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Neogene fluvial systems in the Siwalik Group along the Tinau Khola section, west central Nepal Himalaya

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ABSTRACT

Along the Tinau Khola section of west central Nepal, the Siwalik Group is a 4 km thick pile of fluvial sedimentary sequence of mudstone, sandstone, and conglomerate. It is exposed between the Main Boundary Thrust (MBT) to the north and the Frontal Churia Thrust (FCT), also known as the Main Frontal Thrust (MFT), in the south. The Siwalik Group is lithologically divided into the Arung Khola, Binai Khola and Chitwan formations, in ascending order. Six facies associations (FA1 to FA6) are recognised within the group based on grain size distribution, nature of bedforms, and sandstone-mudstone ratio. The fine-grained sediments of the Lower and Middle members of the Arung Khola Formation belong to the FA1-facies association and were interpreted to have deposited by a low-discharge, low-relief meandering fluvial system. The multiple accumulated thin-layered muddy sandstone sequence in the Upper Member of the Arung Khola and the Lower Member of the Binai Khola formations belong to FA2 and FA3-facies associations and were deposited by a flood flow-dominated meandering fluvial system. The deep sandy braided facies association (FA4) and shallow sandy braided facies association (FA5) are well developed in the Middle and Upper members of the Binai Khola Formation, respectively. The gravelly braided facies association (FA6) is recognised in the Chitwan Formation.

The palaeomagnetically well-studied section of the Tinau Khola allows precise dating of the major change of fluvial system during the deposition of the Siwalk Group. The environment of predominantly shallow meandering rivers with low-relief and low-discharge during the time of deposition of the Arung Khola Formation changed at 9.9 Ma and flooding in the rivers dramatically increased due to the intensification of monsoon precipitation. This hydrographic change also brought the change in facies from the earlier FA1 facies to FA2 and FA3 facies. Change from meandering to braided system occurred at 8.2 Ma because of the obvious regional tectonic upliftment of the Higher Himalaya bringing into FA4 and FA5-facies associations. Finally the FA6-facies association was developed due to the large gravelly braided system development at 2.5 Ma as a result of the Main Boundary Thrust movement along the frontal part of the Himalaya.

INTRODUCTION

The Siwalik Group lying between the Main Boundary Thrust (MBT) and the Frontal Churia Thrust (FCT), also known as the Main Frontal Thrust (MFT), forms the southernmost front of the Himalaya. The group consists of fluvial deposits strongly influenced by the Neogene tectonics of the Himalaya (Parkash et al. 1980). In general, the Himalayan uplift during the Neogene time is reflected in the general coarsening upward sequence of the Siwalik Group. The uplift of the Himalaya started the monsoon precipitation as well as changed the fluvial system in south Asia. The sedimentological studies in the Siwalik Group are important to know the climate change and the development of fluvial systems in the foreland basin of the Himalaya.

The lithostratigraphy of the Siwalik Group in Nepal has been established by Tokuoka et al. (1986, 1990); Sah et al. (1994); Corvinus and Nanda (1994); Dhital et al. (1995); Ulak and Nakayama (1998) and others. The sedimentological studies of the Siwalik Group have shown that there have been sudden changes in the fluvial system during the deposition of the group. Generally four drastic changes have been recognised (Hisatomi and Tanaka 1994; Tanaka 1997; Ulak and Nakayama 1998; Nakayama and Ulak 1999). They are: (i) sudden increase of flood deposits, (ii) change from meandering to braided river system, (iii) onset of predominantly gravelly deposits, and (iv) domination of debris flow deposits. However, in the Tinau Khola section the last change has not been recognised.

The palaeomagnetic polarity indicates the deposition period of the Siwalik Group in Nepal range from 16 to 1 Ma (Tokuoka et al. 1986; Appel et al. 1991; Harrison et al. 1993; Gautam and Appel 1994; Gautam and Rösler 1999; Gautam and Fujiwara 2000). The stable isotope ratios in the Siwalik Group of Nepal indicate that C3 plants changed into C4 plants at 7.0 Ma (Harrison et al. 1993; Quade et al. 1995). Generally, C3 plants are trees, shrubs and grasses favouring a cool growth season, while C4 plants are shrubs and grasses favouring a warm growth season.

This paper mainly focuses on the changes of the fluvial system in the Siwalik Group of the Tinau Khola section based on facies analysis. Timing for apparent changes in the fluvial system is also estimated using the published magnetostratigraphy.

GEOLOGICAL OUTLINE

The Himalaya is the consequence of collision between the Indian and Asian plates. The Himalaya range is composed of thick pile of southward-displaced thrust sheets. The Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Frontal Churia Thrust (FCT) are successively exposed from north to south. Along the Tinau Khola section, the 4 km thick Siwalik Group is divided into four formations: Arung Khola, Binai Khola, Chitwan, and Deorali formations, in ascending order (Tokuoka et al. 1986, 1990; Table1). The Central Churia Thrust (CCT) separates the northern and southern belts of the group in this section (Fig. 1).

The Lower Member of the Arung Khola Formation (*Al*) consists of variegated mudstone (0.5 to 3 m thick) alternating with fine- to very fine-grained, calcareous sandstone (0.2 to 2.5 m thick) with a ratio of mudstone to sandstone 65:35. The palaeosols of reddish purple colour are abundant. The member is more than 500 m thick in the northern belt, but is not exposed in the south. The Middle Member (*Am*) is also characterised by variegated mudstone (1 to 2 m thick) and fine- to medium-grained sandstone (0.2 to 2 m thick), with mudstone/sandstone ration 57:43. The member attains 1,200 m thickness in the northern belt, and more than 250 m in the southern belt. The Upper Member (*Au*) is represented by fine- to coarse-grained sandstone (1 to 3 m thick) and mudstone with the ratio of sandstone to mudstone about 70:30. The thickness of the member is 420 m in the northern belt, and 1,350 m thick in the south. The "pepper and salt" sandstone beds occur in the upper part of the member. This sandstone is characterised by the significant content of biotite and quartz grains derived mainly from the Higher Himalayan crystalline rocks.

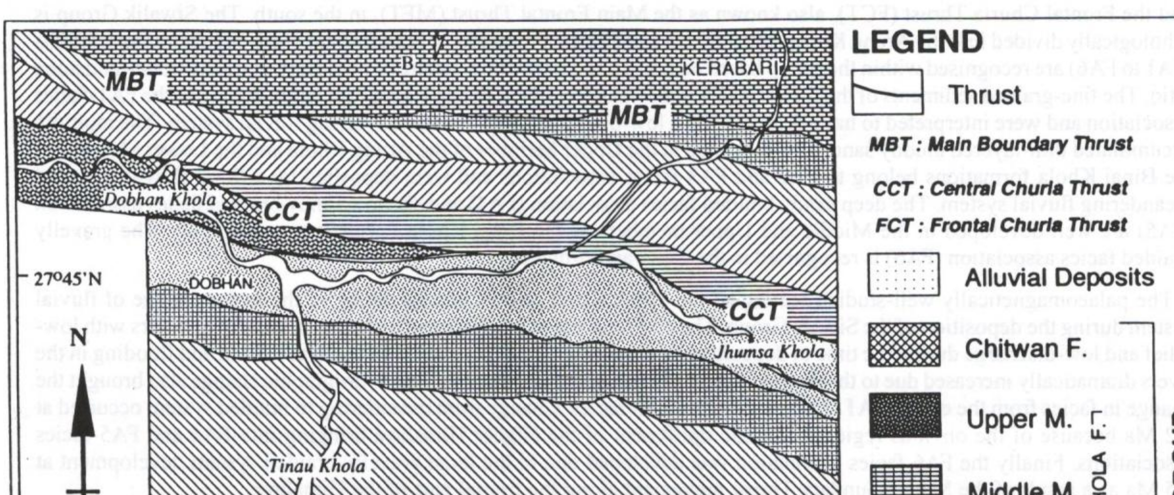

Fig. 1: Geological map of the Tinau Khola area, west central Nepal (after Tokuoka et al. 1990)

Table 1: Lithostratigraphy of the Tinau Khola area, west central Nepal (after Tokuoka et al. 1990)

Lithostratigraphic unit	Thickness (m)	Lithological characteristics
Deorali Formation (*D*) *	450+ [SB]	Poorly sorted, matrix supported boulder-sized, loose conglomerates and lenses of sands and muds. Sandstone boulders are derived from the lower part of the Siwalik Group.
Chitwan Formation (*C*)	200+ [SB]	Well sorted, clast supported, moderately indurated cobble-pebble conglomerates. The clasts of conglomerate are from the Lesser Himalayan terrain.
Binai Khola Formation (B)		
Upper Member (*Bu*)	260 [SB]	Thick bedded, coarse- to very coarse-grained, "pepper and salt" sandstone with pebbly sandstone and rare mudstone. Sandstones are less indurated.
Middle Member (*Bm*)	1220 [SB]	Thick bedded, coarse- to very coarse-grained, moderately indurated"pepper and salt" sandstone with dark grey mudstone and frequently pebbly sandstone. (sst>>ms)
Lower Member (*Bl*)	150+ [NB] 340 [SB]	Medium- to coarse-grained sandstone with dark grey mudstone. Pseudo "pepper and salt" sandstones are found in which the amount of biotite flakes are fewer. (sst>ms)
Arung Khola Formation (A)		
Upper Member (*Au*)	420 [NB] 1350 [SB]	Medium- to coarse-grained, grey sandstone alternating with variagated mudstone. Grey mudstone and "pepper and salt" appearance sandstone rarely occur. (sst>ms)
Middle Member (*Am*)	1200 [NB] 250+ [SB]	Fine-grained, calcareous, grey sandstone interbeds with variegated mudstone. Rare pseudoconglomerates. (ms=sst)
Lower Member (*Al*)	500+ [NB]	Fine-grained, calcareous, greenish grey sandstone interbeds with variegated mudstone and sandstone. Pseudoconglomenrates are common. (ms>>sst)

*indicates not exposed in the Tinau Khola section, west Nepal. [SB]: southern belt, [NB]: northern belt.

The Lower Member of the Binai Khola Formation (*Bl*) is composed of thick, medium- to coarse-grained, grey sandstone (1 to 5 m thick) and dark grey mudstone (0.5 to 1 m thick). The ratio of sandstone, mudstone and conglomerate is 72:25:3. The member is more than 150 m thick in the northern belt, and 340 m thick in the south. The Middle Member (*Bm*) is comprised of thick-bedded, coarse-grained "pepper and salt" sandstone (1-7 m thick) with dark grey mudstone (0.2 to 1.5 m thick) and congrlomerate, having their ratio of 52:16:32, respectively. This member attains 1,220 m thickness in the southern belt. The Upper Member (*Bu*) is characterised by coarse- to very coarse-grained sandstone beds (3 to 10 m thick) with conglomerate (5 to 10 m thick), and it attains 260 m in thickness (southern belt). The proportion of sandstone, mudstone and conglomerate is 45:16:39. Most of the clasts in the conglomerate are derived from the Lesser Himalaya sediments. The Middle and Upper members of the Binai Khola Formation are missing in the northern belt.

The Chitwan Formation comprises of semi-consolidated conglomerates (5 to 7 m thick). The conglomeate beds occupy 71% of the formation and the clasts are pebble- to cobble-sized quartzite, sandstone and shale, derived mainly from the Dumri Formation (Sakai 1983) of the Lesser Himalaya. Along the Tinau Khola section, this formation is more than 200 m thick.

The Deorali Formation is not exposed in the Tinau Khola section. In Binai Khola section, this conglomeratic formation reaching to a thickness of 450 m is characterised by the presence of disorganised, cobble- to boulder-sized sandstone clasts derived form the lower part of the Siwalik Group.

FACIES ASSOCIATION

Representative field sections of the Siwalik Group along the Tinau Khola were studied, and detailed columnar sections prepared. The section represents a typical fluvial autogenetic fining upward successions. We recognised and categorised facies associations based on bedforms, bed contact nature, grain size, sandstone and mudstone ratio, and thickness of sandstone beds. Miall's (1978, 1985, 1996) lithofacies code and architectural elements were followed in this work. Altogether six facies associations (FA1 to FA6) have been recognised (Fig. 2). These facies associations are intimately related to specific lithological units of the study area. Dominant and minor lithofacies types and characteristic architectural element are shown in Table 2.

FA1-Facies Association

Description

The FA1-facies association is characterised by predominance of bioturbated, thick-bedded mudstone (0.5 to 3 m thick) interbedded with fine-grained, greenish-grey, calcareous sandstone (0.2 to 2.5 m thick). Within this facies proportion of mudstone is greater than sandstone. Generally, the fining upward successions are observed in 1.5 to 4 m thick sequence where sandstone gradually pass upward to mudstone. Calcareous nodules are well observed on the 10 to 20 cm thick upper surfaces of fine-grained sandstone beds,

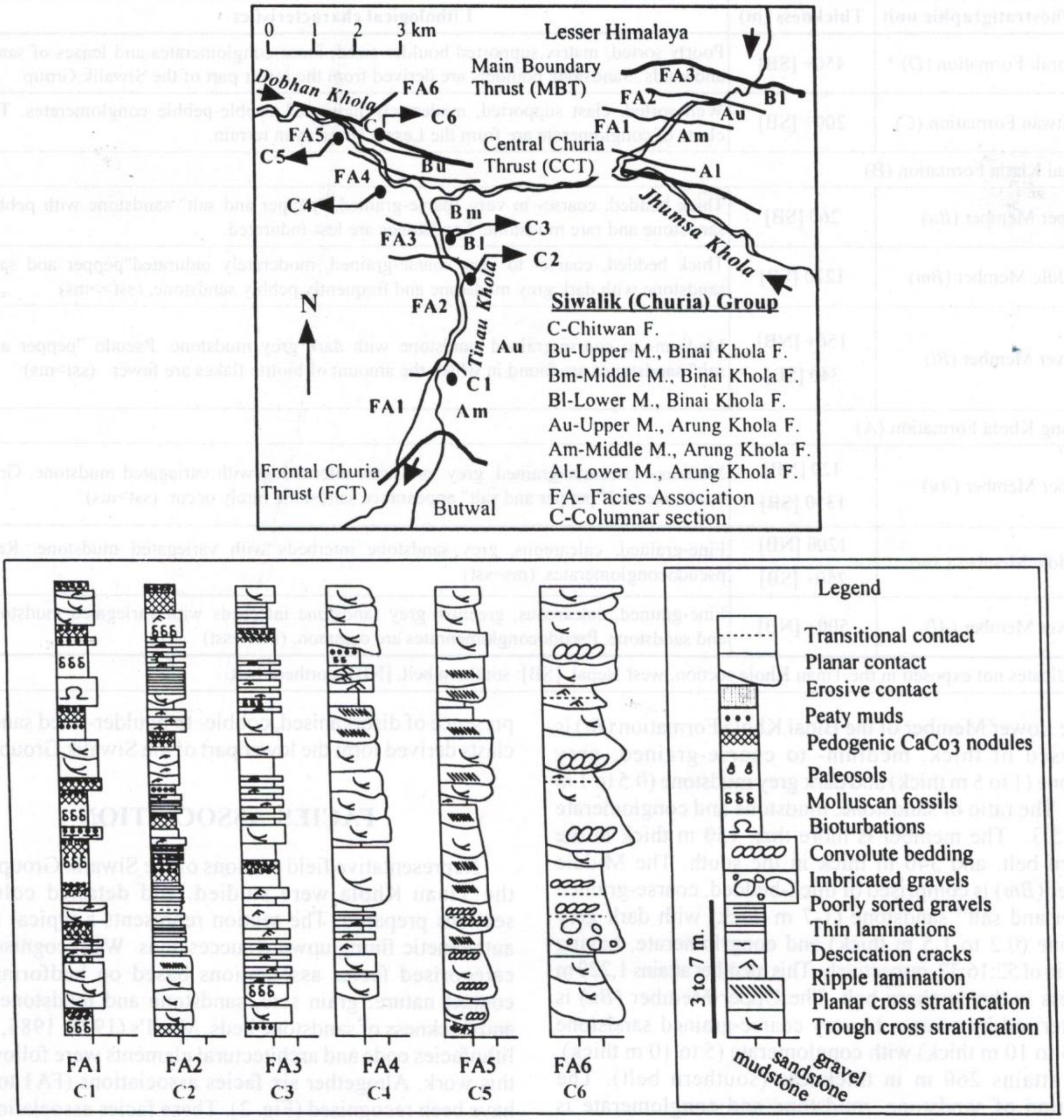

Fig. 2: Representative facies associations (FA) of the Tinau Khola section, west central Nepal

and they also occasionally occur in mudstone. This facies association is also characterised by the presence of palaeosols (1 to 3 m thick) at the top of the fining upward sequence. The mudstones as well as the fine-grained sandstones are highly variegated. The nature of basal contact surface of sandstone beds with the underlying sequence is flat or slightly eroded. Lateral accreted architectures are also found in thick sandstone beds in the area. Ripple laminations, raindrop imprints, mudcracks and trace fossils are commonly preserved in fine- to medium-grained sandstone beds. The FA1-facies association is preserved in the Lower and Middle members and lower part of the Upper Member of the Arung Khola Formation.

Interpretation

Predominance of bioturbated, variegated and thick-bedded mudstone beds, presence of calcareous nodules, abundance of trace fossils in fine-grained sandstone beds (Fig. 3) in the FA1-facies indicate that they are the product of a low-dischage, low-relief meandering river system. Significant amount of palaeosols, presence of vertical accretionary structures, imprint of raindrops and mudcracks suggest the presence of extensive flood plain deposits, and the sediments were exposed for a long time on the flood plain. Presence of greater amount of mudstone than sandstone beds and lateral accretional architectures of sandstone are interpreted as indication of the existence of

Table 2: Brief descriptions of representative facies associations of the Tinau Khola section, west central Nepal

Facies association	Dominant lithofacies type*	Minor lithofacies types*	Characteristic architectural element**	Lithostratigraphic unit of Tinau Khola area	Interpretation
FA1	P, Fr, Fm, Fl, Fsm	St, Sr	FF, SB, LA>LS	Lower and Middle members of the Arung Khola Formation and the Lower part of the Upper Member of the Arung Khola Formation	Meandering river system
FA2	Fl, Fr, P, Sr, Fm, Fsm	St, Sh	FF, SB, LA > DA, LS	Upper part of the Upper Member of the Arung Khola Formation	Flood flow-dominated meandering river system
FA3	St, Sr, Fl, Fm, Fr, P	Fsm, Ss, Sp, Sh	LA, FF, SB > DA	Lower Member of the Binai Khola Formation	Flood flow-dominated shallow sandy meandering river system
FA4	St, Sr, Sp, Ss, Sh	Fsm, Fl, P, Gt	DA, LA, FF, SB	Middle Member of the Binai Khola Formation	Deep sandy braided river system
FA5	St, Sr, Sp, Ss, Sh	Fl, Fsm, Gt, P	SB, DA > LA, HO, FF	Upper Member of the Binai Khola Formation	Shallow braided river system
FA6	Gp, Gt, Gh	St, Ss, Sr, Fms, Gmm	GB> SB, DA, HO	Chitwan Formation	Gravelly braided river system

*Classification from Miall (1978, 1985, and 1996). ** CH recognised in all facies associations.

Fig. 3: Trace fossils in fine-grained sandstone of facies association-FA1 in the Lower Member of the Arung Khola Formation (*Al*).

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

Description

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. Fine-grained sandstone beds are generally very thin (0.5 to 2 m thick), and massive in places. They are represented frequently by multiple accumulated sequence of mudstone and sandstone and preserve ripple lamination including climbing ripples. The coarse-grained beds of sandstone reach up to 4 m. in thickness and show trough cross-stratifications. They are ribbon- to lensoid-shaped, and occasionally form lateral accretional architectures. Mudstone beds are 1 to 2 m in thickness and frequently isolated. The basal contact surface of sandstone beds is commonly slightly eroded to flat. Bioturbation and palaeosols are less than those in the FA1-facies assocaiton (Fig. 4). The 8 to 10 m thick fining upward succession from coarse-grained sandstone to mudstone is common. FA2-facies association is found in the upper part of the Upper Member of the Arung Khola Formation.

Interpretation

The FA2-facies association is interpreted to belong to a flood flow-dominated fine-grained meandering river system. Repeated occurrence of thin layers of muddy sandstone beds within fine to coarse sandstone is interpreted to have formed by successive flood flows. Laminated sandy mudstone and fine-grained sandstone represent depositions from suspension and weak currents. Climbing ripples indicate gradual decrease in the velocity of flood flow. Coarse-grained sandstone with lateral accreted architectures (Fig. 5) reflect bedload deposits of the meandering channels, whereas sheet-like geometry of finer grained sandstone beds reflect their origin to the vertical aggradation by flooding. Vertical lithological variability is susceptible to 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.

FA3-Facies Association

Description

The FA3-facies association is represented by thick-bedded, medium- to coarse-grained sandstone associated with dark grey mudstone and muddy sandstone. Variegated mudstone is very rare, dark grey mudstone beds are thin occasionally subordinates to sandstone. Medium- to coarse-grained sandstone beds show trough cross-stratification, which occasionally forms both lateral and down accretional architectures. Thinly layered muddy sandstone beds

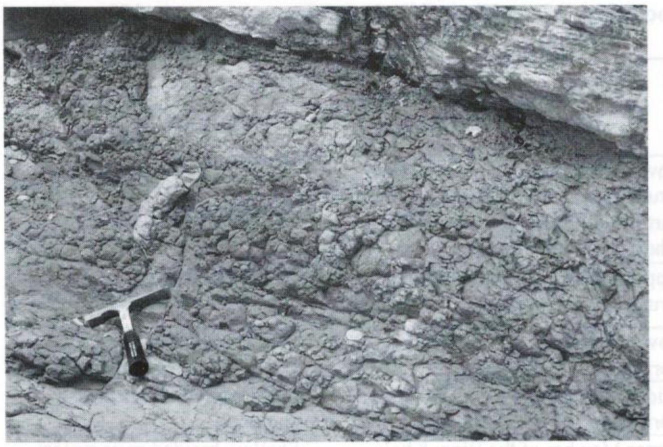

Fig. 4: Biotubated mudstone of the FA2-facies association in the Upper Member of the Arung Khola Formation (*Au*).

Fig. 5: Lateral accreted architecture in sandstone (in the Middle Member of the Arung Khola Formation, *Am*) developed in the FA1- facies association. Dark line indicates the accretionary boundary.

interbedded with mudstone with sheet-like geometry sometimes exhibit ripples, as well as 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 m in thickness. The fining upward fluvial successions (2 to 5 m thick) are conspicuous and common. Well rounded to rounded pebbles are commonly found in the thick-bedded sandstone beds. The Lower Member of the Binai Khola Formation. Only exhibits the FA3-faices association.

Interpretation

The FA3-facies association is also considered to be the product of a sandy meandering river system with flood flow dominant deposits. The evidence for this type of fluvial system is the existence of lateral accreted cross-stratified sandstone and multiple accumulated muddy sandstone beds (Fig. 6). The former beds suggest the deposits by bedload of high sinuosity channel flow, while the latter beds are formed by crevasse splay deposits. The essential difference between the FA2 and FA3-facies associations are in the predominance of finely laminated mudstone beds and fine rippled sediments in FA2 while FA3 facies is characterised by predominance of trough stratified and rippled (ripple marks on the bedding plane, Fig. 7) sandstone beds. This indicates a slight increase in discharge of the rivers from FA2 to FA3 facies.

FA4- Facies Association

Description

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. Here the proportion of mudstone beds are less than in FA3. Large-scaled trough cross-stratification is well preserved in the sandstone beds. 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 about 0.5 to 1 m. Pebbly sandstone beds have sheet-like geometry. The subrounded to rounded pebbles in these sandstone beds are derived from 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 along its long axis. The fining upward sequences (5 to 15 m thick) are distinct, which starts from pebbly sandstone bed with basal erosional surface. The thickness of bedload sediments consisting of coarse- to very coarse-grained sand and pebbly sand which forms the basal parts of the fining upward sequences commonly ranges between 4 and 10 m. The FA4-facies association is observed in the Middle Member of the Binai Khola Formation.

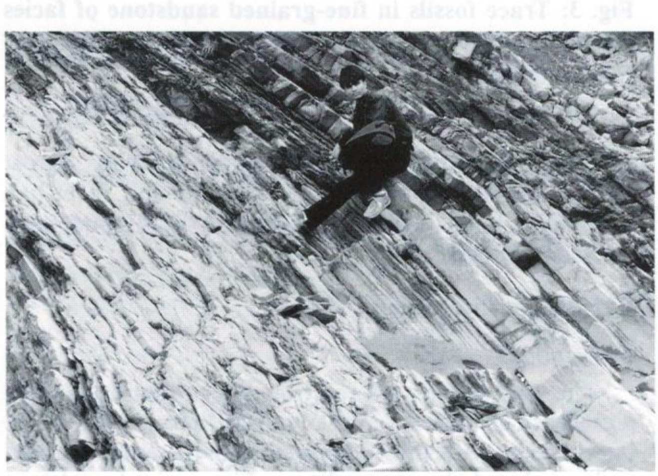

Fig. 6: Multiple accumulation of fine- to medium-grained sandstone interbedded with mudstone beds, which is characteristic feature of the FA2-facies association (the Upper Member of the Arung Khola Formation, *Au*).

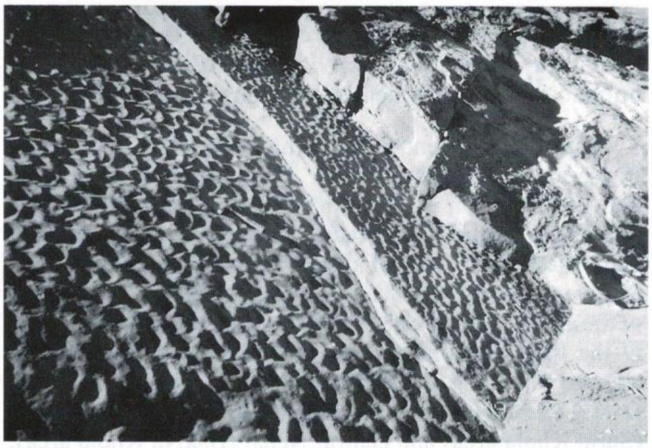

Fig. 7: Ripple marks in fine-grained sandstone represent (FA2-facies association) shallow water condtion during sediment deposition of the Upper Member of the Arung Khola Formation (*Au*).

Interpretation

The FA4-facies association is considered to have developed by a deep sandy braided river system evidenced by the great volume of bedload sandstone with downstream and lateral accretionary 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.

FA5- Facie Association

Description

The FA5-facies association is identified by the presence of thick-bedded, coarse- to very coarse-grained sandstone beds with subordinate pebbly sandstone and dark grey mudstone beds. FA5-facies components are essentially similar to those of FA4-facies except in the presence of trough stratified gravel beds and occurrence of thicker sandstone and pebbly sandstone beds. Coarse- to very coarse-grained sandstone and pebbly sandstone beds are commonly trough- and planar cross-stratified and show multiple accumulation. The sandstone and pebbly sandstone beds invariably shows erosional bases. Ripple laminated and plane-stratified (Fig. 8) sandstone beds are frequently observed in the upper part of thick-bedded sandstones. However, plane-stratified beds are frequently associated with large scale cross-stratification, and are rarely combined with ripple beds. Downstream accretionary architecture is occasionally found in these units. Palaeocurrent directions show little dispersion. Typical characteristic feature of this facies association is the rare occurrence of weakly developed fining upward succession. When present, the thickness of each fining upward succession from coarse-grained sandstone or pebbly sandstone to mudstone ranges from 5 to 10 m. This facies association is found in the Upper Member of the Binai Khola Formation.

Interpretation

The FA5-facies association was developed by a shallow sandy braided river system. Less distinct fining upward successions, sheet-like geometry of sandstone and pebbly sandstone, the development of planar-stratification imply a shallower fluvial system. Multiple accumulations of planar cross-stratified coarse-grained sandstone beds with a small dispersion in palaeocurrent directions is the evidence of the shallow sandy braided river system. The presence of ripple laminations and plane-stratification superimposed in the cross-stratification reflect the fluctuation of palaeoflow discharge. The combination of large-scale cross-stratification and plane-stratification indicates that the beds must have formed under upper flow regime.

FA6- Facies Association

Description

The FA6-facies association is typified by the presence of thick-bedded, clast supported and well-sorted conglomerate, subordinate lenses of reddish brown sandstone and dark grey mudstone. Almost all the clasts are pebble- or cobble-sized, rounded to subrounded in shape and derived from Lesser Himalayan terrain. Planar cross-stratifications are well preserved but trough cross-laminations are poorly developed in the conglomerates. Imbrication of the clasts is apparent. The conglomerates are 5 to 15 m thick, while the interbedded sandstone and mudstone beds range from 0.5 to 1 m in thickness. Fining upward sequence is indistinct due to the presence of numerous erosional surfaces. The palaeocurrent directions measured from the imbricated gravels do not show scatter. FA6-facies association is well developed in the Chitwan Formation.

Interpretation

The FA6-facies association suggests that the sediments were deposited by gravelly braided river system as evidenced by the presence of widespread bedload gravel clasts, and

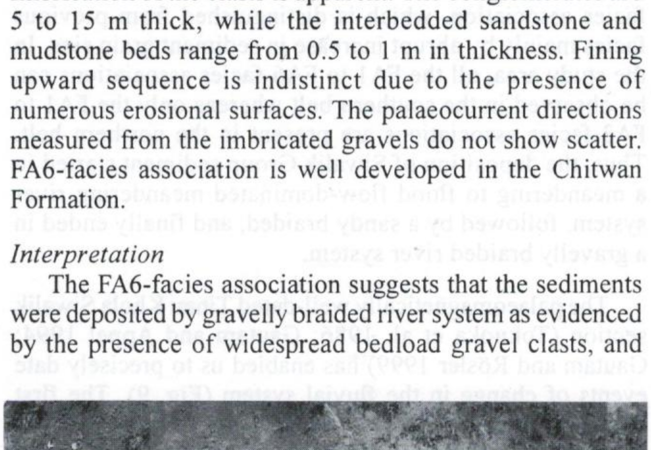

Fig. 8: Planar cross-stratification developed in the "pepper and salt" sandstone of the FA5-facies association (Upper Member of the Binai Khola Formation).

uniformity in palaeocurrent direction. Numerous erosional surfaces and predominance of conglomerate over other rock types may imply that the river system was relatively shallow and/or having unstable channels.

CHANGES IN SIWALIK FLUVIAL SYSTEM

The following four main types of fluvial system are recognised during the sedimentation period of the Siwalk Group in the Tinau Khola section (i) The earliest stage of the Siwalik sediment deposition began in a fine-grained meandering river system belonging to the FA1-facies association as described above. During this stage evidence of a long-term exposure of the flood plain and back swamp deposits is found. (ii) The second stage represented by the FA2 and FA3-facies associations is a fluvial environment with dominant assemblages of flood and crevasse splay sediment deposition. These facies associations indicate that the sedimentation took place in a flood flow-dominated meandering river systems. (iii) The third stage with the FA4 and FA5-facies associations is represented by deposits formed by a sandy braided river system as evidenced by the presence of thick-bedded, coarse- to very coarse-grained sandstone beds. (iv) Lastly, during the fourth stage the fluvial system changed into a gravelly braided river system characterised by the FA6-facies association, which is distinguished from previous facies mainly by abrupt increase in sediment grain size. In the study area, all the FA1 to FA6-facies associations can be observed in the southern belt whereas only the FA1 to FA3-facies associations are present in the northern belt. Thus, the deposition of Siwalik Group sediment started in a meandering to flood flow-dominated meandering river system, followed by a sandy braided, and finally ended in a gravelly braided river system.

The palaeomagnetically well-dated Tinau Khola Siwalik section (Tokuoka et al. 1986; Gautam and Appel 1994; Gautam and Rösler 1999) has enabled us to precisely date events of change in the fluvial system (Fig. 9). The first change from fine-grained meandering to flood flow-dominated river system occurred at 9.9 Ma. The sandy braided river system started to develop at 8.2 Ma. The change from the sandy braided to the gravelly braided river system occurred approximately at 2.5 Ma. The time estimation of the beginning of the fine-grained meandering system is difficult as the lowermost part of the Siwalik Group in the Tinau Khola area is not exposed and the basal section is bounded by the Frontal Churia Thrust. However, as the oldest dated basal section of the Siwalik Group in the Arung-Tinau Khola area is about 14 Ma, fine-grained meandering river system may have evolved before that time.

CAUSES OF CHANGE IN THE FLUVIAL SYSTEM

A fluvial system can be influenced and changed by autogenetic as well as allogenetic factors. The main controlling factors are climate change and tectonics. In the Himalaya, the tectonic activity was responsible for the initiation and development of the monsoon climate.

The second event during which the change from the fine-grained meandering river system to the flood flow-dominated system in the Siwalik Basin of the Tinau Khola area had occurred at 9.9 Ma is considered to be climatically controlled. The uplift of the Himalaya to a considerable height in the north must have affected the general circulation of the atmosphere to cause the monsoon precipitation. Onset of the Indian summer monsoon climate thus would cause abundant flooding in the Siwalik Basin. Nakayama and Ulak (1999) also found the occurrence of similar event from west (Surai Khola area) and central Nepal (Bakiya Ḵhola area). The timing of onset of the monsoon in these areas including the Tinau Khola section ranges from 10.5 to 9.5 Ma (Nakayama and Ulak 1999). This change in fluvial system was thus caused by an allogenetic factor. Further more, the stratigraphic positions at which these changes have occurred lie at the same horizon in all the three areas and coincide with the first appearances of "pepper and salt" sandstone. The onset of the deposition of the "pepper and salt" sandstone also indicates initiation of erosion in the crystalline rocks of the Higher Himalaya.

The third event characterised by the onset of the sandy braided river system corresponds to the drastic increment of "pepper and salt" sand in the Siwalik Group. This indicates that by this time the Higher Himalayan terrain was uplifted high along the MCT causing rapid erosion. The MCT was active during 22-15 Ma (Searle 1995; Harrison et al. 1997; Kaneko 1997), and has been intermittently active. Even during the second event of flood flow-dominant environment, thrusting along the MCT can be suspected. At the beginning of the third event represented by the sandy braided river system substantial uplift of the Higher Himalayan terrain must have occurred to provide the great volume of the "pepper and salt" sand, and to form the sandy braided system. Similar events are also recognised in the west and central Nepal (Nakayama and Ulak 1999). However, there is a systematic variation from east to west in the time of onset of the flood flow-dominated meandering river system and change from meandering to braided river system. The flood flow-dominated meandering river system occurred at 10.5 Ma and 9.5 Ma in central and western Nepal respectively (Nakayama and Ulak 1999), whereas it occurred at 9.9 Ma in the Tinau Khola area lying in between the above two areas. Simalrly, the timing of change from meandering to braided river system occurred at 9.0 and 6.5 Ma in the Bakiya Khola and Surai Khola areas respectively. But in the Tinau Khola area this event occurred at 8.2 Ma.

The fourth event represented by the gravelly braided river system started at 2.5 Ma. The gravels are essentially derived from the Lesser Himalayan rocks. This suggests that this event was tectonically controlled by activities along the MBT. Initial movement on the MBT in India and Pakistan occurred prior to 10 Ma (Andrew et al. 1995) and the fault

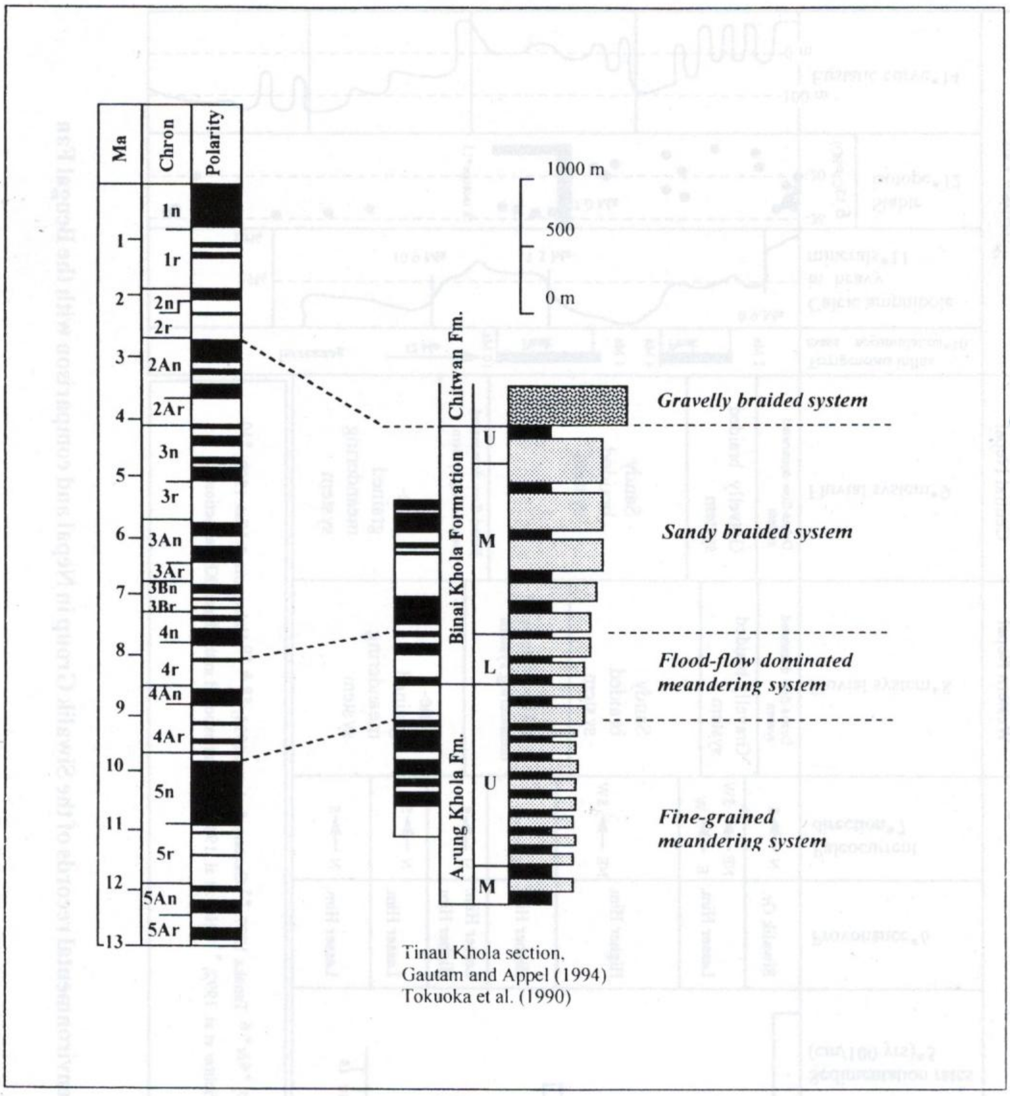

Fig. 9: Magnetostratigraphic frame work (Gautam and Appel 1994) and timing of change in the river systems along the Tinau Khola section, west central Nepal. Palaeomagnetic time scale from Cande and Kent (1995).

was active during the Middle Siwalik sedimentation period in Nepal Himalaya (Le Fort 1996). Though sediments derived from the Lesser Himalaya terrain can be recognised even in the Arung Khola Formation, but the proportion of gravel suddenly increases from 2.5 Ma. The movement along the MBT must have uplifted the Lesser Himalaya and/or must have shortened the distance between the Siwalik Basin and the Lesser Himalayan terrain, which could provide predominantly gravel-sized sediments to the Siwalik Basin.

The controlling factors and the timing of the beginning of the first event is unclear. As discussed above, the first event of deposition of the Siwalik Group by the meandering river system, may have occurred before 14 Ma. The low hinterland relief and the climate may be the most probable controlling factors.

Fig. 10 shows the summary of the timing of development of the fluvial system and palaeoenvironmental changes of the Siwalik Group. The data from the Bengal submarine fan are added as the reference. Environmental change during the deposition of the Siwalik Basin and its relation to the Bangal Fan deposits are discussed more detailed in Nakayama and Ulak (1999).

CONCLUSIONS

Six main facies associations (FA1 to FA6) are recognised in the Neogene fluvial sediments of the Siwalik Group in the Tinau Khola area of west central Nepal. They are interpreted as fine-grained meandering (FA1), flood flow-dominated meandering (FA2), sandy meandering (FA3), deep braided (FA4), shallow braided (FA5) and gravelly braided (FA6)

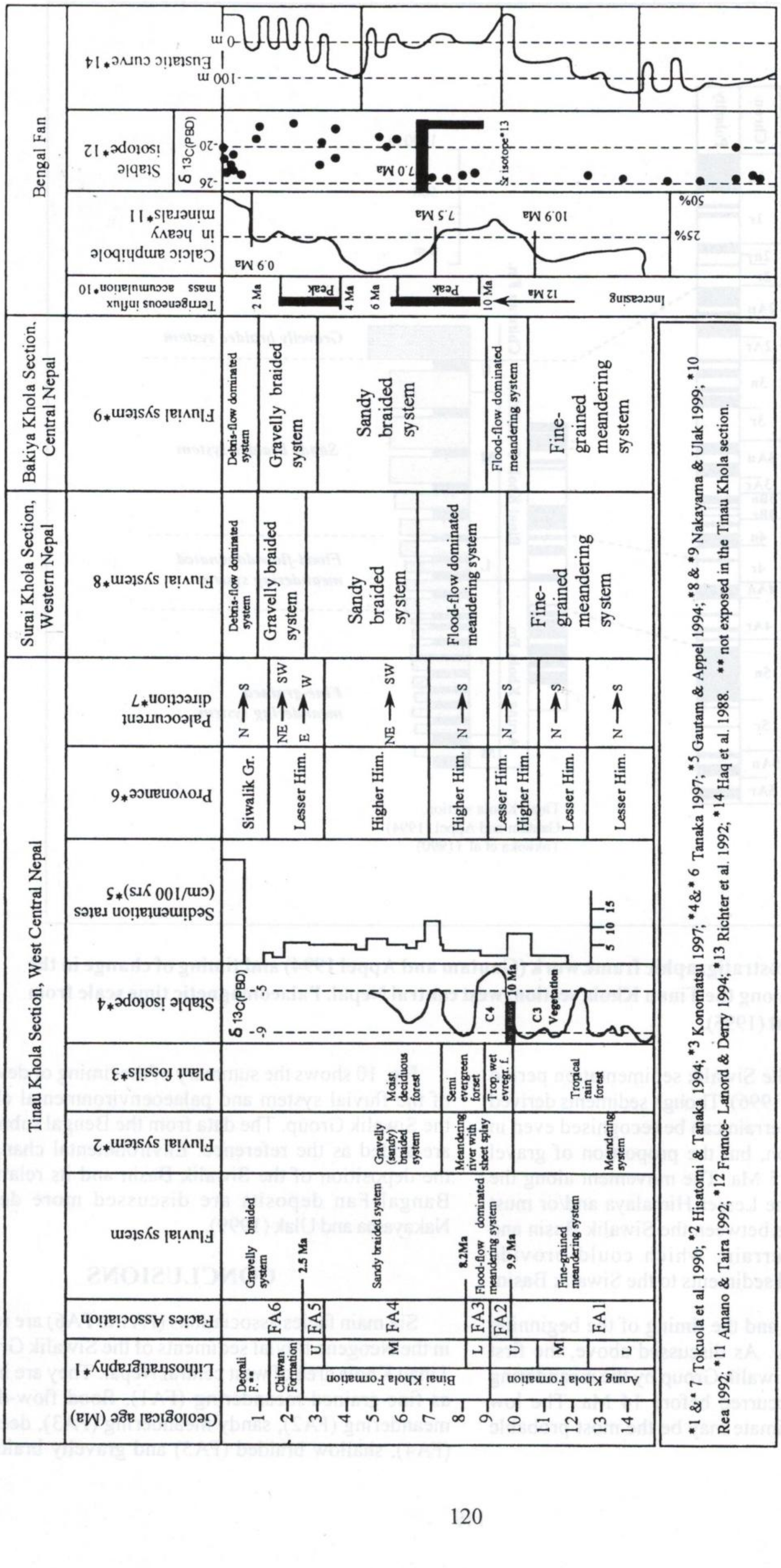

Fig 10: Summary of fluvial system and palaeoenvironmental records of the Siwalik Group in Nepal and comparison with the Bengal Fan

*1 & *7 Tokuoka et al 1990; *2 Hisatomi & Tanaka 1994; *3 Konomatsu 1997; *4& *6 Tanaka 1997; *5 Gautam & Appel 1994; *8 & *9 Nakayama & Ulak 1999; *10 Rea 1992; *11 Amano & Taira 1992; *12 France-Lanord & Derry 1994; *13 Richter et al. 1992; *14 Haq et al. 1988. ** not exposed in the Tinau Khola section.

river systems. The first event probably started before 14 Ma, and is closely related to inception of the deposition of Siwalik Group in a meandering river system. The second event began at 9.9 Ma and is characterised by the predominance of flood derived sediments. This event represents an expansion of the Indian monsoon. The third event which started at 8.2 Ma is a change from meandering to braided fluvial system. Initiation of a gravelly braided system is the fourth event, which occurred at 2.5 Ma.

The second event, i.e. initiation of the flood flow-dominated meandering system was climatically controlled. The inception of the Indian monsoon caused a drastic increase of precipitation to cause frequent seasonal flood flows in the fluvial system. The third event, which marks the onset of the braided system, was caused by a rapid uplift of the Higher Himalayan terrain, which reached sufficient height to provide a great amount of feldspar and biotite grains in the sediments. The onset of the fourth event, the onset of the gravelly braided river system, was tectonically controlled and must have been due to the rapid movement along the Main Boundary Thrust (MBT).

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