalaya

Prakash Das Ulak
Department of Geology, Tri–Chandra Campus,
Tribhuvan University, Kathmandu, Nepal
(Email: prakashulak@yahoo.com)

ABSTRACT

Four facies associations (i.e., FA1 to FA4) are recognised in the Siwalik molasse of the Chatara–Barahakshetra area in east Nepal. They are classified based on the proportion of sandstone and mudstone, individual bed thickness, and bedform types. The facies associations are intimately related to the lithostratigraphic units of the Siwalik Group. The lower and upper members of the Lower Siwaliks (FA1- and FA2-facies associations, respectively) are inferred to be the products of fine-grained meandering and flood flow-dominated meandering fluvial systems, respectively. Similarly, the lower and middle members of the Middle Siwaliks (FA3- and FA4-facies associations, respectively) are interpreted as the deposits of sandy meandering and sandy braided fluvial systems, respectively.

INTRODUCTION

The Siwalik Group is delimited in the north by the Main Boundary Thrust (MBT), which brings with it the Lesser Himalayan rocks. The southern limit of the Siwaliks is marked by the Frontal Churia Thrust (or Main Frontal Thrust), which overrides the sediments of the Indo-Gangetic Plain (Fig. 1). The Siwalik Group is also called the Churia Group in Nepal. This vast pile of Neogene molasse deposited on the southern flank of the Himalaya is made up of fluvial cycles of mudstone, sandstone, and conglomerate. Though the Siwalik Group as a whole constitutes a coarsening-upward sequence, its individual cycles show a fining-upward trend.

Pilgrim (1908, 1934) and Berry et al. (1982) established the lithostratigraphy and biostratigraphy, respectively of the Potwar Basin in Pakistan. Similarly, Opdyke et al. (1982) and Johnson et al. (1982) carried out respectively the palaeomagnetic study and absolute dating of the Siwaliks in the Potwar Basin.

The lithostratigraphy of the Siwalik Group in the Nepal Himalaya was established by Auden (1935), Glennie and Ziegler (1964), Hagen (1969), Sharma (1973), Yoshida and Arita (1982), Tokuoka et al. (1986), Schelling (1992), Corvinus and Nanda (1994), Sah et al. (1994), Dhital et al. (1995), and Ulak and Nakayama (1998). It is subdivided into the Lower, Middle, and Upper Siwaliks, in an ascending order. According to the previous studies, the Lower Siwaliks are composed of fine- to medium-grained, grey coloured sandstone interbedded with variegated mudstone. The Middle Siwaliks are comprised of very thick-bedded, medium- to coarse-grained, grey sandstone alternating with mudstone. Here, the mudstone is grey to dark grey in colour and the sandstone is grey with black specks giving rise to "pepper and salt" appearance owing to the presence of quartz and biotite. The Upper Siwaliks are characterised by thick-bedded conglomerates with lenses of sand and mud. Petrographically, the Lower Siwaliks are characterised by quartz arenites (Chaudhary 1982; Tokuoka and Yoshida, 1984; Tokuoka et al. 1986) and staurolite grains are the markers for the Lower Siwaliks (Chaudhary and Gill 1981). The rocks of the Middle Siwaliks are easily recognised by the presence of lithic arenites (Chaudhary 1982; Tokuoka and Yoshida 1984; Tokuoka et al. 1986; Hisatomi 1990), consisting of kyanite grains (Chaudhary and Gill 1981; Tokuoka et al. 1986; Hisatomi 1990). The conglomerates of the Upper Siwaliks contain sillimanite grains as markers (Chaudhary and Gill 1981).

The sediments of the Siwalik Group in the Potwar Basin were deposited by the Neogene tectonics of the Himalaya (Parkash et al. 1980). The Siwalik sediments were deposited by meandering fluvial system which subsequently changed into a braided fluvial system (Zaleha 1997 a, b; Khan et al. 1997; Willis 1993).

The evolution of fluvial system during the deposition of the Siwalik Group was studied by Nakajima (1982), Hisatomi and Tanaka (1994), Ulak and Nakayama (1998), Nakayama and Ulak (1999), and Ulak and Nakayama (2001). They have shown that a meandering fluvial system appeared at the initial stage, and then it changed gradually into a braided fluvial system then and to a gravelly braided system. These studies have shown that the changes were caused by the southwards propagation of major thrusts (e.g., the Main Central Thrust and MBT) along the Himalayan front.

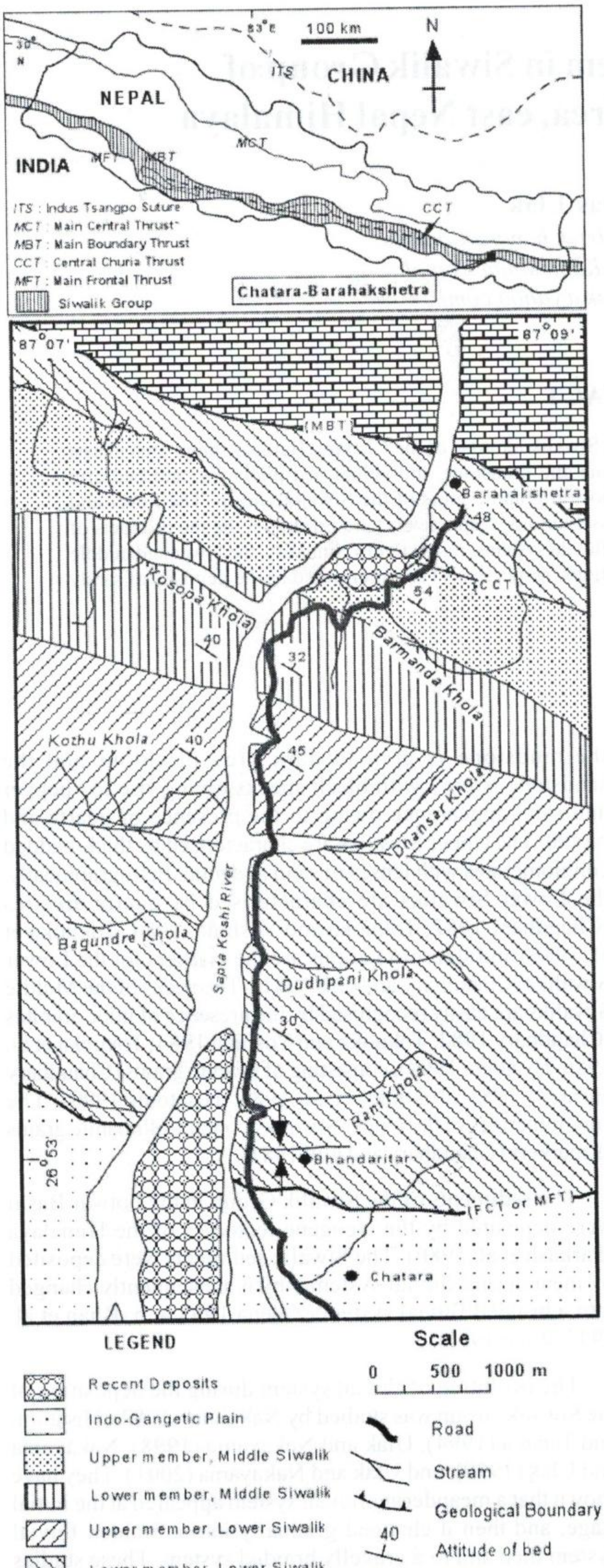


Fig. 1: Geological map of Chatara–Barahakshetra area

The magnetic polarity of the Siwalik Group of the Nepal Himalaya was studied by Tokuoka et al. (1986), Appel et al. (1991), Harrison et al. (1993), Gautam and Appel (1994), and Gautam and Fujiwara (2000). According to them, the rocks range in age from 16 to 1 Ma.

This study attempts to reveal the sedimentological characteristics of the Siwalik Group along the Chatara–Barahakshetra section in east Nepal. It deals mainly with the environmental changes of fluvial styles on the basis of facies associations.

LITHOSTRATIGRAPHY

DMG (1994) studied the lithostratigraphy of the Siwaliks in east Nepal. On the basis of lithology and grain size, the Siwalik Group in the study section has been slightly modified from the previously established stratigraphy, and subdivided mainly into the Lower Siwaliks (lower and upper members) and Middle Siwaliks (lower and upper members). The typical Upper Siwaliks are absent. The Siwaliks crop out in the Chatara–Barahakshetra road (Fig. 1, Table 1) cut and their total thickness is about 3050 m.

Lower Siwaliks

The Lower Siwaliks are represented by very fine- to medium-grained, greenish grey, calcareous sandstone interbedded with variegated, bioturbated mudstone. They are further subdivided into the lower and upper members, based on the thickness of sandstone and mudstone beds as well as the grain size of sandstone. It attains a thickness of about 1475 m.

Lower member of the Lower Siwaliks

The lower member of the Lower Siwaliks is identified by the dominance of bioturbated and variegated mudstone over very fine- to fine-grained, greenish grey to dark grey sandstone. Sandstones are highly indurated due to the presence of calcareous cement. The lower member of the Lower Siwaliks attains a thickness of about 575 m in the south belt.

Upper member of the Lower Siwaliks

The upper member of the Lower Siwaliks is characterised by alternating beds of medium- to coarse-grained, grey sandstones and variegated to dark grey mudstones, in which sandstone beds are thicker than mudstone beds. In the upper part of the member, the sandstone rarely shows "pepper and salt" like appearance. Molluscan fossils are found in the upper part of the mudstone beds. The upper member of this formation is well exposed along the Saptakoshi River and reaches a thickness of 900 m.

Middle Siwaliks

The Middle Siwaliks are represented by thick-bedded, medium- to very coarse-grained, light grey sandstones interbedded with dark grey mudstones. The sandstones have

Table 1: Lithostratigraphy of the Siwalik Group along Chatara–Barahakshetra section, east Nepal

Lithostratyigraphy		Thickness (m)	Lithological characteristics
Middle Siwaliks	Upper member	575+	Thick-bedded, coarse- to very coarse-grained, "pepper and salt" sandstone with pebbly sandstone. Sandstones are less indurated (sst>>mst).
	Lower member	1000	Medium- to coarse-grained, sandstone with dark mudstone. "Pepper and salt" sandstone are found in which the amount of biotite flakes are less (sst>mst).
Lower Siwaliks	Upper member	1550	Medium- to coarse-grained, "pepper and salt" texture, grey sandstone alternates with bioturbated, variegated to dark grey mudstone (sst>mst).
	Lower member	575+	Fine-grained, calcareous, greenish grey to gery sandstone interbedded with bioturbated, variegated mudstone and siltstone (mst>>sst).

"pepper and salt" like texture. Pebbly sandstones are also observed at some places. A large number of plant as well as molluscan fossils are found in the grey mudstone. The Middle Siwaliks are subdivided into the lower and upper members, in an ascending order, and attain about 1575 m in thickness.

Lower member of the Middle Siwaliks

The lower member of the Middle Siwaliks is comprised of thick-bedded, coarse- to very coarse-grained "pepper and salt" sandstone and grey mudstone. The mudstone beds are comparatively thinner and less variegated than those of the Lower Siwaliks. The dark grey mudstone beds are thinly laminated and contain leaf as well as molluscan fossils. Coarse- to very coarse-grained, multistoreyed sandstone beds are common and they are less indurated.

This unit is exposed around the suspension bridge of the Saptakoshi River and attains a total thickness of about 1000 m.

Upper member of the Middle Siwaliks

This member is well exposed to the north of the Barmanda Khola, Kosopa Khola and south of the Baraha temple and is about 575 m thick.

Commonly developed multistoreyed beds of coarse- to very coarse-grained pebbly sandstone are the characteristic features of the upper member of the Middle Siwaliks. The pebbly sandstone contains the clasts of quartzite, gneiss, and limestone derived from the Lesser Himalaya. Molluscan fossils are also found in the mudstone.

The Siwalik rocks of the Chatara–Barahakshetra area are correlated with the other sections of the Siwalik Group (Table 2). The lower member of the Lower Siwaliks is correlated with the Jungli Khola Member of the Chor Khola Formation (Dhital et al. 1995), Middle Member of the Arung Khola Formation (Tokuoka et al. 1986), and Middle Member of the Rapti Formation (Ulak and Nakayama 1998). The upper member of the Lower Siwaliks is correlated with the Shivgarhi Member of the Chor Khola Formation (Dhital et al. 1995), Upper Member of the Arung Khola Formation (Tokuoka et al. 1986), and Upper Member of the Rapti Formation (Ulak and Nakayama, 1998). Similarly, the lower member of the Middle Siwaliks is correlated with the lower part of the Surai Khola Formation (Dhital et al. 1995), Lower Member of the Binai Khola Formation (Tokuoka et al. 1986), and Lower Member of the Amlekhganj Formation (Ulak and Nakayama 1998). The upper member of the Middle Siwaliks is correlated with the middle part of the Surai Khola Formation (Dhital et al. 1995), Upper Member of the Binai Khola Formation (Tokuoka et al. 1986), and Middle Member of the Amlekhganj Formation (Ulak and Nakayama 1998).

FACIES ASSOCIATIONS

Detailed columnar sections from fluvial fining-upward successions of the Siwalik Group along the Chatara–Barahakshetra section were prepared and studied in the field. The facies associations are categorised based on bedforms, bed contact nature, grain size, sandstone and mudstone ratio, and thickness of sandstone beds. The lithofacies code and architectural elements of Miall (1978, 1985, and 1996) were followed. Altogether four facies associations (FA1 to FA4) were recognised in the study section. These facies associations are intimately related to the specific lithological units of the study area. The FA1- to FA4-facies association corresponds to each member of the Lower and Middle Siwaliks. Representative columnar sections of these facies association are shown in Fig. 2. Dominant and minor lithofacies types and characteristic architectural element are shown in Table 3.

Table 2: Lithostratigraphic correlation of the Chatara–Barahakshetra area, east Nepal, with other sections of the Siwalik group in Nepal Himalaya

Chatara–Barahakshetra section, east Nepal	Hetauda–Bakiya Khola section, central Nepal (Sah et al. 1994; Ulak and Nakayama 1998)	Arung Khola–Binai Khola section, west-central Nepal (Tokuoka et al. 1986, 88, 90)	Surai Khola section, west Nepal (Corvinus and Nanda 1994; Dhital et al. 1995)
Middle Siwaliks	Amlekhganj Formation	Binai Khola Formation	Surai Khola Formation
Lower Siwaliks	Rapti Formation	Arung Khola Formation	Chor Khola Formation Bankas Formation

FA1-facies association

The FA1-facies association is characterised by the predominance of bioturbated, variegated, thick-bedded (0.2 to 4.0 m) mudstone interbedded with fine-grained, greenish-grey to dark grey, calcareous sandstone (0.2 to 2.0 m thick) and sometimes fine-grained sandstones are variegated, representing the finest facies association. Within this facies, mudstone predominates over sandstone. Each fining-upward sequence is about 2 to 3 m thick. It begins with trough cross-bedded sandstone at the base and ends at mudstone (generally, 1 to 2 m thick palaeosols) at the top. The nature of basal contact of sandstone with the underlying sequence is flat or slightly eroded. Calcareous nodules are well observed on the upper surfaces of fine-grained sandstone

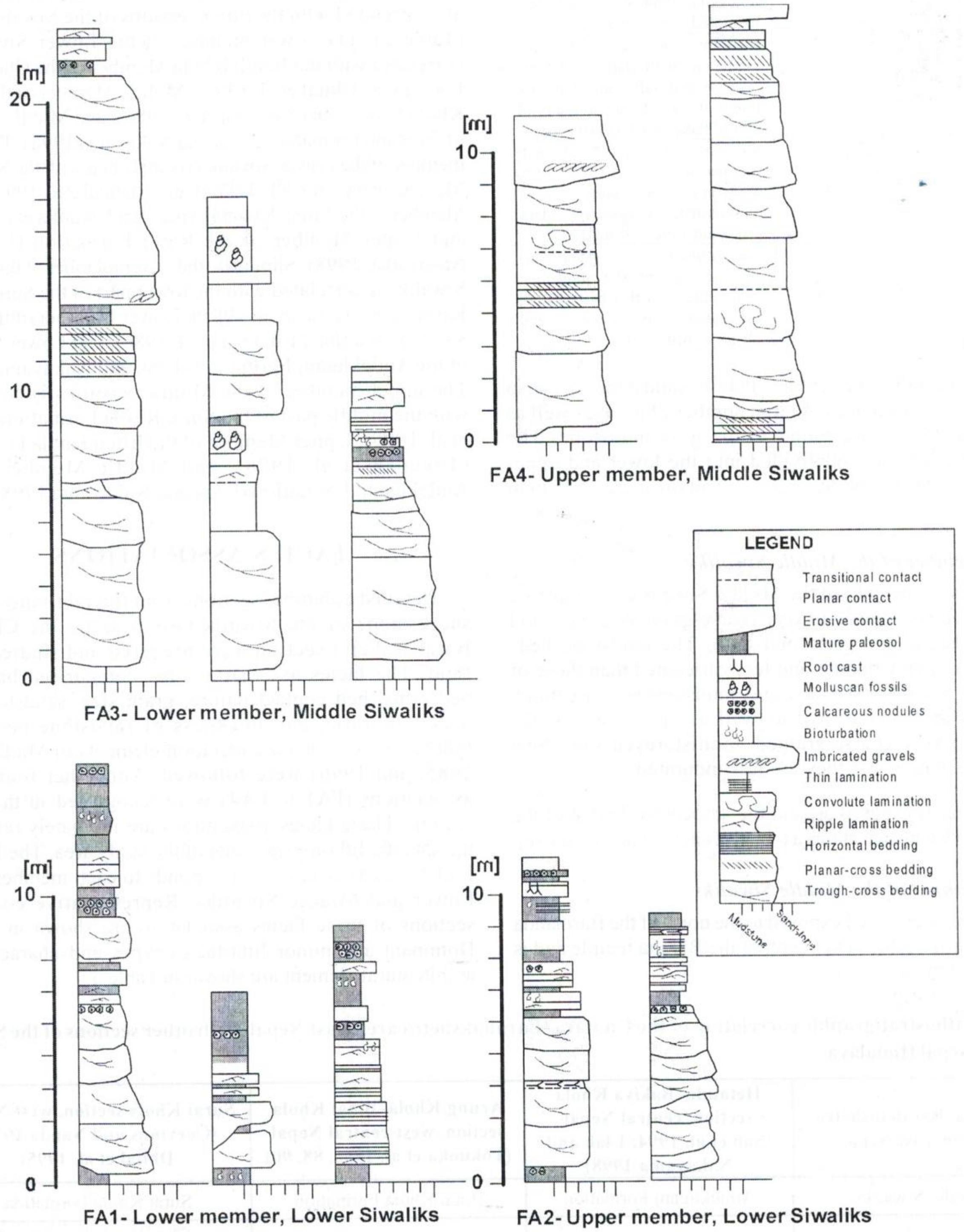


Fig. 2: Representative facies associations of Chatara–Barahakshetra section, east Nepal

Table 3: Description and interpretation of the facies association along the Chatara–Barahakshetra section, east Nepal

Facies association (FA)	Dominant lithofacies types*	Minor lithofacies types*	Characteristic architectural element**	Stratigraphic units of Chatara–Barahakshetra section, east Nepal	Interpretation
FA1	P, Fr, Fm, Sr, Fl	St, Sr	FF, SB, LA, > LS	Lower member of the Lower Siwaliks	Fine-grained meandering river system
FA2	St, Sr, Fl, Fm,	Fsm, Ss, Sp, Sh	LA, FF, SB, > DA	Upper member of the Lower Siwaliks	Flood flow-dominated meandering river system
FA3	St, Sr, Sp, Ss,	Fsm, Fl, P, Sh, Gt	DA, LA, FF, SB	Lower member of the Middle Siwaliks	Sandy meandering river system
FA4	St, Sp, Fms, Sr	Fl, P, C	DA, FF, SB, > LA	Upper member of the Middle Siwaliks	Sandy braided river system

*Classification from Miall (1978, 1996). **Channel (**CH**) recognised in all facies associations. Classification from Miall (1985, 1996). **C**-Coal, carbonaceous mud; **P**-Palaeosol carbonate; **Fr**-Mud, silt, roots, bioturbated; **Fm**-Silt, mud, massive; **Fl**-Sand, silt, mud, fine lamination, **Fms**-Silt, mud, massive; **Ss**-Sand, fine to coarse, scours; **Sp**-Sand, fine to coarse; planar cross-beds, **St**-Sand, fine to coarse, trough cross-beds; **Sr**-Sand, very fine to coarse, ripple cross-lamination; **Sh**-Sand, fine to coarse, horizontal lamination; **Gt**-Gravel, stratified, trough cross-beds; **FF**-Floodplain fines; **LA**-Lateral accretion; **DA**-Downstream accretion; **SB**-Sandy bedforms; **LS**-Laminated sand sheets.

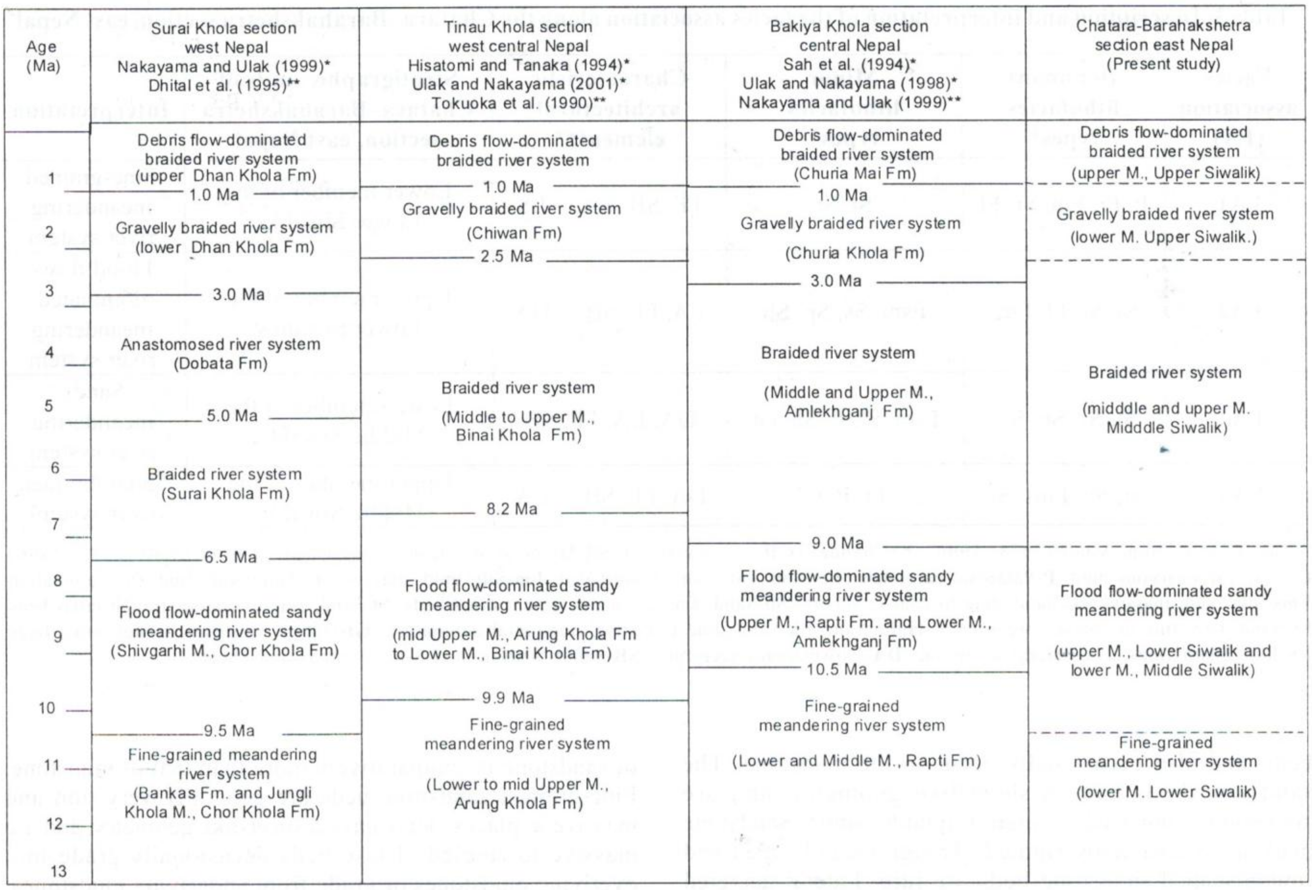
beds, and also occasionally occur in the mudstone. The sandstone beds have a sheet-like geometry, and are commonly composed of slightly muddy sands. Sandstone beds are occasionally rippled. Trough cross-bedded and ribbon-shaped sandstone beds are rare. Lateral accreted architectures are also found in these beds. Ripple laminations, raindrop imprints and trace fossils are preserved in fine-grained sandstone beds. The FA1-facies association is preserved in the lower member of the Lower Siwaliks.

The FA1-facies association is thought to be the product of a fine-grained meandering fluvial system due to the presence of bioturbated, variegated mudstone beds, calcareous nodules and trace fossils in fine-grained sandstone and mudstone beds. A significant amount of palaeosols, imprint of raindrops assign the presence of extensive floodplain deposits of the meandering river, and the sediments were exposed for a long time on the flood plain. The presence of a greater amount of mudstone than sandstone beds and lateral accretionary architectures of sandstone are interpreted as indication of the existence of high sinuosity meandering river system carrying a great amount of suspended load. The rippled and sheet-like sandstone beds interbedded within mudstone beds represent crevasse splay deposits.

FA2-facies association

The FA2-facies association is recognised by the presence of medium- to coarse-grained, light grey sandstone interbedded with thinly layered muddy sandstone and variegated to dark grey mudstone. It is represented frequently by multiple accumulated sequences of mudstone and sandstone, and preserves rippled lamination. The amount of sandstone is comparatively more than that of mudstone. Fine-grained sandstone beds are generally very thin and massive in places. They have a sheet-like geometry, and are massive to rippled. These beds occasionally grade into overlying mudstones or grade from underlying mudstones. Coarse-grained sandstone beds reach up to 4 m in thickness and show trough cross-stratifications, which are ribbon-shaped with lateral accretionary architecture. Fine sandstone beds are 10 to 70 cm thick, and some of the coarser sandstone beds are of about 10 m thick, whereas mudstone beds are of about 1 to 2 m thick. The coarser sandstone to mudstone succession of this facies association shows a typical form of fining-upward sequence. The thickness of such sequence varies from 2 to 4 m beginning from coarse-grained sandstone to mudstone. The basal contact surface of the sandstone beds is normally slightly eroded to flat. The FA2-facies association is found in the upper member of the Lower Siwaliks.

The FA2-facies association is interpreted as the product of a flood flow-dominated fine-grained meandering fluvial system. Repeatedly occurrence of thin layers of muddy sandstone within fine- to coarse-grained sandstone support that interpretation. Laminated sandy mudstone and fine-grained sandstone show that the deposition was caused by weak water currents. Coarse-grained sandstone with laterally accreted architectures reflect bed load deposits of the meandering channels, whereas sheet-like geometry of finer grained sandstone beds reflect their origin by the vertical aggradation due to flooding. Vertical lithological variability shows a small change in depositional process. Interbedded palaeosols with laminated fine- to medium-grained sandstone beds indicate the seasonal or long-term drying out on the flood plain.



Fm- Formation; M.-Member, * evolution of fluvial system after the authors, ** Lithostratigraphy after the authors.

Fig. 3: Summary on the evolution of the fluvial system in Nepal Himalaya

FA3-facies association

The FA3-facies association is represented by thick-bedded, medium- to coarse-grained sandstone associated with dark grey mudstone and muddy sandstone. Dark grey mudstone beds are thin, occasionally subordinates to sandstone. Medium- to coarse-grained sandstone beds show trough cross-stratifications, which occasionally form both lateral and vertical accretional architectures. Trough cross-beds are developed in the coarse sandstones, forming lateral accretional architecture. The muddy multistoreyed sandstones, commonly interbedded with mudstones, show sheet-like geometry, and some of them contain ripple marks. Thinly layered muddy sandstone beds, which are interbedded with mudstone sometimes exhibit ripple marks and convolute beddings. The basal contact of each fluvial succession is erosional. Sandstone beds are generally 1 to 3 m thick and increase up to 5 m at some places, and mudstone beds are 0.5 to 2.0 m in thickness. The fining-upward fluvial successions (2 to 5 m thick) are prominent. The lower member of the Middle Siwaliks exhibits the FA3-faices association.

The FA3-facies association is also considered to be the product of a sandy meandering fluvial system with flood flow-dominant deposits. The lateral accreted cross-stratified sandstone and multiple accumulated muddy sandstone beds are the evidence of that environment. The cross-stratified sandstone beds suggest the deposits by bed load of high sinuosity channel flow, and the muddy sandstone beds are formed by crevasse splay or suspension load deposits. The characteristic feature of the FA2-facies association is the predominance of finely laminated mudstone beds and fine rippled sediments that differs from the FA3 facies association, which is characterised by predominance of trough stratified and rippled sandstone beds. This indicates a slight increase in discharge of the rivers from FA2 to FA3 facies associations.

FA4-facies association

The FA4-facies association is characterised by the presence of thick-bedded, coarse- to very coarse-grained sandstone, pebbly sandstone and dark grey mudstone beds. Proportion of mudstone beds lowers than in the FA3 facies association. Large-scaled trough cross-stratification is well preserved in the sandstone beds. These sheet-like multistoreyed beds show down and lateral accretions with uncompleted ribbon shapes. The coarse- to very coarse-grained sandstone and pebbly sandstone beds sometimes form downstream accretionary and lateral accretionary architectures. The thickness of individual sandstone beds ranges from 1 to 5 m, and pebbly sandstone beds are of about 0.5 to 1 m thick. The subrounded to rounded pebbles in these sandstone beds are derived from the Lesser Himalayan rocks. Majority of the clasts are quartzite with 1 to 5 cm in diameter. The maximum size of mudclasts found in sandstone beds is about 15 cm (long axis). The fining-upward sequences (5 to 15 m thick) are distinct that start from pebbly sandstone bed with basal erosional surface. The thickness of bedload sediments consisting of coarse- to very coarse-grained sand and pebbly sand commonly ranges between 4 and 10 m. The FA4-facies association is observed in the upper member of the Middle Siwaliks.

The FA4-facies association is considered to have developed by a sandy braided fluvial system, which is clarified by the great volume of bedload sandstone with downstream architecture. Existence of intraformational mudclasts at the bottom of each fluvial succession suggests bank-cut materials produced during lateral migration of the channel. Commonly occurring thick fining-upward sequences and presence of thick units of sandstone and pebbly sandstone beds with erosional bases suggest the existence of deep channel flows.

EVOLUTION OF FLUVIAL SYSTEM

Mainly two types of fluvial systems were identified in the Siwalik Group of the Chatara–Barahakshetra area. In the initial stage of deposition, the meandering fluvial system predominated, and the floodplain was exposed for a long time, which is shown by the FA1-facies association. The second stage was represented by the FA2- and FA3-facies associations, in which a fluvial environment with dominant assemblages of flood sediment deposition had taken place. These facies associations indicate that the sedimentation took place in a flood flow-dominated meandering and sandy meandering fluvial systems. The third stage of deposition is represented by the FA4-facies associations, which is characterised by deposits formed in a sandy braided fluvial system. This system is also evidenced by the presence of thick-bedded, coarse- to very coarse-grained sandstone beds with sporadic pebbles.

In the study area, all the FA1- to FA4-facies associations can be observed in the south belt whereas only the FA1-facies associations are present in the north belt. Thus, the deposition of the Siwalik Group sediments in Chatara–Barahakshetra area started in a meandering and flood flow-dominated meandering fluvial system, and was followed by a sandy braided system.

Periods of changes in fluvial system in the Chatara–Barahakshetra area is not presented due to the lack of the palaeomagnetic age determination. The flood flow-dominated meandering system occurred at 10.5, 9.9, and 9.5 Ma in the Bakiya Khola (central Nepal), Tinau Khola (west-central Nepal), and Surai Khola (west Nepal), respectively (Fig. 3; Ulak and Nakayama 1998; Nakayama and Ulak 1999; Ulak and Nakayama 2001). It is considered that the development of flood flow-dominated meandering system along the Chatara–Barahakshetra section took place before or around 10.5 Ma.

The change from a meandering to a braided fluvial system occurred at 9.0, 8.2, and 6.5 Ma in the Bakiya Khola (central Nepal), Tinau Khola (west-central Nepal), and Surai Khola (west Nepal), respectively (Fig. 3; Ulak and Nakayama 1998; Nakayama and Ulak 1999; Ulak and Nakayama 2001). However, it is assumed that the development of braided fluvial system might have occurred between 8.2 and 6.5 Ma in the Chatara–Barahakshetra section, east Nepal.

CONCLUSIONS

On the basis of the lithological characteristics, the Siwalik Group of the Chatara–Barahakshetra area is divided into the Lower and Middle Siwaliks, in an ascending order. They are further subdivided into the lower and upper members.

Four facies associations, which are intimately related to the lithostratigraphic units, are recognised. The sediments of the lower and upper members of the Lower Siwaliks represent (FA1- and FA2-facies associations, respectively) deposits by the fine-grained meandering fluvial system and the flood flow-dominated meandering fluvial systems, respectively. In contrast, the lower and upper members of the Middle Siwaliks (FA3- and FA4-facies associations, respectively) are interpreted to result from deposits by a sandy meandering fluvial and sandy braided fluvial system, respectively.

The development of the braided fluvial system from meandering system should have occurred during 8.2 to 6.5 Ma in the Chatara–Barahakshetra area in east Nepal.

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