Sedimentary Facies Analysis of the Fluvial Environment in the Siwalik Group of Eastern Nepal: Deciphering its Relation to Contemporary Himalayan Tectonics, Climate and Sea-Level Change.

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Abstract

The Siwalik Group, ranging from the Early Miocene to Pleistocene, is believed to be controlled by contemporary Himalayan tectonics and climate. In this study, we established the fluvial system responsible for the deposition of the Siwalik succession along the Muksar Khola section and its controlling factors. Five sedimentary facies associations are identified which are interpreted as the deposits of flood plain dominated fine-grained meandering river (FA1), flood dominated overbank environment (FA2), sandy meandering river (FA3), anastomosing river (FA4), and debris flow dominated gravelly braided river (FA5). These change in fluvial style occurred around 10.5 Ma, 10.0 Ma, 5.9 Ma and 3.5 Ma due to the effects of hinterland tectonics, climate and sea-level change. The thick succession of intraformational conglomerate reveals the intensification of monsoon started around 10.5 Ma in the eastern Nepal Himalaya. The present study show asynchronous exhumation of the Himalaya east to west brought significant difference on the fluvial environment of the Neogene foreland basin. Moreover, this study also reveals continuous drifting of the foreland basin towards the hinterland concerning depositional age.

1. Introduction

Siwalik Group is exposed in the southernmost hill range made up of molasse deposit which is bounded by the Main Boundary Thrust (MBT) to the north and the Himalayan Frontal Thrust (HFT) in the south (Gansser, 1964; Corvinus, 1993). These sediments were derived from the Himalaya and deposited by the fluvial system (Tandon, 1976; Parkash et al., 1980; Tokuoka et al., 1990; Hisatomi and Tanaka, 1994; Willis, 1993b) in the paleo-Gangetic basin during the Early Miocene to Pleistocene time (Appel and Rosler, 1994; Gautam and Appel, 1994; Rosler et al., 1997; Gautam and Fujiwara, 2000; Ojha et al., 2009). Lithostratigraphy of the Siwalik Group has been established by various researchers having proposed a two-fold to five-fold classification of the Siwalik Group (Piligram, 1913, Tokuoka et al., 1990; Dhital et al., 1995; Ulak and Nakayama, 1998). The sedimentological studies show that meandering and the braided river system dominated the fluvial style during the deposition of the Siwaliks (Hisatomi and Tanaka, 1994; Zaleha, 1997; Ulak and Nakayama, 2001; Ulak, 2009; Sigdel and Sakai, 2016), though anastomosed river system has also been recorded in few sections (Huyghe et al., 2005; Nakayama and Ulak, 1999).

In the previous studies of the Siwaliks in various section along the Himalaya, the appearance of the Middle Siwalik sub-group represented by the ‘Salt and pepper’ sandstone, supplied from the Higher Himalaya that existed as a positive relief at that time due to tectonic upliftment (Khan et al., 1997; Kumar et al., 1999; 2003a; 2003b; Kumar and Tandon, 1985; Zaleha, 1997) is observed to be followed by the change in the river-style from meandering to the sandy braided river system. This change in the fluvial system is considered to be controlled by both autocyclic as well as an allocyclic process like hinterland tectonics, climate and size of drainage basins (Willis, 1993a; Zaleha, 1997; Nakayama and Ulak, 1999; Huyghe et al., 2005). Meanwhile, various Himalayan researchers suggested that the exhumation history of the Himalaya was not synchronous laterally, it was observed early in the western part compared to the eastern part (Robinson et al., 2001; Yin, 2006; Ojha et al., 2009). Therefore, if the tectonics was one of the factors controlling the change in the river system of the Neogene foreland basin, then asynchronous exhumation history of the Himalaya from west to east should also have brought a significant difference in the timing of a change in the fluvial environment laterally. Moreover, fluvial behaviour is governed not only by the interplay between tectonics and climate but also by sea-level change (Burbank et al., 1992; Goodbred and Kuehl, 2000a; 2000b). In the Siwalik Group along the Darjeeling-Sikkim and Arunachal Pradesh evidence of sediment deposited in deltaic and open Marine depositional settings is reported (Taral et al., 2018; 2019). The present study area lies in the eastern part of the Nepal Himalaya near to the Darjeeling-Sikkim section. Therefore, the contemporary exhumation history of the hinterland, climate and sea-level change should have a direct impact on the fluvial environment, though the effect of the sea-level change was not mentioned in the previous studies of the fluvial environment of the Siwalik Group.

In this study, we focused on establishing the fluvial environment in the Muksar Khola section of the eastern Nepal Himalaya based on the facies analysis. The evolution of the fluvial environment and their change are recorded based on the magnetostratigraphy of Ojha et al. (2009). The possible factors controlling the fluvial environment in the present study are discussed.

2. Geological Outline

The present study area lies in the eastern part of the Nepal Himalaya (Fig. 1-A). The Siwalik Group in this area is divided into three belts by the Main Dun Thrust (MDT) and the Kamala-Tawa thrust (KTT) (Shrestha and Sharma, 1996). The present study deals with the Siwalik Group in the southern belt, bounded by the MDT in the north and the MFT in the south. Lithostratigraphy of the Siwalik Group in the southern belt along the Muksar Khola section is established by Rai and Yoshida (2020). The > 4 km thick Siwalik Group is divided into the Lower Siwalik sub-group, the lower member of the Middle Siwalik sub-group, the upper member of the Middle Siwalik sub-group and the Upper Siwalik sub-group (Fig. 1-B). The Lower Siwalik sub-group comprises of grey, fine-grained indurated sandstone with dark greenish grey and purple, mottled mudstone. About 80 m thick successions of intraformational conglomerate (composed of mudstone clast with medium- to very coarse-grained sandstone matrix) is present within the middle part of the exposed section of the Lower Siwalik sub-group. The lower member of the Middle Siwalik sub-group is characterized by “salt and pepper” appearance medium-grained sandstone, with dark greenish grey mudstone to siltstone. The upper member of the Middle Siwalik sub-group consists of light grey, medium- to coarse-grained sandstone with some pebbly layers and grey to dark grey mudstone to siltstone. Sandstones are less indurated with a decrease in the amount of biotite grains and the proportion of mudstone is increased compared to the lower member of the Middle Siwalik sub-group. The Upper Siwalik sub-group is made up of poorly-sorted, pebble to cobble conglomerate. These conglomerate beds are frequently interbedded with thick massive, coarse-grained sandstone and dull-yellow to yellowish-grey mudstone to siltstone beds. The magnetostratigraphic study by Ojha et al. (2009) indicates that the ~ 2500m thick Middle Siwalik sub-group of the Muksar Khola was deposited between 10.0 and 3.5 Ma.

Previous studies of the eastern Nepal Himalaya shows a change in the hinterland exhumation rate, fast exhumation similar to the central and western Nepal was observed during the deposition of the lower member of the Middle Siwalik sub-group but was absent during the deposition of the upper member of the Middle Siwalik sub-group (Chirouze et al., 2012; Rai et al., in press). This fast exhumation was observed after 11.0 Ma as rapid uplift of the HHC occurred due to activation of out-of-sequence Thrust known as the Sun Koshi Thrust (Schelling and Arita, 1991; Rai et al., in press). Similarly after ~ 5.5 Ma, rapid subsidence of the foreland basin was observed as a result of thrust loading of the MBT (Ojha et al., 2009; Rai et al., in press). The climate of the eastern Nepal Himalaya was more or less similar to the Central Nepal Himalaya (Quade et al., 1995). Though the exact time frame of vegetation change from C3 to C4 is not clear, comparing the stratigraphic thickness by Quade et al. (1995) with Ojha et al. (2009) suggest, this change in the vegetation probably occurred around 6 Ma to 7 Ma. This change in the vegetation suggests a greater seasonality reflected by stronger monsoon (Quade et al., 1989; 1995).

3. Methods

This study was carried out in eastern Nepal along the Muksar Khola section. Field data were acquired based on the topographic map of 1:25000 scale. Lithofacies were identified based on grain size and texture of beds and associated sedimentary structure. Architectural elements were classified based on the nature of internal and external geometry and the bounding surfaces. Mainly foresets of cross-stratifications were measured for the paleocurrent analysis. The paleo-flow direction was estimated using standard methods (Tucker, 2003). Based on these lithofacies, architectural elements and paleocurrent directions, facies associations were classified following the code of Miall (1977, 1985, 2000 and 2006). Route map and detail sedimentological logs were made to evaluate the precise boundary of these facies. The paleomagnetic data by Ojha et al. (2009) was used to determine the specific age for each facies association. Based on this facies association, river systems were interpreted.

4. Results

4.1. Facies Associations

Based on sandstone-mudstone ratio, grain size, assemblages of sedimentary structures and the nature of the beds, 12 sedimentary lithofacies and five facies associations have been recognized. These are summarized in Tables 1 and 2 and representative photographs of each lithofacies are shown in Figs. 2 and 3. Representative sedimentological logs of each facies associations are shown in Fig. 4 and their locations in Fig. 5.

4.1.1. Facies Association 1 (FA1)

Description

This facies association is characterized by a predominance of thick-bedded mudstone interbedded with very fine- to medium-grained sandstone. Normally, fining-upward sequences of fine-grained sandstone to mudstone are found in this facies association. Mudstones are olive-grey to dark-grey and reddish-brown with thickness ranging from 0.4 to 2.0 m. Dominating mudstone show facies Fm and are mostly bioturbated, mottled or variegated (Fig. 3-F). Facies Fl are also abundant in mudstone with occasional occurrence of facies C.

Sandstone beds normally range between 0.15–1.5 m in thickness, though there are few beds with thickness more than 4 m (Fig. 4, Sc-1&4). Thick to very thick beds (> 70 cm) of fine- to medium-grained sandstone show facies Sp with an erosive basal surface, whereas in the thick beds (30–60 cm) facies Sh or Sr dominates. Lateral accretionary structures are mainly observed in these beds. Medium to thick beds of fine-grained sandstone are massive and occasionally show facies Sh or Sr. Very fine- to fine-grained sandstone shows both fining- and coarsening-upward succession with comparatively flat basal surface and usually occurs at an interval within very thick beds of mudstone with facies Fm or P (Fig. 4, Sc-4). Thin to medium bedded very fine-grained sandstones are bioturbated if not shows facies Sr to Fl (Fig. 6-A). Calcareous nodules are often observed on 15–25 cm thick upper portion of the fine-grained sandstone and mudstone beds. Sandpipes oriented perpendicular to bed with diameter ca. 3 cm (Fig. 3-C), roots and rootlets are observed in mudstone and very fine-grained sandstone. Though the data for paleocurrent analysis in this facies association is limited but show a dispersive flow pattern (Fig. 5). Facies association FA1 is preserved in the Lower Siwalik sub-group.

Interpretation

Thick to very thick beds of fine- to medium-grained sandstone showing planar cross-stratification and ripple lamination with erosive basal surface represents channel deposits (Miall, 2006). Medium to thick massive looking, fine-grained sandstone with occasional ripple or parallel lamination represents sheet flow (Miall, 2006). Medium-bedded very fine- to fine-grained sandstone with either fining- or coarsening-upward succession with bioturbation, if not ripple lamination, occurring at an interval within flood plain deposits suggests crevasse deposits (Nakayama and Ulak, 1999; Miall, 2006). Thin to medium beds of very fine-grained sandstones showing parallel to ripple laminations and fine-to medium-grained sandstone with paleo flow direction normal to channel are levee deposits (Singh, 1972). Variegated and bioturbated mudstone with sandpipes and rootlets, presence of calcareous nodules indicate long term exposure of the flood plain (Nakayama and Ulak, 1999). Laminated and peaty mudstone represents the waning stage of river flood and swamp deposits indicating the overbank deposits (Miall, 2000; 2006). Sandstone with lateral accretionary structures along with dispersive paleoflow pattern and frequent crevasse splay suggests a river with high sinuosity. The dominance of the flood plain deposits along with the meandering nature of the river suggest FA1 is deposited by the flood plain dominated fine-grained meandering river system.

4.1.2. Facies Association 2 (FA2)

Description

This facies association is characterized by thick to very thickly bedded (0.4- >4.0 m), poorly-sorted, clast-supported intraformational conglomerate (Fig. 6-B). These intraformational conglomerate are massive and composed of siltstone clast with medium- to very coarse-grained sandstone matrix with non-erosional basal surface. These siltstone clasts are greenish-grey in colour and angular to sub-angular in shape (some clasts shows soft deformation) with an average diameter of 1–2 cm (some clasts are elongated up 10 cm). The average ratio of clast and matrix is about 70% and 30% respectively. In the lower part of this facies association, massive coarse-grained sandstone beds with flat basal surface ranging 0.1 to 0.8 m in thickness are observed in between these intraformational conglomerate beds. In the upper part of this facies association, sandstone facies disappears and occasional 0.4 to 0.5 m thick mudstones with facies Fl are observed (Fig. 4, Sc-2). Thin to medium beds of fine-grained sandstone (overall thickness of around 10 m) with facies Sr and Fl is observed at the top of this succession (Fig. 4, Sc-2 & 6-C). The FA2 facies association is preserved in the Lower Siwalik sub-group within facies association FA1 with a thickness of about 80 to 90m.

Interpretation

The formation of intraformational conglomerate suggests bank failure due to the rapid lowering of water level during the waning stage of flood (Gohain and Prakash, 1990; Singh et al., 1993; Plink-Bjorklund, 2015). Angular to sub-angular shape of clast indicates the immature sediments (Reineck and Singh 1980). The structureless beds with planer basal surface suggest deposition by debris flow (Miall, 2006). Therefore composition, shape and the proportion of the clast of the conglomerate states that these clasts were not transported for long distance, i.e. source of these clasts was proximal to the deposition place probably the overbank deposits. The massive sandstone bed with a flat basal surface occurring in between conglomerate beds are the sheet flow deposits (Martin and Turner, 1998; Miall, 2006). The laminated mudstone present in between the conglomerate is deposited in a lower flow regime due to a sudden decrease in the velocity and depth of water indicating the termination of the flood. Thin to medium beds of fine-grained sandstone with facies Sr and Fl observed at the top intraformational conglomerate represents a levee deposit (Miall, 2006). The absence of channel deposits and dominance of overbank architectural elements suggests this facies association FA2 is deposited in the flood dominated overbank environment.

4.1.3. Facies Association 3 (FA3)

Description

This facies association is dominated by sandstone facies with subordinate mudstone facies (Table. 2). It is characterized by very thickly bedded, “salt and pepper” textured medium- to coarse-grained sandstone associated with very fine-to fine-grained sandstones and dark to greenish-grey mudstone. Sandstone shows both amalgamated and individual beds. Amalgamated sandstone beds occur intermittently with varying thickness ranging from 4 to 20 m (Fig. 6-D). These amalgamated sandstone beds consist of a 1.0 to 3.0 m thick individual sedimentary cycle dominated by facies Sp and undulating amalgamation surface. The individual cycle shows weakly developed fining-upward succession starting from coarse-grained sandstone at the base to medium- to coarse-grained sandstone at the top (Fig. 4, Sc-5) (some time amalgamation surface is unclear due to identical grain size). Towards the younger section individual cycle of fining upward succession ranges from coarse- to fine-grained sandstone, occasionally thin mudstone to siltstone barrier are preserved along the undulating amalgamation surface (Fig. 4, Sc8) separating amalgamated beds. Sub-angular to angular elongated mud clasts (up to 20–30 cm in length, Fig. 6-E) are sporadically observed at the base of these amalgamated beds. Non-amalgamated sandstone beds are fine- to coarse-grained with thickness ranging from 0.2 to > 3.0 m. Facies Sp is mainly observed in thick to very thick sandstone beds (Fig. 2-E) with occasional channel lags at the base (Fig. 6-F). These lags are composed of mud clast and coal fragments. The nature of the basal contact surface of sandstone beds is slightly erosive. Lateral accretionary structures are often observed in these beds (Fig. 6-G). Thickly bedded (50–90 cm) fine- to medium-grained sheet-line sandstone beds show both fining and coarsening upward sequence with abundant ripple lamination. These beds show planar basal surface and are sometimes associated with mud clast. Medium to thickly bedded (25–50 cm) very fine- to fine-grained sandstone are mostly bioturbated if not ripple or parallel lamination are observed and occurs intercalated with mudstone.

Mudstones are dominantly dark grey coloured and their thickness ranges from 0.2 to 2.0 m. These mudstones are mostly bioturbated or mottled, though parallel laminations are also observed in few beds. Calcareous nodules are observed on the upper portion of very fine- to fine-grained sandstone and mudstone beds. Sandpipes (ca. 12 cm long perpendicular to bed with diameter ca. 3 cm) are frequently observed in very fine-grained sandstone and mudstone. Paleocurrent shows the flow direction frequently changed towards south-east and south-west with high dispersion (Fig. 5). The FA3 facies association is preserved in the lower member of the Middle Siwalik sub-group.

Interpretation

The occurrence of amalgamated sandstone beds suggests deposition by channel with high deposition rate, high flow energy with a high erosive capacity (Zhang et al., 2017). Unclear amalgamation surface shows erosive features and occurs frequently within channel deposits whereas the increase in the distance from the main channel makes amalgamation surface more distinct with the occurrence of mudstone barriers (Walker 1966). Therefore, a weakly developed fining upward sequence with occasional unclear amalgamation surface in the lower section followed by the distinct amalgamation surface in upper section suggests a shift of the channel. Thick to very thick sandstone beds showing fining upward sequence with channel lags and planner cross-stratification, represent deposits from the main channel (Miall, 2006). Thickly bedded, bioturbated sheet-like fine- to medium-grained sandstone with fining- or coarsening-upward succession and occasionally preserved ripple lamination (Fig. 4, Sc-6&7) represents crevasse splay deposits. Very fine-grained sandstones intercalated with mudstone and showing parallel to ripple laminations suggests levee deposits (Miall, 2006). Thick bioturbated mudstone represents overbank deposits. Laminated mudstone represents the waning stage of river flood and swamp deposits. High dispersion of paleo-flow direction, fining upward sequence of sandstone with mudstone lag and laterally accretion, and thick flood plain deposits with intermittent crevasse deposits resemble the meandering river deposits (Miall, 2006). On these bases, FA3 is considered to be deposited by the sandy meandering river system.

4.1.4. Facies Association 4 (FA4)

Description

This facies association is characterized by very thickly bedded coarse-to very coarse-grained sandstone with subordinate pebbly sandstone associated with thickly bedded fine- to medium-grained sandstone and dark grey mudstone. Sandstones are less indurated and lack a “salt and pepper” texture compared to the sandstone of FA3. The thickness of sandstone beds ranges from 1.0 to 5.0 m with well-maintained fining-upward succession (Fig. 6-H). Facies St (Fig. 2-D) are abundant compared to facies Sp and pebbly sandstone layers are observed as a lens at the base with mostly sub-rounded quartzite clast. Very thickly bedded (> 1 m), fine- to coarse-grained sandstones are massive with faint traces of cross-stratification and show down-stream accretion. Thickly bedded medium- to coarse-grained sandstone shows coarsening upward succession and are massive or bioturbated, whereas fine-grained sandstone are medium to thickly bedded (30–70 cm) and mostly bioturbated, occasionally ripple or parallel lamination are observed. These sandstones are mostly associated or interlayered within mudstone beds. Both the proportion and thickness of mudstone is increased in this facies association. The overall thickness of mudstone ranges > 20 m with individual beds ranging from 0.3 to 3.0 m. Mudstones are mostly gleyed and bioturbated but occasionally parallel laminated mudstone (Fl) is also observed. Variegated mudstone and carbonaceous layers are also observed sporadically at the upper section of this facies association. Paleocurrent shows the flow direction changed towards south-east from the south-west with high dispersion (Fig. 5). This facies association FA4 is observed in the upper section of the upper member of the Middle Siwalik sub-group.

Interpretation

Coarse- to very coarse-grained sandstone with pebbly lags represent the channel deposits. Increase downstream accretion and absence of lateral accretion suggests bar deposits related to the braided river system (Almeida et al., 2016). Massive or bioturbated sandstone within mudstone and showing coarsening upward succession are crevasse deposits or sheet flow deposits (Martin and Turner, 1998) representing overbank deposits. Bioturbated fine-grained sandstone with occasional ripple lamination interlayered with laminated or bioturbated mudstone suggests levee deposits. Thick to very thick mudstone suggest the overbank deposits and presence of either variegated or carbonaceous layers suggest the long time exposure. Crevasse deposits, high dispersion and repeated change in the paleo flow direction (Fig. 5) show the sinuous nature of the channel. The well-developed fining upward succession of sandstone beds, increase in the proportion of flood plain with crevasse or sheet flow deposits suggests the sinuous nature of the channel. Though Anastomosing river system is hard to demonstrate in the stratigraphic log (Makaske, 2001), but Miall (2006) suggested anastomosing river show channel deposits bounded by large flood plain deposits. The evidence of both the braided and meandering nature of the river and large proportion of overbank deposit bounding the sandstone beds suggests anastomosing river system (Bridge and Demicco, 2008; Makaske, 2001). Therefore, FA4 is considered to be deposited by the anastomosing river system.

4.1.5. Facies Association 5 (FA5)

Description

This facies association is characterized by very thick beds of poorly-sorted pebble to cobble conglomerate with very coarse-grained sand to granules matrix. These conglomerate beds are associated with coarse- to very coarse-grained sandstone and dull yellowish-grey mudstone (Fig. 6-I) and mostly show sharp non-erosional basal surface. Conglomerate consists of dominant quartzite clast and purple meta-sandstone with few amounts of sandstone, mudstone and gneiss and are mostly sub-rounded (Fig. 6-J). These conglomerates mostly are structureless (Fig. 2-A) or show inverse grading (Fig. 2-B). Stratified conglomerates (Fig. 2-C) are mostly observed at the lower section of this facies association. These inversely graded and stratified conglomerate beds are 0.8 to 2.0 m thick, amalgamated to form > 5.0m thick succession. Sandstone thickness ranges from 1.0 to 3.0 m (occasionally > 3.0m). These sandstone beds are almost massive. Few beds showing slight fining-upward sequence bears faint parallel cross-stratification. Isolated pebbles are abundant in sandstone, sometimes up to pebbly sandstone. Mudstones are thickly bedded (▯4m) and bioturbated without any pedogenic features. This facies association FA5 is found in the Upper Siwalik sub-group.

Interpretation

Poorly-sorted conglomerate with inverse grading is considered to be the deposits of debris flow (Blair and McPherson, 1994; Miall 2006, Nakayama and Ulak 1999). Coarse- to very coarse-grained sandstones and pebbly sandstones with a lack of well-developed fining-upward sequence represents a braided river system (Nakayama and Ulak 1999). Thick bioturbated mudstone represents flood plain deposits (Miall, 2006). Domination of poorly-sorted conglomerate with inverse grading in this facies association suggests this FA5 is deposited by debris flow dominated gravelly braided river system. The presence of thick sandstone and mudstone beds within the conglomerate beds will be further discussed in the discussion section.

4.2. Depositional Process

The facies analysis is a very useful tool to understand the particular depositional environment. Based on the facies association three fluvial styles namely meandering, anastomosing and braided river system have been recognized, responsible for the deposition of the Siwalik Group of rocks in the Muksar Khola section (Fig. 7). Deposition began with flood plain dominated fine-grained meandering river system (FA1). This river system encountered a large scale flood depositing a very thick succession of intraformational conglomerate at around 10.6 Ma (?) as flood dominated overbank environment (FA2). Since Ojha et al., (2009) magnetostratigraphy does not cover the section of the Lower Siwalik sub-group before 10.0 Ma. This age of ~ 10.6 Ma (?) was estimated using their oldest sedimentation rate of 0.33 mm/yr. and thickness of 210 m from the sedimentological log of the present study. Although this age is quite speculative due to the lack of proper age data and uncertainties on the sedimentation rate. Therefore based on the evidence from other studies (that will be discussed later) we consider this age as 10.5 Ma. The dominance of the sandy beds in the meandering river system (FA3) was increased after 10.0 Ma. Sporadic deposition of the amalgamated sandstone succession for a limited period is observed in this facies association. These successions are mainly noticed around 10.0 Ma, 9.4 Ma, 7.7 Ma and 6.2 Ma (Fig. 7). After 5.9 Ma sediments were deposited by an anastomosing river system (FA4). The change from the anastomosing river system to the debris flow dominated gravelly braided river system (FA5) occurred around 3.5 Ma.

5. Discussion

5.1 Intraformational conglomerate and its relation to the monsoon intensification.

The dramatic occurrence of a large succession of the intraformational conglomerate is unique in the present study area. Such a large succession of the intraformational conglomerate has not been reported in the other Siwalik succession. Even in the previous studies of the Muksar Khola section, it has been excluded by various researchers (like Quade et al., 1995; Robinson et al., 2001; Chirouze et al., 2012). As mention above formation of an intraformational conglomerate is related to the bank failure during the waning stage of a flood. Singh et al. (1993) suggested during the falling stage of the flood, banks are undercut by the current initiating the development of shear cracks. Further parts of the bank slump and melts away, in the case of the cohesive muddy bank, they break into large blocks. These large blocks change to angular and then to rounded clasts with a decrease in size as they roll along the channel floor for some distance. Such collapse of fluvial banks initiates sediment-laden currents movement across and along the fluvial channel (Martin and Turner, 1998). In the present study, this conglomerate consists of angular to sub-angular shape of mud clast which indicates immature sediments that were not transported for a longer distance. If this conglomerate was deposited by the main channel there would be a possibility of longer transportation and soon disintegration of these clasts. Therefore, we consider this was not deposited by the main channel collapsing adjacent flood plain rather it was deposited in the overbank setting more distal to the main channel due to the collapse of the distal alluvial terraces.

Alluvial terraces are developed as a result of cyclic deposition of alluvial sediments and incision of alluvial plain (Oldknow and Hooke, 2017). The causes of incision is a complex issue, a mixture of various processes like climate, tectonics, eustatic fluctuations (Miall, 2006; Tandon et al., 2006; Oldknow and Hooke, 2017). Zaitlin et al. (1994) suggested rivers proximal to coastal areas undergo incision during the fall of sea level and aggradation as sea-level rise. Similarly, incision due to climatic effects also occur, which are mediated through variations and increase in water discharge, when the discharge exceeds than that needed for transport of the available sediment, river promotes incision (Bogaart et al., 2003). The deposition of such very thick succession of intraformational conglomerate after 10.5 Ma has unique coincidence with rapid fall of the sea level around 10.5 Ma (Haq et al., 1988), rapid exhumation of the eastern Nepal Himalaya around 11.0 Ma and intensification of the Monsoon in the central Nepal Himalaya at 10.5 Ma (Nakayama and Ulak, 1999). Therefore, the sudden fall of the sea level should have favoured the river incision on the foreland basin creating alluvial terraces as mention above (Fig. 8A). During high flood event when water level drastically rises it submerse the overbank and shear cracks are developed due to undercutting of distal alluvial terrace during its waning stage. This subjects to the collapse of the distal alluvial terrace (Fig. 8B). The increase in the distance from the main channel causes a slowdown of the flow velocity due to which mud clast are not transported for a long distance preventing it from further rework. The occurrence of massive coarse-grained sheet-like sandstone beds within the intraformational conglomerate beds (Fig. 4, Sc1) also suggests the increase in the flow velocity since the Lower Siwalik sub-group is dominated by fine- to medium-grained sandstone. At normal flow conditions, this coarse-grained sandstone should have been trapped somewhere upstream because experiments show travel distance decreases with an increase in the particle size (Church and Hassan, 1992; Parsons and Stromberg, 1998). Generally, high magnitude floods are triggered only during abnormal or strengthened monsoon season (Plink-Bjorklund, 2015). In modern rivers, such large-scale erosion of the banks has also been observed at the end of the monsoon season in the modern Koshi River with 300 m x 200 m areas of scattered slumped blocks (Singh et al., 1993; Plink-Bjorklund, 2015). Therefore the occurrence of this intraformational conglomerate in the present study area at around 10.5 Ma should be related to waning stage of high-magnitude floods suggesting the intensification of monsoon in the eastern Nepal Himalaya. The timing of this flood event in the present study is also coeval to the time of onset of monsoon intensification in central Nepal and can be correlated to the peak sediment accumulation observed in Indus and Bengal fans between 9.0 Ma to 6.0 Ma which was derived from the Himalaya probably due to the uplift and erosion of the Himalaya (Rea, 1992).

5.2 Controlling factors for change in river system.

Generally, channel styles are determined by the channel slope and bankfull discharge (Leopold and Wolman, 1957). The slope of the channel is controlled by the tectonics or change in the sea level (Smith and Smith, 1980; Smith, 1986; Burbank, 1992); whereas, discharge is related to tectonics and climate (Goodbred and Kuehl, 2000a; Clift and Giosan, 2014; Clift, 2017). In eastern Nepal, fast exhumation was observed after 11.0 Ma. Similarly, the eustatic curve by Haq et al. (1988) shows the rise in the sea level before 10.5 Ma (Fig. 7). Therefore, the low slope angle due to sea-level rise and absence of the hinterland exhumation must be the reason for the meandering river system before 10.5 Ma.

During the deposition of the lower member of the Middle Siwalik sub-group, fast exhumation was observed in the eastern Nepal Himalaya similar to its western and central counterpart. This exhumation of the hinterland could have increased the channel slope angle and sediment supply resulting in a domination of the braided river system similar to western and central Nepal. The evolution of the braided river system in western and central Nepal has a similar trend with hinterland exhumation i.e. around 9.5 Ma in the Karnali River section and 6.5 Ma in the Surai Khola section (Table: 3). But, the tectonic history of eastern Nepal is quite different from central and western Nepal. In western and the central Nepal Himalaya, observed fast exhumation of the hinterland was due to the formation of the duplex structure which began at 12 – 10 Ma and 9.8 Ma respectively (Huyghe et al., 2001; Robinson et al., 2003; Herman et al., 2010). In the eastern Nepal Himalaya, such a duplex structure was developed only after 4.0 Ma (Haviv et al., 2009; Rai et al., in press). The tectonic activity of hinterland during the deposition time of the lower member of the Middle Siwalik sub-group was the activation of the Sun Koshi Thrust (Schelling and Arita, 1991; Rai et al., in press). Therefore, the possible explanation may be asymmetric subsidence (Burbank, 1992) of the foreland basin in eastern Nepal Himalaya. According to Burbank (1992), if thrusting is the primary cause of mountain uplift, the resultant crustal thickening causes more subsidence and deposition in the proximal parts of the foreland resulting in the restriction of the fan to the proximal area. Contrary to this if enhanced erosion is the cause, then flexural uplift occurs across the foreland basin due to isostatic adjustment which displaces sediments to a more distal part of the basin. The imbrication of thrusts in duplex structure results in regional uplift compared to the single thrust that breaches the surface, enhancing a comparatively high rate of erosion. Robinson et al. (2001) also mention the absence of duplex structure resulted in less erosional unroofing in eastern Nepal Himalaya compared to western and central Nepal Himalaya. Therefore, the activation of the out-of-sequence thrust and absence of duplex structure in eastern Nepal Himalaya could have resulted in this asymmetric subsidence and lead more sediments to be trapped in the proximal part of the basin, resulting in the starvation of sediments at the distal part where the present lower member of the Middle Siwalik sub-group was deposited.

Despite this, the occasional episodic occurrence of a very thick succession of amalgamated sandstone beds in limited thickness within the sandy meandering river system (FA3) at ca. 9.4 Ma, 7.7 Ma and 6.2 Ma suggests some change in the fluvial condition. Sandstone amalgamation usually occurs in the central region of the channel suggesting a high rate of flow energy, deposition and erosive capacity (Zhang et al., 2017). The sub-angular to angular elongated mud clasts (up to 20–30 cm in length) that are observed on the base of the amalgamated sandstone (Fig. 6-E) suggest the erosive nature of flow and give evidence of flooding as discussed above. Other than this, the timing of the occurrence of these thick succession of amalgamated sandstone succession in the present study is coeval to the timing of sea-level fall and rise (Fig. 7). The eustatic curve of Haq et al. (1988) shows a change in the sea level around 10.5 Ma, 8.7 Ma, 6.6 Ma, 5.5 Ma and 3.8 Ma. Therefore, the occasional occurrence of this very thick succession of the amalgamated sandstone should be the result of the interplay of high discharge and sea-level rise. The absence of evidence related to river incision as discussed above during the sea-level fall may be either due to the rate of sea-level fall or the shift of depositional area. If we see the eustatic curve (Fig. 7), the rate of sea-level fall around 8.4 Ma and 6.4 Ma is not sudden and on a large scale as observed around 10.5 Ma. Also, the dominating grain size of Facies 3 is medium- to coarse-grained sandstone suggesting depositional area somewhere upstream to the depositional area of Facies 1, suggesting a shift of the depositional area more proximal to the hinterland.

Anastomosing of rivers are controlled by both climatic and geological conditions where anabranching of new channels are mainly due to the avulsion process (Nanson and Knighton, 1996; Makaske, 2001). The frequency of avulsion increases with an increase in sedimentation rate (Bridge and Leeder, 1979; Bryant et al., 1995) and base-level rise (Tornqvist, 1994; Makaske, 2001). The rise of the base level may be due to the rise in the sea level (Smith and Smith, 1980) and the subsidence of the foreland basin (Smith 1986).

The subsidence of the foreland basin and rise in the sea level during the deposition of the upper member of the Middle Siwalik sub-group (Fig. 7) fulfils the condition of base-level rise. Furthermore, an increase in seasonality observed by the shift of C3 plants to C4 plants can be considered another contributing factor. Increasing seasonality suggests strengthened monsoon (Quade et al., 1989; 1995) and an arid to semi-arid climatic condition where bankfull discharge exceeds rarely more than once a year (Gibling et al., 1998). Such bankfull discharge occurs during the high magnitude floods triggered by a strengthened monsoon. During a normal time of such conditions, deposition of the sediments takes place in-channel, consequently, the channel loses the capacity to accommodate sediments in the next flood and become liable to avulsion (Makaske, 2001). Various researchers also suggested the avulsion process takes place during a large flood (Like Brizga and Finlayson, 1990; Mack and Leeder, 1998).

The eustatic curve after 6.0 Ma mainly shows three falls and a rise of the sea level (Fi. 7). Considering our previous discussion this effect of sea-level change should have brought some change in the lithology, but such distinct lithological changes are absent. The probable consideration might be the shift of the depositional area more proximal to the hinterland. The sea-level rise resulted in an overall rise of the base level of the foreland basin, but the deposition area was far from the sea. Therefore, it was more controlled by the hinterland tectonics and climate. Due to this the small changes in the sea level was overprint and was not traced on the lithology of the upper member of the Middle Siwalik sub-group. This shift of the depositional basin towards the hinterland concerning the depositional age suggests the foreland basin was continuously drifted north towards the hinterland.

5.3 Significance of thick mudstone beds in Upper Siwalik sub-group

The gravelly braided river system marked by the abrupt increase in the grain size to gravel size in the Upper Siwalik sub-group indicates a shift of the depositional basins more proximal to the hinterland. The composition of the conglomerate suggests the supply of the gravels mainly from the Ramechap and Tumlingtar Group of the Lesser Himalaya Series. Very thick beds of sandstone (ca. 3 m) and mudstone (~4.0 m) observed associated with a conglomerate in the present study area is quite unusual, since studies along the Siwalik section in central and western Nepal, mention absence or very limited thickness of sandstone and mudstone beds associated with such conglomerate (Nakayama and Ulak, 1999; Ulak and Nakayama, 2001; Sigdel and Sakai, 2016). Generally, debris flows are more common in inner alluvial fan (Blair and McPherson, 1994; Miall, 2006) where boulder conglomerate are reported in both paleo and modern fluvial system (Singh et al., 1993; Nakayama and Ulak, 1999; Ulak and Nakayama, 2001; Miall, 2006; Sigdel and Sakai, 2016). The absence of boulder size clast (where the size of clast hardly reaches cobble size) in the present study reveals either presence of a small alluvial fans or long-distance travel of debris flow. If we see the modern river system in the foothill of the Himalaya many small and medium rivers exist in between big river system. Willis (1993b) suggested the idea of small rivers in the fan and interfan areas that drains local area. Therefore one possibility is the existence of a similar environment where small river fans exist and share a common or proximal basin during the deposition of FA5.

On the other hand, such progradation of gravels was reported in the Nalad Khad and Jawalamukhi section of the Himachal Pradesh (Brozovic and Burbank, 2000). Brozovic and Burbank (2000) suggested three hypothesises for such progradation of gravels. (1) Increase in the discharge and sediment flux of rivers due to climate change, (2) Initiation of the Main Boundary thrust led to significant erosional relief developing above it and (3) Decrease in the subsidence rates of the foreland basin due to gradual hinterland erosion without major tectonism. If we consider increase in the seasonality resulting in a strong monsoon as a factor for high discharge and sediment flux in the present study, then similar lithology should have been observed in the central Nepal Siwalik section, since the timing of monsoon intensification and vegetation change at the present study area and central Nepal are coeval. Therefore, the presence of gravel progradation only in the present study area denies the possibility of climate change as the controlling factor. In eastern Nepal, the activation of the MBT at the frontal margin of the Himalaya already started around 5.5 Ma (Ojha et al., 2009; Rai et al., in press), but activation of the duplex structure at the rear of the Himalaya after 4.0 Ma should have slowed down the movement of the MBT. Hence decrease in the movement of the MBT should have consequently reduced the subsidence rate. Therefore, either existence of the small alluvial fans or a decrease in the subsidence rate of the foreland basin may be the reason for the gravel progradation in the present study area.

6. Conclusions

We started this study with a view that does the asynchronous exhumation of the Himalaya from west to east and change in sea level brought any significant effects on the fluvial system in the foreland basin. From the above discussion, we came up with the following conclusions.

Five facies association are recognized in the Neogene fluvial sediments of the Siwaliks in the Muksar Khola section of eastern Nepal. They are interpreted as flood plain dominated fine-grained meandering river (FA1), flood dominated overbank environment (FA2), sandy meandering river (FA3), anastomosing river (FA4) and debris flow dominated braided river (FA5). This change in the river system occurred at around 10.5 Ma, 10.0 Ma, 5.9 Ma and 3.5 Ma respectively.

The large succession of an intraformational conglomerate in the present study gives the evidence of a high magnitude river flooding suggesting monsoon intensification in the eastern Nepal Himalaya at 10.5 Ma as a result of uplift of the eastern Nepal Himalaya.

The present study shows the hinterland tectonics, climate and the fluctuation of the sea level has significant effects on the Neogene foreland basin in the eastern Nepal Himalaya. The sea-level rise and absence of the hinterland exhumation during the deposition of the Lower Siwalik sub-group and absence of duplex structure during the deposition of the lower member of the Middle Siwalik sub-group in the eastern Nepal Himalaya resulted in the domination of the meandering river system. The rise in the base level due to rise in the sea level rise along with subsidence of foreland basin and increase in the seasonality is considered as the controlling factors for the domination of the anastomosing river during the deposition of the upper member of the Middle Siwalik sub-group.

The present study reveals continuous drifting of the foreland basin towards the hinterland. The effects of sea-level change during the deposition of the Lower Siwalik sub-group suggests the deposition area was more proximal to the sea and distal to the hinterland. Similarly, this effect of the sea-level change was minimum during the deposition of the lower member of the Middle Siwalik sub-group and almost absent during the deposition of the upper member of the Middle Siwalik sub-group.

7. Declarations

Availability of data and material

All data generated or analysed during this study are included in this manuscript.

Competing interests

The authors declare that they have no competing interests.

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The authors declare that there is any funding that could influence the results of this study

Author’s Contributions

The first author conceptualized the research. The field study was carried out by both the author. The analysis and interpretation of data, as well as manuscript, was drafted by the first author under the supervision of the second author. Both the author read and approved the final manuscript.

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8. References

1. Almeida RP, Freitas BT, Turra BB, Figueiredo FT, Marconato A, Janikian L (2016) Reconstructing fluvial bar surfaces from compound cross-strata and the interpretation of bar accretion direction in large river deposits. Sedimentology 63: 609-628.

2. Appel E, Rosler W (1994) Magnetic polarity stratigraphy of the Neogene Surai Khola section (Siwaliks, SW Nepal). Himal Geol 15: 63-68.
3. Blair TC, MCPherson JG (1994) Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. J Sed Res 64: 450-489.
4. Bogaart PW, Van Balen RT, Kasse C, Vandenberghe J (2003) Process-based modelling of fluvial system response to rapid climate change I. Model formulation and generic applications: Quat Sci Rev 22: 2077-2095.
5. Bridge JS, Leeder MR (1979) A simulation model of alluvial stratigraphy. Sedimentology 26, 617-644.
6. Bridge JS, Demicco RV (2008) Earth surface processes, landforms and sediment deposits. Cambridge University Press, UK.
7. Brizga SO, Finlayson BL (1990) Channel avulsion and river metamorphosis: the case of the Thomson river, Victoria, Australia. Earth Surf Proc Land 15: 391-404.
8. Brozovic N, Burbank DW (2000) Dynamic fluvial systems and gravel progradation in the Himalayan foreland. Geol Soc Am Bull 112: 394-412.
9. Bryant M, Falk P, Paola C (1995) Experimental study of avulsion frequency and rate of deposition. Geology 23 (4): 365-368.
10. Burbank DW (1992) Causes of recent Himalayan Uplift deduced from deposited patterns in the Ganges basin. Nature 357: 680-683.
11. Chirouze F, Bernet M, Huyghe P, Erens V, Dupont-Nivet G, Senebier F (2012) Detrital thermochronology and sediment petrology of the middle Siwaliks along the Muksar Khola section in eastern Nepal. J Asian Earth Sci 44: 94-106.
12. Church M, Hassan MA (1992) Size and distance of travel of unconstrained clasts on a streambed. Water Resour Res 28: 299-303.
13. Clift PD (2017) Cenozoic sedimentary records of climate-tectonic coupling in the Western Himalaya. Prog Earth and Planet Sci 4: 1-22.
14. Clift PD, Giosan L (2014) Sediment fluxes and buffering in the post-glacial Indus Basin. Basin Res 26: 369-386.
15. Coleman JM (1969) Brahmaputra River: channel processes and sedimentation. Sediment Geol 3: 129-239.
16. Corvinus G (1993) The Siwalik group of sediments at Surai Khola in western Nepal and its palaeontological record. J Nepal Geol Soc 9: 21-35.
17. Dhital MR, Gajurel AP, Pathak D, Paudel LP, 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 4:, 1-70.
18. Gansser A (1964) Geology of the Himalayas. Interscience Publishers, Wiley, London.

19. Gautam P, Appel E (1994) Magnetic-polarity stratigraphy of Siwalik Group sediments of Tinau Khola section in west central Nepal, revisited. Geophys J Int 117: 223-34.
20. Gautam P, Fujiwara Y (2000) Magnetic polarity stratigraphy of Siwalik Group of Karnali River section in Western Central Nepal. Geophys J Int 142: 812-24.
21. Gibling MR, Nanson GR, Maroulis JC (1998) Anastomosing river sedimentation in the Channel Country of central Australia. Sedimentology 45: 595-619.
22. Gohain K, Parkash B (1990) Morphology of the Kosi megafan. In: Rachocki AH, Church M (eds) Alluvial Fans: A Field Approach, John Wiley and Son Ltd, Chichester, UK, pp 151-178.
23. Goodbred SL Jr, Kuehl SA (2000a) Enormous Ganges-Brahmaputra sediment discharge during strengthened early Holocenemonsoon: Geology 28: 1083-1086.
24. Goodbred SL Jr, Kuehl SA (2000b) The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: Late Quaternary stratigraphy and evolution of the Ganges-Brahmaputra delta: Sediment Geol 133: 227-248.
25. Haq BU, Hardenbol J, Vial PR (1988) Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea-Level Changes: An Integrated Approach Soc Econ Paleontol Mineral Spec Publ 42: 71-108.
26. Haviv I, Avouac J, Farley KA, Harrison MT, Heizler MT, Prabhat NC, Maheo G (2009) Uplift and exhumation along the Arun River (Eastern Nepal): implications for the mechanism of uplift of the High Himalaya and the coupling between erosion and tectonics. In: Abstract of AGU Fall Meeting 2009, Abstract # T31E-07.
27. Hisatomi K, Tanaka S (1994) Climatic and environmental changes at 9 and 7.5 Ma in the Churia (Siwalik) Group, west-central Nepal. Himal Geol 15: 161-180.
28. Herman F, Copeland P, Avouac JP, Bollinger L, Maheo G, Le Fort P, Rai S, Foster D, Pecher A, Stuwe K, Henry P (2010) Exhumation, crustal deformation, and thermal structure of the Nepal Himalaya derived from the inversion of thermochronological and thermobarometric data and modeling of the topography. J Geophys Res 115 (B6): B06407.
29. Huyghe P, Galy A, Mugnier JL, France-Lanord C (2001) Propagation of the thrust system and erosion in the Lesser Himalaya: Geochemical and sedimentological evidences. Geology 29: 1007-1010.
30. Huyghe P, Mugnier JL, Gajurel AP, Delcaillau B (2005) Tectonic and climatic control of the changes in the sedimentary record of the Karnali River section (Siwaliks of western Nepal). Isl Arc 14: 311-327.
31. Khan IA, Bridge JS, Kappelman J, Wilson R (1997) Evolution of Miocene fluvial environments, eastern Potwar plateau, Northern Pakistan. Sedimentology 44: 221-251.
32. Kumar R, Tandon SK (1985) Sedimentology of Plio-Pleistocene late orogenic deposits associated with intraplate subduction-The Upper Siwalik sub-group of a part of Panjab sub-Himalaya, India. Sediment Geol 42: 105-159.
33. Kumar R, Ghosh SK, Sangode SJ (1999) Evolution of a Neogene fluvial system in a Himalayan foreland basin, India. Geol Soc Am Spec Pap 328: 239-256.

34. Kumar R, Ghosh SK, Sangode SJ (2003a) Mio-Pliocene sedimentation history in the northwestern part of the Himalayan Foreland Basin, India. Curr Sci 84: 1006-1013.
35. Kumar R, Ghosh SK, Mazari RK, Sangode SJ (2003b) Tectonic impact on the fluvial deposits of Plio-Pleistocene Himalayan foreland basin, India. Sediment Geol 158: 209-234.
36. Leopold LB, Wolman MG (1957) River channel patterns: braided, meandering and straight. US Geol Surv Prof Pap 282B: 39-85.
37. Lourens LJ, Hilgen FJ, Laskar J, Shackleton NJ, Wilson D (2004) The Neogene Period. In: Gradstein FM, Ogg JG, Smith AG (eds) A Geologic Time Scale 2004, Cambridge Univ Press, Cambridge, pp 409-440.
38. Mack GH, Leeder MR (1998) Channel shifting of the Rio Grande, southern Rio Grande rift: implications for alluvial stratigraphic models. Sediment Geol 117: 207-219.
39. Makaske B (2001) Anastomosing rivers: a review of their classification, origin and sedimentary products: Earth-Sci Rev 53: 149-196.
40. Martin CAL, Turner BR (1998) Origins of massive-type sandstones in braided river systems. Earth-Sci Rev 44: 15-38.
41. Miall AD (1977) A Review of the Braided River Depositional Environment. Earth-Sci Rev 13: 1-62.
42. Miall AD (1985). Architectural-element analysis: A new method of facies analysis applied to fluvial deposits. Earth-Sci Rev 22: 261-308.
43. Miall AD (2000) Principles of sedimentary basin analysis, 3rd edn. Springer, Verlag Berlin Heidelberg.
44. Miall AD (2006) The Geology of Fluvial Deposits, Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer, Verlag Berlin Heidelberg.
45. Nakayama K, Ulak PD (1999) Evolution of fluvial style in the Siwalik Group in the foothills of the Nepal Himalaya. Sediment Geol 125: 205-24.
46. Nanson GC, Knighton AD (1996) Anabranching rivers: their cause, character and classification. Earth Surf Proc Land 21: 217-239.
47. Ojha TP, Butler RF, Decelles PG, Quade J (2009) Magnetic polarity stratigraphy of the Neogene foreland basin deposits of Nepal. Basin Res 21: 61-90.
48. Oldknow CJ, Hooke JM (2017) Alluvial terrace development and changing landscape connectivity in the Great Karoo, South Africa. Insights from the Wilgerbosch River catchment, Sneeuberg. Geomorphology 288: 12-18.
49. Parsons AJ, Stromberg SGL (1998) Experiment analysis of size and distance of travel of unconstrained particles in interrill flow. Water Resour res 34 (9): 2377-2381.
50. Piligram GE (1913) The correlation of the Siwaliks with mammal horizons of Europe. Rec Geol Surv India 43 (4): 264-326.
51. Plink-Bjorlund P (2015) Morphodynamics of rivers strongly affected by monsoon precipitation: Review of depositional style and forcing factors. Sediment Geol 323: 110-147.

52. Prakash B, Sharma RP, Roy AK (1980) The Siwalik Group (molasse) - sediments shed by collision of continental plates. Sediment Geol 25: 127-159.
53. Quade J, Cerling TE, Bowman JR (1989) Development of asian monsoon revealed by marked ecological shift during the latest miocene in northern pakistan. Nature 342 (6246): 163-166.
54. Quade J, Cater JML, Ojha TP, Adam J, Harrison TM (1995) Late Miocene environmental change in Nepal and the Northern Indian subcontinent: Stable isotopic evidence from paleosols. Geol Soc Am Bull 107: 1381-1397.
55. Rai LK, Yoshida K (2020) Lithostratigraphy of the Siwalik Group along the Muksar Khola section, Siraha-Udayapur District, Eastern Nepal Himalaya. J Nepal Geol Soc 60: 207-224.
56. Rai LK, Yoshida K, Takeshi K (in press) Reconstruction of the exhumation of the eastern Nepal Himalaya based on provenance changes. Sedimentary Geology. https://doi.org/10.1016/j.sedgeo.2021.105920
57. Rea D K (1992) Delivery of Himalayan sediment to the northern Indian Ocean and its relation to global climate, sea level, uplift, and seawater strontium, in Duncan, R., et al. (Eds.), Synthesis of results from scientific drilling in the Indian Ocean. AGU Geophys Monogr 70: 387-402.
58. Reineck HE, Singh IB (1980) Depositional Sedimentary Environments: with reference to terrigenous clastics. Springer, Berlin.
59. Robinson DM, Decelles PG, Patchett PJ, Garzione CN (2001) The kinematic history of the Nepalese Himalaya interpreted from Nd isotopes. Earth Planet Sci Lett 192: 507-521.
60. Robinson DM, DeCelles PG, Garzione CN, Pearson ON, Harrison TM, Catlos EJ (2003) Kinematic model for the Main Central Thrust in Nepal. Geology 31: 359-362.
61. Rosler W, Metzler W, Appel E (1997) Neogene magnetic polarity stratigraphy of some fluviatile Siwalik sections, Nepal. Geophys J Int 130: 89-111.
62. Schelling D, Arita K (1991) Thrust tectonics, central shortening, and the structure of the far-eastern Nepal Himalaya. Tectonics 10: 851-862.
63. Shrestha RB, Sharma SR (1996) The lower Siwalik-basement unconformity in the sub-Himalaya of eastern Nepal and its significance. J Nepal Geol Soc 13: 29-36.
64. Sigdel A, Sakai T (2016) Sedimentary facies analysis os the fluvial systems in the Siwalik Group, Karnali River section, Nepal Himalaya, and their significance for understanding the paleoclimate and Himalayan tectonics. J Nepal Geol Soc 51: 11-26.
65. Singh AB (1972) On the bedding in the natural-levee and point bar deposits of the Gomti River, Uttar Pradesh, India. Sediment Geol 7: 309-317.
66. Singh H, Parkash B, Gohain K (1993) Facies analysis of the Kosi megafan deposits. Sediment Geol 85: 87-113.
67. Smith DG (1986) Anastomosing river deposits, sedimentation rates and basin subsidence, Magdalena River, northwestern Colombia, South America. Sediment Geol 46: 177-196.

68. Smith DG, Smith ND (1980) Sedimentation in anastomosed river systems: examples from alluvial valleys near Banff, Alberta: J Sediment Petrol 50: 157-164.
69. Tandon SK (1976) Siwalik sedimentation in a part of the Kumaun Himalaya, India. Sediment Geol 16: 131-154.
70. Tandon SK, Gibling MR, Sinha S, Singh V, Ghazanfari P, Dasgupta A, Jain M, Jaim V (2006) Alluvial valleys of the Ganga plains, India: Timing and causes of Incision. SEPM Spec Publ 85: 15-35.
71. Taral S, Sarkar S, Chakraborty T (2018) An ichnological model for a deltaic depositional system: New insights from the Neogene Siwalik Foreland Basin of Darjeeling- Sikkim Himalaya. Palaeogeogr Palaeoclimatol Palaeoecol 511: 188-207.
72. Taral S, Chakraborty T, Huyghe P, Van Der Beek P, Vogeli N, Dupont-Nivet G (2019) Shallow marine to fluvial transition in the Siwalik succession of the Kameng River section, Arunachal Himalaya and its implication for forelan basin. J Asian Earth Sci 184: 103980. https://doi.org/10.1016/j.jseaes.2019.103980
73. Tokuoka T, Takayasu K, Hisatomi K, Yamasaki H, Tanaka S, Konomatu M, Sah RB, Roy SM (1990) The Churia (Siwalik) Group of Tinau Khola-Binai Khola area, west-central Nepal. Mem Fac Sci Shimane Univ 24: 71-88.
74. Tornqvist TE (1994) Middle and late Holocene avulsion history of the River Rhine ŽRhine–Meuse delta Netherlands. Geology 22: 711-714.
75. Tucker ME (2003) Sedimentary rocks in the Field (3rd ed.). England, Jhon Wiley and Sons Ltd.
76. Ulak PD (2009) Lithostratigraphy and late Cenozoic fluvial styles of Siwalik Group along Kankai River section, East Nepal Himalaya. Bull Dept Geol Tribhuvan Univ 12: 63-74.
77. Ulak PD, 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 6: 1-14.
78. Ulak PD, Nakayama K (2001) Neogene fluvial systems in the Siwalik Group along the Tinau Khola section, West Central Nepal Himalaya. J Nepal Geol Soc 25: 111-22.
79. Walker RG (1966) Shale grit and Grindslow shales: Transition from turbidite to shallow water sediments in the upper Carboniferous of northern England. J Sediment Res 1: 90-114.
80. Willis BJ (1993a) Ancient river systems in the Himalayan foredeep, Chinji village area, northern Pakistan. Sediment Geol 88: 1-76.
81. Willis BJ (1993b) Evolution of Miocene fluvial systems in the Himalayan foredeep through a two kilometer-thick succession in northern Pakistan. Sediment Geol 88: 77-121.
82. Yin A (2006) Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. Earth-Sci Rev 76 (1-2): 1-131.
83. Zaitlin BA, Dalrymple RW, Boyd R (1994) The stratigraphic organization of incised-valley systems associated with relative sealevel change, in Dalrymple, R.W., Boyd, R., and Zaitlin, B.A. (Eds.), Incised-Valley Systems: Origin and Sedimentary Sequences: SEPM Spec Publ 51: 45-60.

84. Zaleha MJ (1997) Intra- and extrabasinal controls on fluvial deposition in the Miocene Indo–Gangetic foreland basin, northern Pakistan. Sedimentology 44: 369-390.
85. Zhang L, Wanf H, Li Y, Pan M (2017) Quantitaive characterization of sandstone amalgamation and its impact on reservoir connectivity. Petrol Explor Develop 44(2): 226-233.

9. Tables

Due to technical limitations, tables are only available as a download in the Supplemental Files section.

Figures

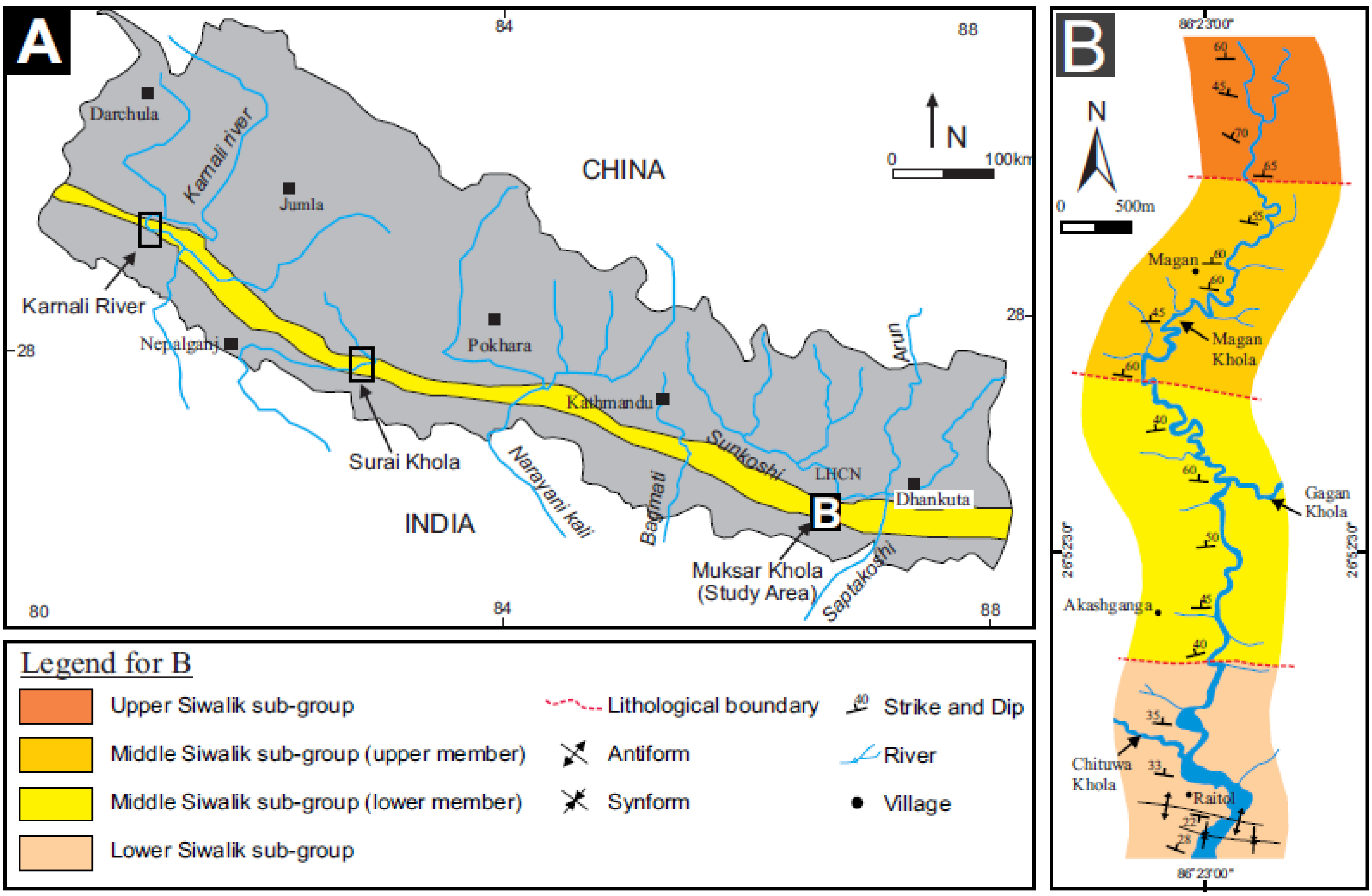

Figure 1

A) Location of the present study area with other previously studied Siwalik section; B) Geological Map of the study area (modified after Rai and Yoshida, 2020). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

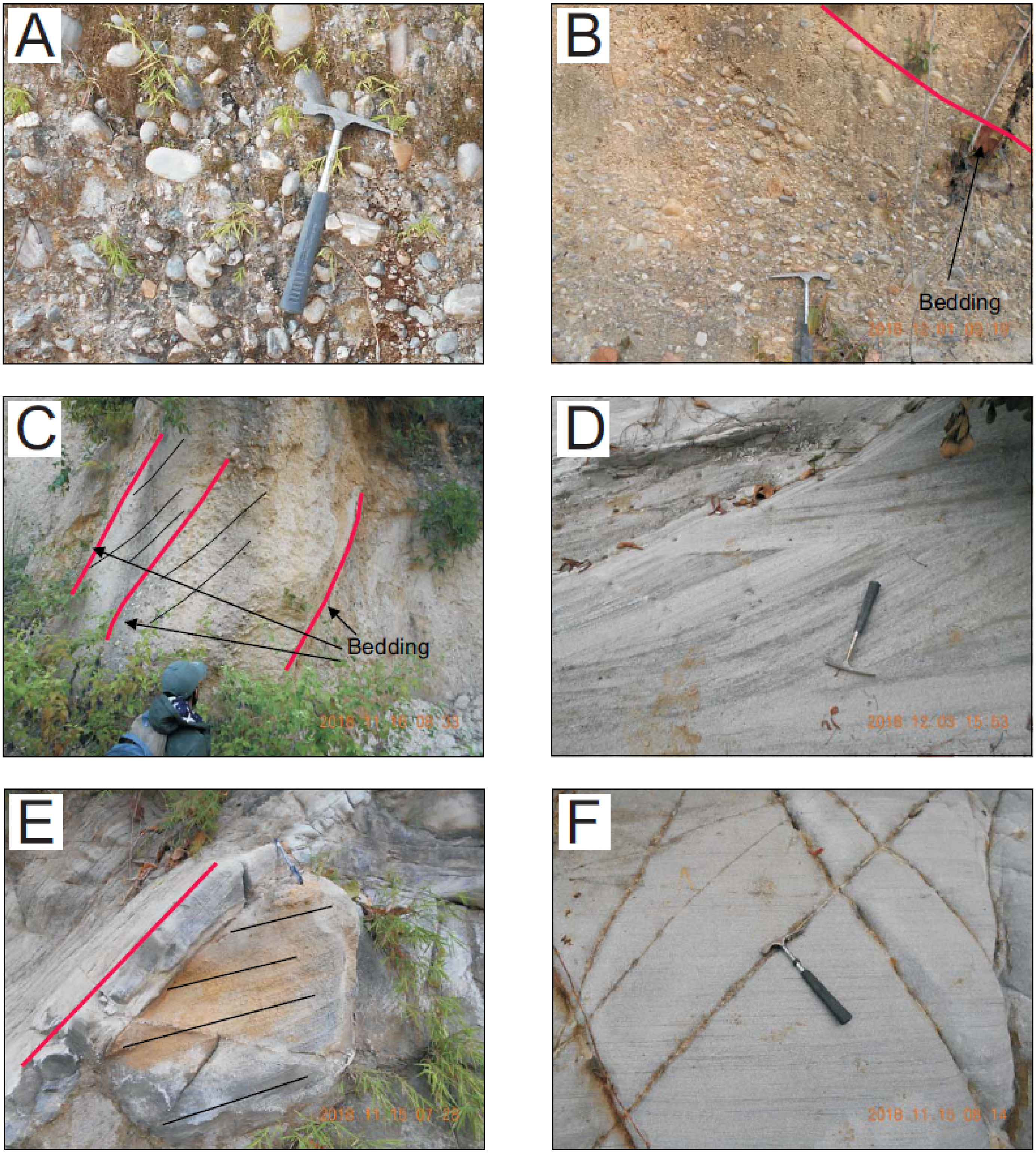

Figure 2

Outcrop photographs of the lithofacies, A) Matrix supported poorly sorted pebble to cobble size massive gravel (Gmm); B) Matrix supported gravel with grading (Gmg); C) Stratified gravel (Gp); D) Trough cross-stratification (St); E) Planer cross-stratification (Sp); F) Horizontal lamination (Sh).

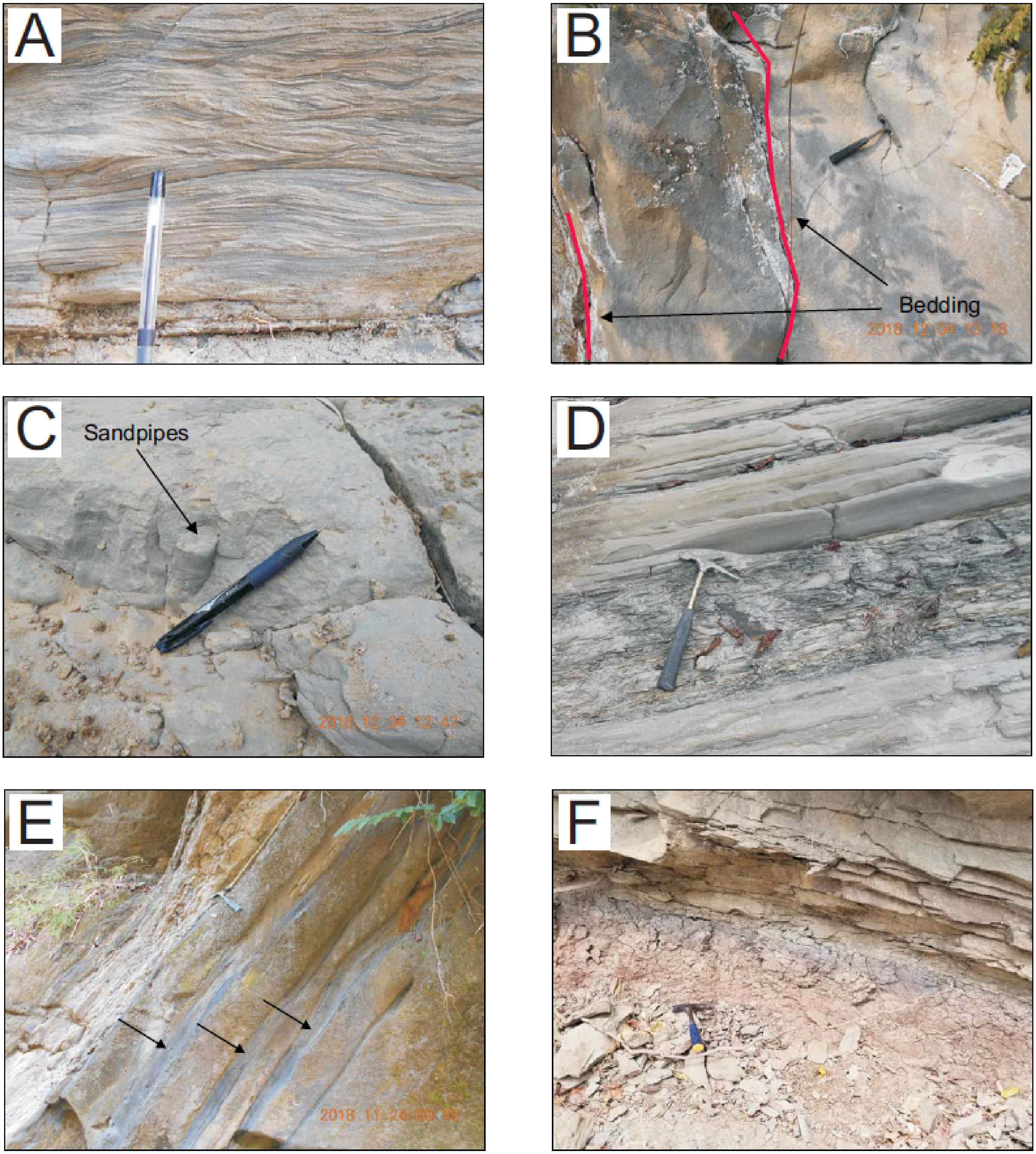

Figure 3

Outcrop photographs of the lithofacies, A) Ripple cross lamination (Sr); B) Massive sandstone (Sm); C) Massive mudstone with sandpipes (Fm); D) Laminated mudstone (Fl); E) Peaty mudstone (C); F) Reddish-brown paleosols (P).

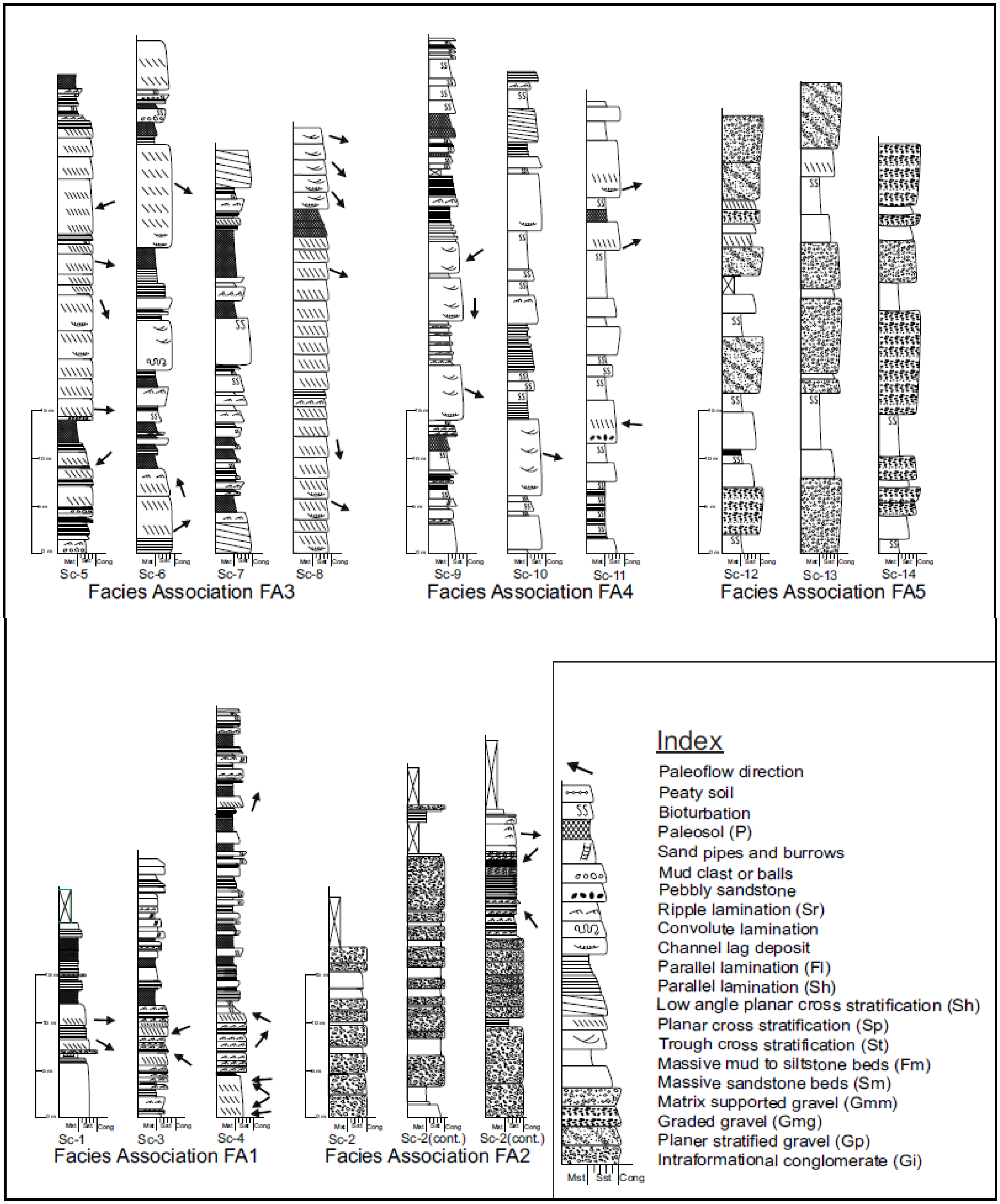

Figure 4

Representative sedimentological log of the facies association of the Siwalik Group along the Muksar Khola Section (Location is given in fig 5).

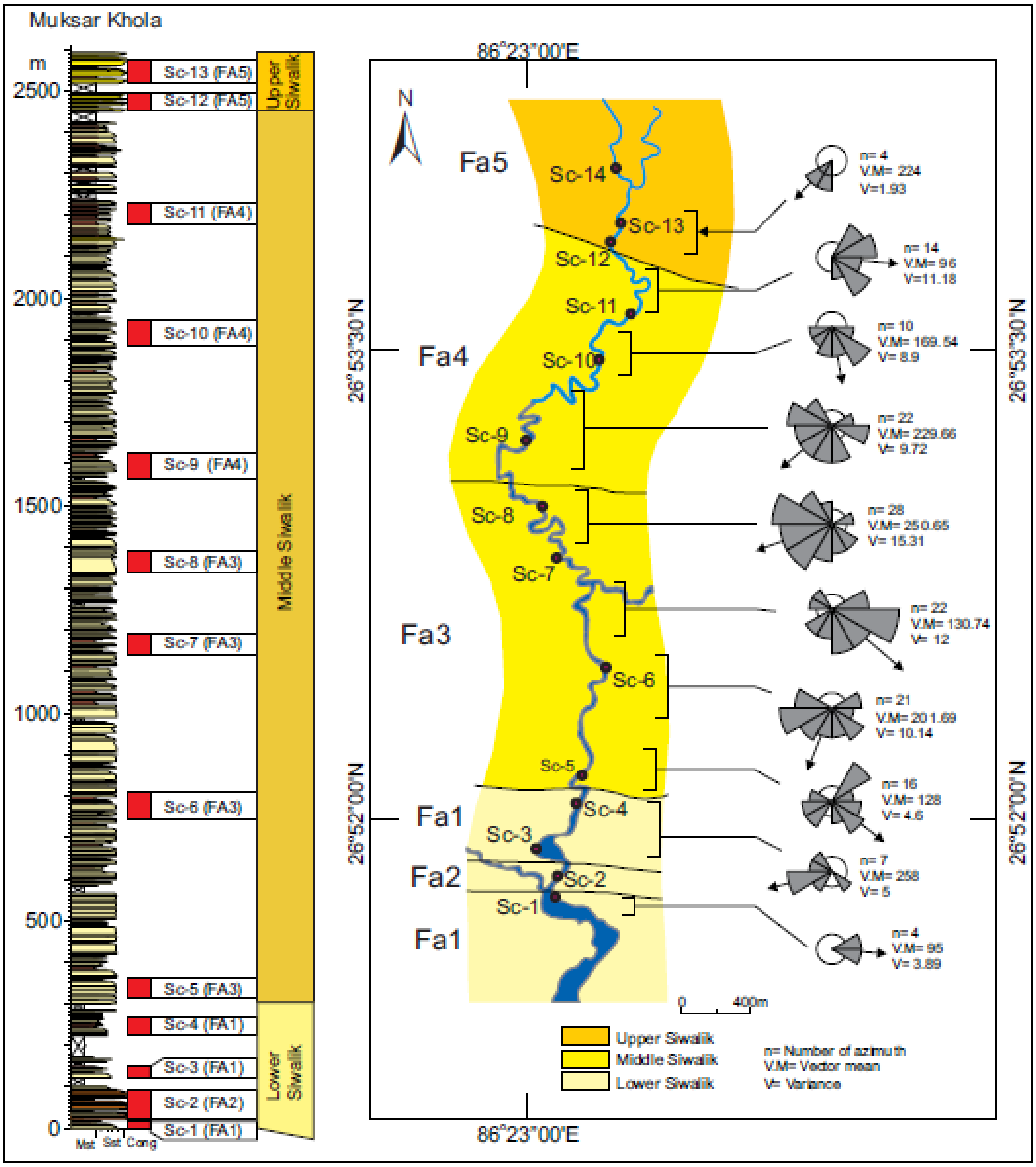

Figure 5

Location of the section of facies association presented in Fig 4 in terms of the entire sedimentological logs (left) and geological map (right). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

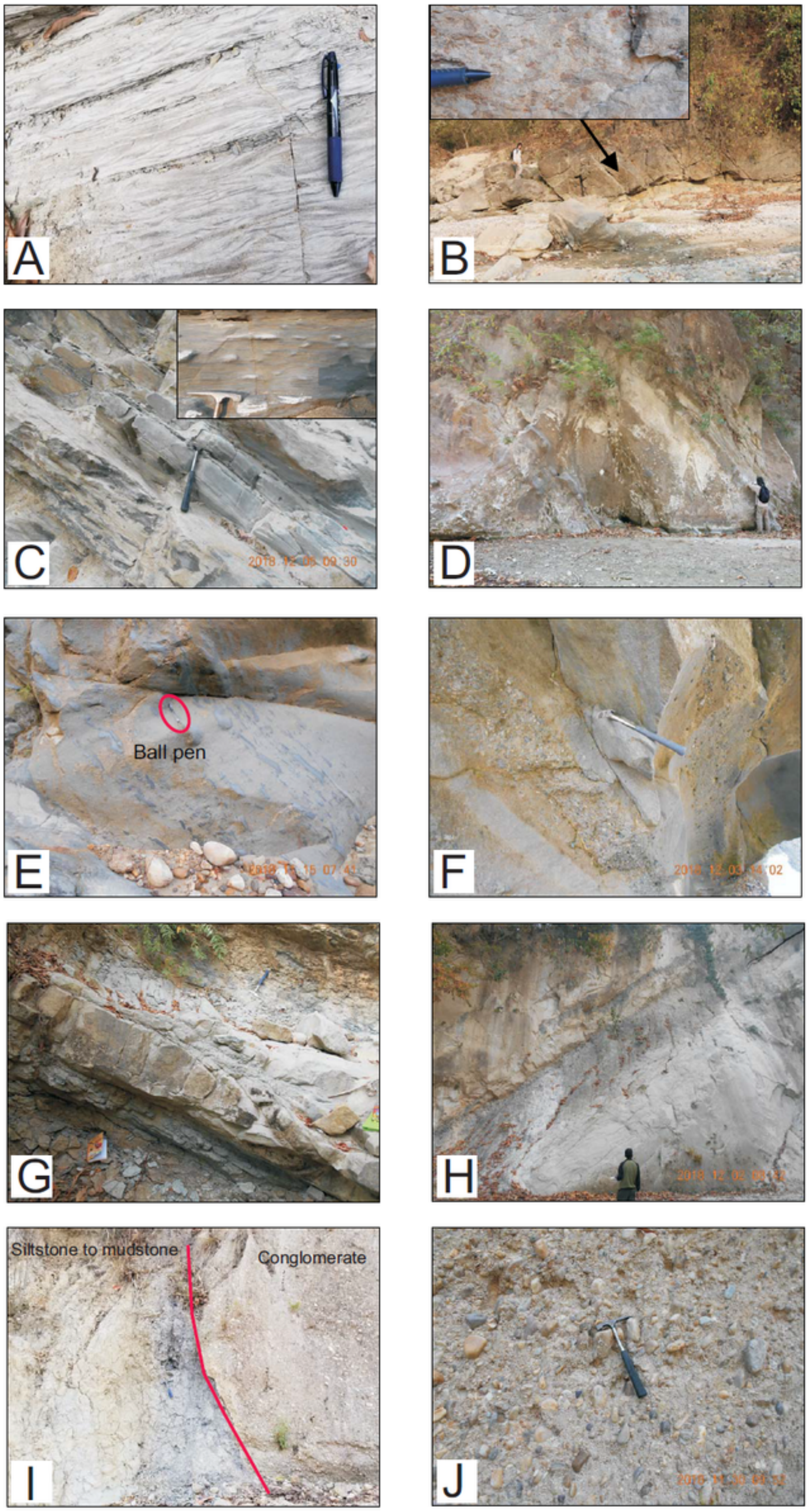

Figure 6

Outcrop photographs of, A) Ripple lamination on the very fine-grained sandstone (FA1); B) Intraformational conglomerate with mud clast (FA2); C) Parallel to ripple lamination observed in the fine grained sandstone representing levee deposits (FA1); D) Amalgamated sandstone bed (FA3); E) Sub-angular to angular mud clast observed on the base of amalgamated sandstone (FA3); F) Channel lag deposits (FA3); G) Laterally accreted sandstone bed (FA3) ; H) Fining upward sequence observed in a very thick bed of sandstone (FA4); I) Silt to mudstone bed and matrix supported conglomerate (FA5); J) Matrix supported conglomerate with sub-rounded, pebble to cobble sized clast (FA5).

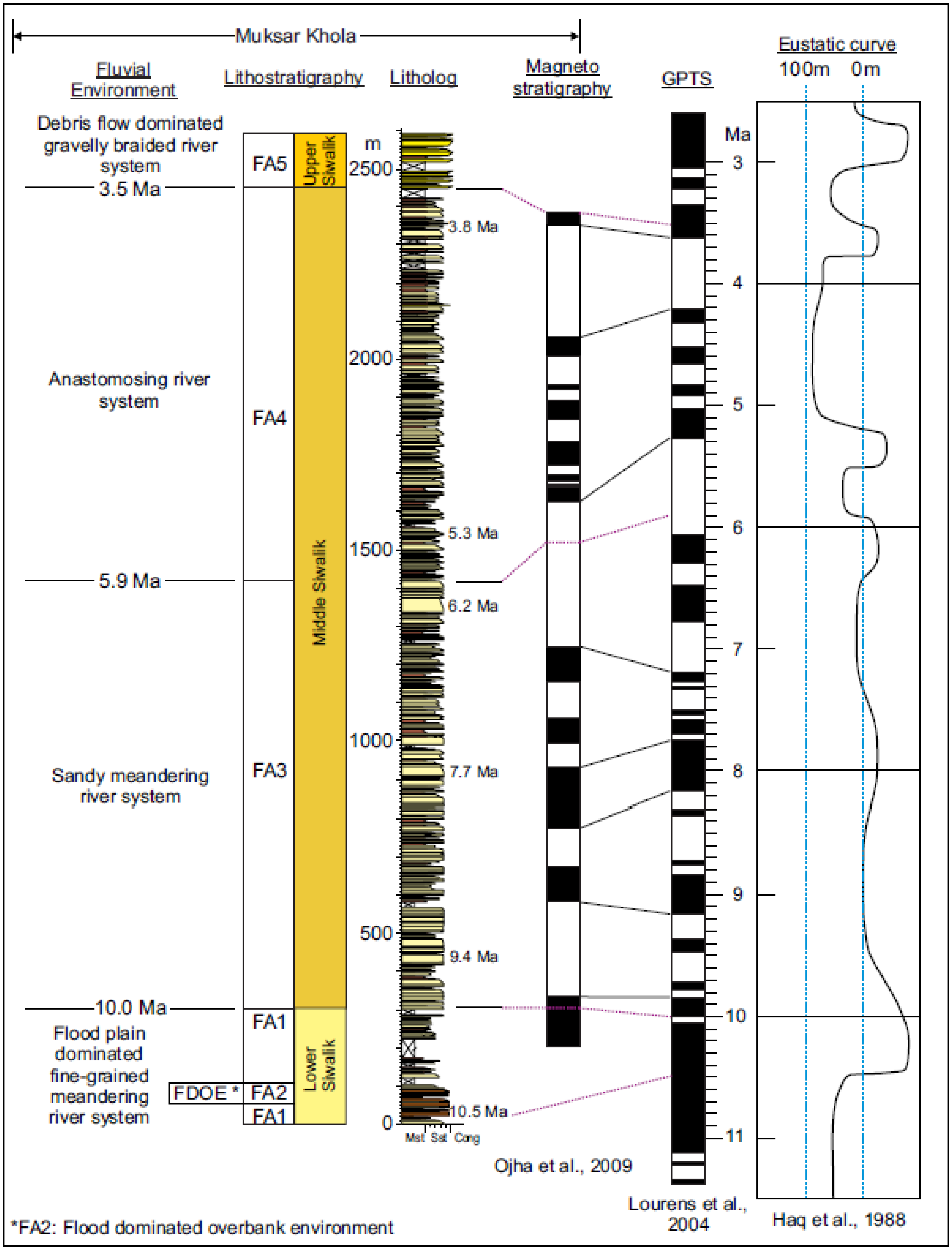

Figure 7

Evolution of the fluvial style in the present study area based on a magnetostratigraphic time frame (modified from Ojha et al. 2009) and the eustatic curve (modified from Haq et al., 1988).

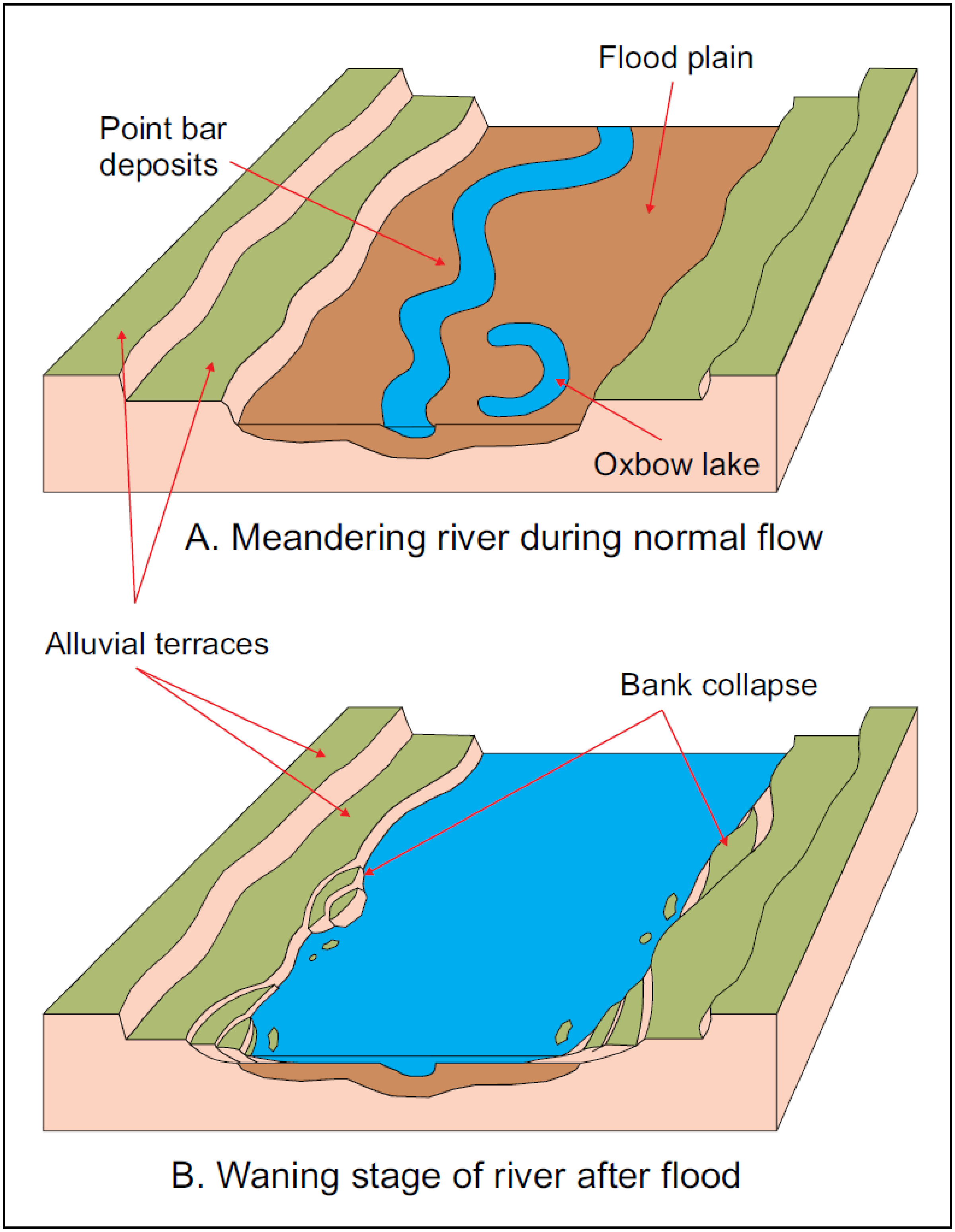

Figure 8

Schematic diagram showing A) Meandering river during normal flow condition and B) Waning stage of river after flood.

Supplementary Files

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- GraphicalAbstract.jpg
- Tables.pdf