Rai and Yoshida *Progress in Earth and Planetary Science* (2021) 8:49
https://doi.org/10.1186/s40645-021-00444-5

Progress in Earth and Planetary Science

RESEARCH ARTICLE

Open Access

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

Lalit Kumar Rai[1*] and Kohki Yoshida[2]

Abstract

The Siwalik Group, ranging from the Early Miocene to Pleistocene, is believed to be deposited in the fluvial environment and controlled by contemporary Himalayan tectonics and climate. In this study, we established the fluvial environment and its controlling factors responsible for the deposition of the Siwalik succession along the Muksar Khola section in the eastern Nepal Himalaya. Five sedimentary facies associations are identified; these 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 changes in the fluvial system occurred around 10.5 Ma, 10.0 Ma, 5.9 Ma and 3.5 Ma, defined by existing magnetostratigraphy constraints, due to the effects of hinterland tectonics, climate and sea-level change and continuous drifting of the foreland basin towards the hinterland concerning depositional age. The thick succession of an intraformational conglomerate reveals intensification of the monsoon started around 10.5 Ma in the eastern Nepal Himalaya. The present study also shows asynchronous exhumation of the Himalaya from east to west brought a significant difference in the fluvial environment of the Neogene foreland basin.

Keywords: Miocene, Siwaliks, Facies, Fluvial, Sea-level change, Eastern Nepal Himalaya

1 Introduction

Himalaya was gradually uplifted due to the collision of the Indian sub-continent with the Eurasian plate at ca. 50 Ma (Le Fort 1975; Burbank 1992). Various tectonic activities have been recorded in the Himalaya after this collision (Burchfiel et al. 1992). This gradual change in the paleogeography influenced the atmospheric circulation (Raymo and Ruddiman 1992) triggering the Asian monsoon (Kutzbach et al. 1989; Clift et al. 2008; Boos and Kuang 2010; Armstrong and Allen 2011), which in turn controlled the weathering and erosional process that was responsible for the deposition of sediments in the foreland basin (Parkash et al. 1980; Tokuoka et al. 1990; Willis 1993b; Zaleha 1997). The Siwalik Group is made up of this molasse deposits (Corvinus 1993) 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). Presently, it is exposed as the southernmost hill range bounded by the Main Boundary

* Correspondence: lalitrai83@gmail.com
[1]Department of Science and Technology, Graduate School of Medicine, Science and Technology, Shinshu University, Matsumoto, Japan
Full list of author information is available at the end of the article

Thrust (MBT) to the north and the Main Frontal Thrust in the south (Gansser 1964).

In the previous studies of the Siwalik Group along various sections of 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 systems from meandering to the sandy braided river system (Hisatomi and Tanaka 1994; Zaleha 1997; Ulak and Nakayama 2001; Ulak 2009; Sigdel and Sakai 2016). These two river systems are observed as a dominating fluvial system during the deposition of the Siwaliks, although anastomosing river system has also been recorded in few sections (Huyghe et al. 2005; Nakayama and Ulak 1999). This change in the fluvial system is considered to be controlled by both autocyclic as well as allocyclic processes like hinterland tectonics, climate, and size of drainage basins (Willis 1993a; Zaleha 1997; Nakayama and Ulak 1999; Huyghe et al. 2005).

Meanwhile, various researchers suggested that the exhumation history of the Himalaya, as well as the climate, was not synchronous laterally; it was observed early in the western part compared with the eastern part (Quade et al. 1995; Robinson et al. 2001; Yin 2006; Ojha et al. 2009; Vogeli et al. 2017). Therefore, if the tectonics and climate are the factors controlling the change in the river system of the Neogene foreland basin, then these differences in the Himalaya from west to east should also have brought a significant difference in the fluvial environment and its timing laterally. Moreover, fluvial behaviour is governed not only by the interplay between tectonics and climate but also by sea-level change (Burbank 1992; Goodbred Jr and Kuehl 2000a; Goodbred Jr and Kuehl 2000b). The Siwalik Group in the eastern Himalaya sections like Darjeeling-Sikkim, Bhutan and the Arunachal Pradesh report the evidence of sediment deposited in deltaic and open marine depositional settings (Coutand et al. 2016; Taral et al. 2018, 2019). The present study area lies in the eastern part of the Nepal Himalaya near the Darjeeling-Sikkim section. Therefore, the contemporary exhumation history of the hinterland, climate as well as sea-level change should influence 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 eastern Nepal (Ulak 2009).

In this study, we focused on establishing the fluvial environment of the Siwalik Group along the Muksar Khola section in the eastern Nepal Himalaya based on facies analysis to understand its evolution and its controlling factors. Interpretation will be carried out using the depositional age determined by Ojha et al. (2009).

2 Geological outline

The present study area lies in the eastern part of the Nepal Himalaya (Fig. 1A). In this area, the Siwalik Group is divided into three belts by the Main Dun Thrust and the Kamala-Tawa Thrust (Shrestha and Sharma 1996). The present study deals with the Siwalik Group in the southern belt, bounded by the Main Dun Thrust in the north and the Main Frontal Thrust 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. 1B). The Lower Siwalik sub-group comprises grey, fine-grained indurated sandstone with dark greenish grey and purple mottled mudstone. About 80 to 90 m thick successions of intraformational conglomerate (composed of mudstone clast with medium- to very coarse-grained sandstone matrix) are 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 proportion of biotite grains, and the mudstone shows increased proportion compared with the lower member of the Middle Siwalik sub-group. The Upper Siwalik sub-group is composed of a 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 ~ 2500 m thick Middle Siwalik sub-group along 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; a 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). This fast exhumation was observed after 11.0 Ma as rapid uplift of the Higher Himalayan Crystalline occurred due to the activation of an out-of-sequence thrust known as the Sun Koshi Thrust (Rai et al. 2021). Similarly, after ~ 5.5 Ma, rapid subsidence of the foreland basin was observed as a result of the thrust loading of the MBT (Ojha et al. 2009; Rai et al. 2021). The climate of the eastern Nepal Himalaya

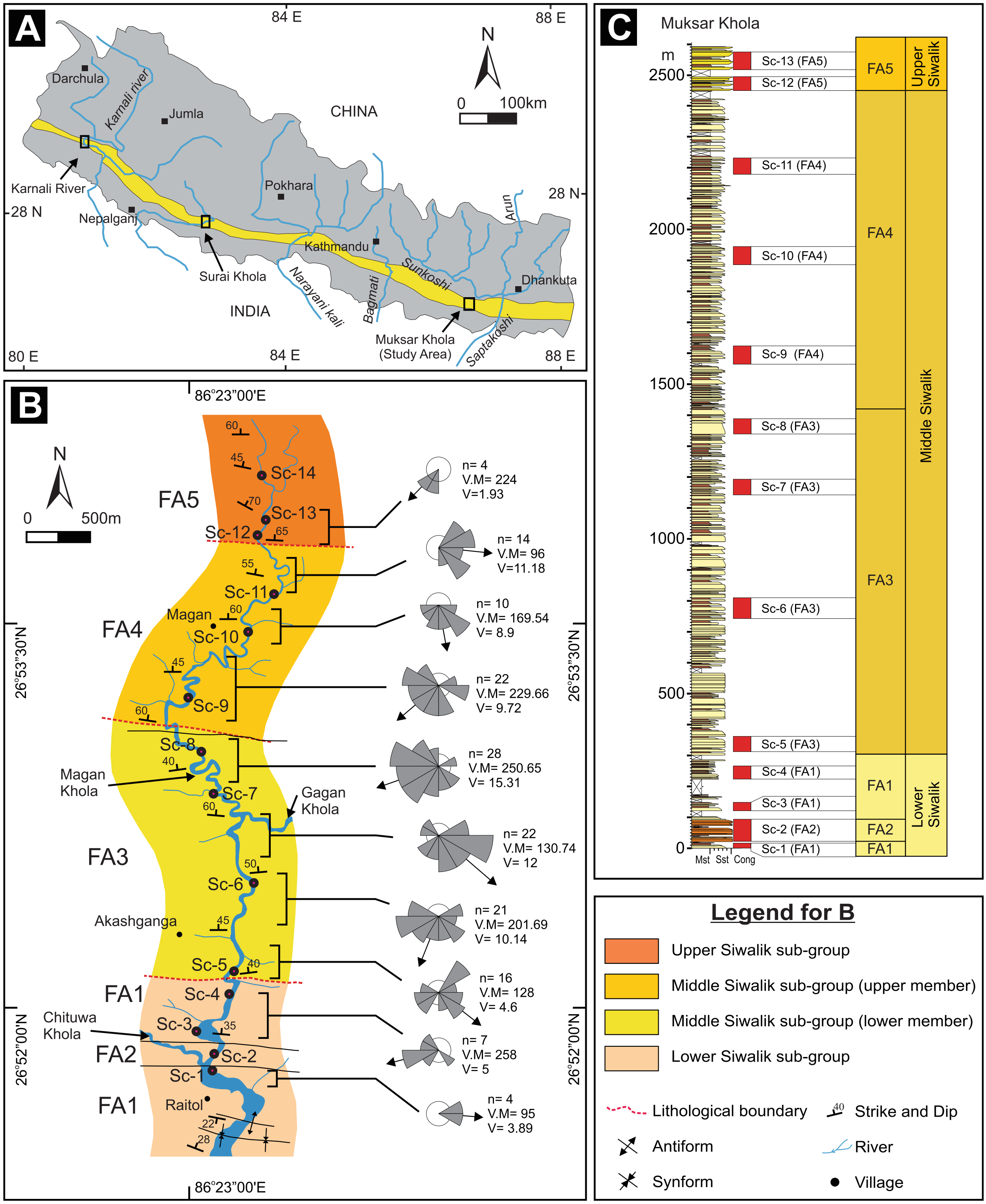


Fig. 1 **A** Map of Nepal (in grey) showing the Siwaliks range (in yellow) and the location of the present study area along with the Surai Khola section studied by Nakayama and Ulak (1999) and Karnali River section studied by Huyghe et al. (2005) and Sigdel and Sakai (2016); **B** geological map of the Siwaliks along the Muksar Khola section (modified after Rai and Yoshida 2020) showing the location of representative sedimentological log of the facies association and paleocurrent analysis; **C** sedimentological log of the Muksar Khola section (modified after Rai and Yoshida 2020) showing the location of sedimentological log of representative facies association (Sc-14 of FA5 lies beyond the sedimentological log)

shows a more or less similar trend to the Central Nepal Himalaya (Quade et al. 1995), but lacks the exact time frame of vegetation change from C3 to C4 plant. Comparing the stratigraphic thickness of Quade et al. (1995) with the magnetostratigraphy of Ojha et al. (2009), this change in the vegetation probably occurred around 6 to 7 Ma. This change in the vegetation suggests a greater seasonality reflected by a stronger monsoon (Quade et al. 1989, 1995).

3 Methods

In this study, field data were acquired based on the topographic map of the 1:25,000 scale. Lithofacies were identified based on the grain size and texture of the beds and associated sedimentary structures. Architectural elements were classified based on the nature of the internal and external geometry of the beds and their bounding surfaces. Mainly, foresets of the cross-stratifications were measured for the paleocurrent analysis. The paleoflow 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, 2006). Route map and detail sedimentological logs were made to evaluate the precise boundary of the facies associations. 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. The lithofacies are summarized in Table 1, and the representative photographs of each lithofacies are shown in Fig. 2. The recognized facies associations along with its associate lithofacies and architectural elements are summarized in Table 2. Representative sedimentological logs of each facies associations are shown in Fig. 3 and their locations in Fig. 1B & C.

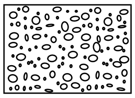
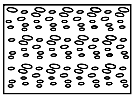
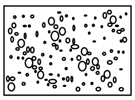
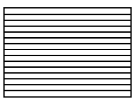
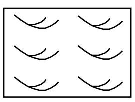
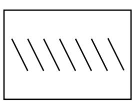
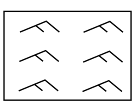
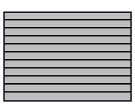
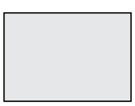
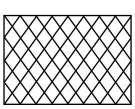
4.1.1 Facies association 1 (FA1)

4.1.1.1 Description This facies association is characterized by a predominance of thickly bedded mudstone interbedded with very fine- to medium-grained sandstone. Normally, fining-upward successions from 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. Mudstone is dominated by facies Fm (mostly bioturbated), with abundant facies Fl and facies P (Fig. 2A). Facies C is also observed occasionally (Fig. 2B).

Sandstone beds normally range between 0.15 and 1.5 m in thickness, though there are few beds with a thickness of more than 4 m (Fig. 3, 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 Sr and Sh dominates. Lateral accretionary structures are mainly observed in these beds. Medium- to thickly bedded fine-grained sandstone is massive with occasional occurrence of facies Sr. Very fine- to fine-grained sandstones display both fining- and coarsening-upward succession with facies Fm (Fig. 2C) and often possess concretions. The basal surface is comparatively flat and usually occurs at an interval within very thick beds of mudstone (Fig. 3, Sc-4). Thin- to medium-bedded very fine-grained sandstones are bioturbated if not show facies Fl (Fig. 2D). Calcareous nodules are often observed on 15–25 cm thick upper portion of the fine-grained sandstone and mudstone beds. Sandpipes oriented almost perpendicular to bed with diameter ca. 3 cm (Fig. 2C), roots and rootlets are observed in mudstone and very fine-grained sandstone. Though the paleocurrent data are limited in this facies association but still show a dispersive flow pattern (Fig. 1B). Facies association FA1 is preserved in the Lower Siwalik sub-group.

4.1.1.2 Interpretation Thick to very thick beds of fine- to medium-grained sandstone showing planar cross-stratification and ripple cross lamination with erosive basal surface represents channel deposits (Miall 2006). Medium to thick massive, fine-grained sandstone with an occasional ripple cross-lamination represents sheet flow (Miall 2006). Medium-bedded very fine- to fine-grained sandstone with either fining- or coarsening-upward succession with concretions, 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 cross-laminations are levee deposits (Singh 1972). The flat basal surface of these fine-grained sandstones and its occurrence at an interval within very thick beds of mudstone suggests overbank deposits (Miall 2006). Laminated and peaty mudstone represents the waning stage of river flood and swamp deposits indicating the overbank deposits (Miall 2000, 2006). Variegated and bioturbated mudstone with sandpipes, rootlets and the presence of calcareous nodules indicate long term exposure of the flood plain (Nakayama and Ulak 1999). Sandstone with lateral accretionary structures along with dispersive paleoflow pattern and frequent crevasse splay suggests a river with high sinuosity. Therefore, FA1 is interpreted as the deposits of a flood plain-dominated fine-grained meandering river system.

Table 1 Description and interpretation of the depositional facies of the Siwalik Group along the Muksar Khola section

Facies Code	Symbol	Facies Characteristics	Sedimentary Structures	Interpretation	Remarks
Gmm		Matrix supported, poorly sorted massive gravel Thickness 2 to 8 m	Structureless or weak grading	Plastic debris flow (high strength, viscous), longitudinal bars, channel lag deposits (Miall, 1977; 2000; 2006)	Fig: 2-L
Gmg		Matrix supported gravel Thickness 2 to 8 m	Inverse grading Grading clast and/or matrix	Pseudoplastic debris flow (low strength, viscous), longitudinal bars, channel lag deposits (Miall, 1977;2000; 2006)	Fig: 2-K
Gp		Pebble sized clast stratified in matrix of medium- to coarse-grained sandstones Thickness upto 2 m	Planar cross beds	Transverse bedforms, linguoid bars or deltaic growths from older bar remnants (Miall, 1977; 2000; 2006)	Fig: 2-J
Sh		Fine- to medium-grained sandstones, occasionally concreted Thickness upto 0.4 m	Horizontal lamination with parting or streaming lineation	Planar bed flow (intermediate to upper flow regime or lower flow regime) (Miall, 1977; 2000; 2006)	Fig: 2-I
St		Medium- to coarse-grained sandstones, occasionally pebbly Thickness upto 2 m	Solitary or grouped trough cross beds	Migration of linguoid 3D dunes (lower flow regime) (Miall, 1977; 2000; 2006)	Fig: 2-H
Sm		Medium- to coarse-grained sandstones Thickness upto 1.5 m	Massive or faint lamination	Sediment gravity flow deposits, resulting from high concentration of sediment / water mixture (Martin and Turner, 1998; Miall, 2000; 2006)	Fig: 2-G
Sp		Fine- to coarse-grained sandstones, mudclast are occasionally present Thickness upto 1 m	Solitary or grouped planar cross beds	Migration transverse and linguoid 2D dunes (lower flow regime) (Miall, 1977; 2000; 2006)	Fig: 2-F
Sr		Fine- to medium-grained sandstones, occasionally concreted Thickness upto 0.4 m	Ripple cross lamination	Ripples (lower flow regime) (Miall, 1977; 2000; 2006)	Fig: 2-E
Fl		Inter-lamination of mud, silt and very fine-grained sand with occasional very small ripples Thickness upto 1 m	Fine parallel lamination	Overbank or waning flood deposits (Miall, 1977; 2000; 2006)	Fig: 2-D
Fm		Mudstones to very fine-grained sandstones Thickness upto 0.3 m	Massive or bioturbated	Overbank, abandoned channel, or drape deposits (Miall, 1977; 2000; 2006)	Fig: 2-C
C		Peaty mudstones Thickness upto 0.15 m	Plant, mud films	Vegetated swamp deposits (Miall, 2000; 2006)	Fig: 2-B
P		Variegated with nodules and concretions Thickness upto 2 m	Pedogenic features	Soil with chemical precipitation (Miall, 2000; 2006)	Fig: 2-A

4.1.2 Facies association 2 (FA2)

4.1.2.1 Description This facies association is mainly characterized by the thick- to very thickly bedded (0.4 to > 4.0 m), poorly sorted, clast-supported intraformational conglomerate (Fig. 4A) with few beds of coarse-grained sandstone and mudstone. The intraformational conglomerate is composed up of siltstone clast and medium- to very coarse-grained sandstone matrix and shows facies Gmm. These siltstone clasts are greenish-grey in colour and angular to subangular in shape (some clasts shows ductile deformation) with an average

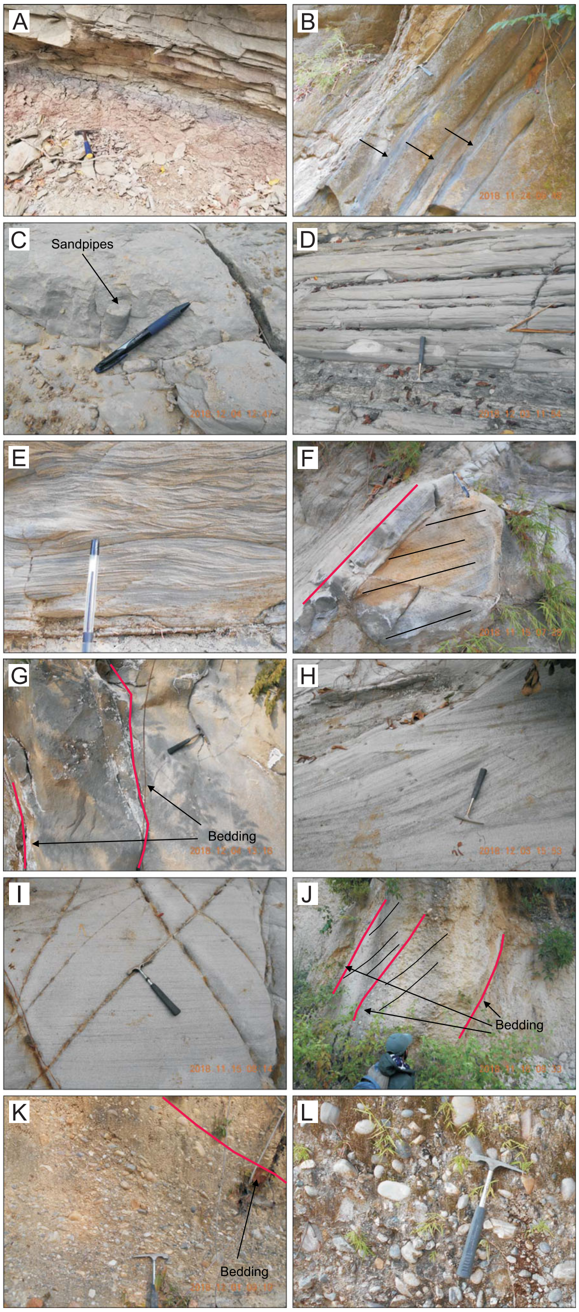


Fig. 2 Representative outcrop photographs of the 12 lithofacies. **A** Reddish-brown mudstone (facies P) from FA1, **B** peaty mudstone (facies C) from FA1, **C** massive mudstone (facies Fm) with sandpipes from FA1, **D** mudstone to very fine–grained sandstone with parallel lamination (facies Fl) from FA1, **E** fine-grained sandstone with ripple cross-lamination (facies Sr) from FA2, **F** medium-grained sandstone with planer cross-stratification (facies Sp) from FA3, **G** massive (facies Sm) sandstone from FA3, **H** sandstone with trough cross-stratification (facies St) from FA4, **I** sandstone with horizontal lamination (facies Sh) from FA4, **J** conglomerate showing weak planer cross-stratification (facies Gp) from FA5, **K** matrix-supported gravelly conglomerate with inverse grading (facies Gmg) from FA5, **L** matrix-supported poorly sorted pebble to cobble size massive conglomerate (facies Gmm) from FA5

diameter of 1–4 cm (some clasts show elongation up to 10 cm). The average ratio of clast and matrix is about 70% and 30% respectively. This intraformational conglomerate shows a non-erosional basal surface. Coarse-grained sandstone beds with facies Sm are observed at the lower part of this facies association within the beds of intraformational conglomerate. These massive sandstones have a flat basal surface with thickness ranging from 0.1 to 0.8 m. In the upper part of this facies association, sandstone facies disappears with occasional occurrence of 0.4 to 0.5 m thick mudstones with facies Fl (Fig. 3, Sc-2). Facies Fm is also occasionally observed in mudstone but very rare. At the top of this facies association, thin to medium beds of fine-grained sandstone (overall thickness of around 10 m) with facies Sr (Fig. 2E) interbedded with facies Fl is observed (Figs. 3, Sc-2 & 4B). The FA2 facies association is preserved in the Lower Siwalik sub-group within facies association FA1 with a thickness of about 80 to 90 m.

4.1.2.2 Interpretation An intraformational conglomerate suggests bank failure due to the rapid lowering of water levels during the waning stage of a flood (Gohain and Parkash 1990; Singh et al. 1993; Plink-Bjorklund 2015). 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). But an angular to subangular shape of mud clast indicates immature sediments that were not transported for a longer distance (Reineck and Singh 1980) (i.e., the source of these clasts were proximal to the place of deposition). If this conglomerate was deposited by the main channel undercutting the adjacent overbank deposits, there would be a possibility of much longer transportation and soon disintegration of these clasts. Moreover, the structureless beds of intraformational conglomerate with planer basal surface also suggest this was not deposited by channel, rather by some debris flow (Miall 2006). Therefore, we consider that this was not deposited by the main channel collapsing adjacent flood plain during the waning stage of the flood, but in the overbank setting, more distal to the main channel due to the collapse of the distal alluvial terraces. This collapse of the alluvial terraces was probably triggered by the flood which covered the adjacent flood plain and undercut the alluvial terraces similar to the bank cut during the waning stage of a flood. The increase in the

Table 2 Facies associations of the Siwalik Group in the Muksar Khola section

Facies association	Dominant lithofacies type	Minor lithofacies type	Architectural elements	Lithostratigraphic unit	Interpretation
FA5	Gmm, Gmg, Sm, Fm	Gp, Sp	CH, GB, SB, FF	Upper Siwalik	Debris flow–dominated gravelly braided river
FA4	St, Sp, Sm, Fm, Fl	Gmm, Sh, Sr, P	CH, SB, CS, LV, FF, DA	Middle Siwalik	Anastomosing river
FA3	Sp, Sr, Sh, Fm	St, Sm, Fl, P	CH, SB, CS, LV, FF, LA	Middle Siwalik	Sandy meandering river
FA2	Gmm, Sm	Sr, Fl, Fm	GB, SB, LV, FF	Lower Siwalik	Flood-dominated overbank environment
FA1	Sr, Fl, Fm, P	Sp, Sh, C	CH, SB, CS, LV, FF, LA	Lower Siwalik	Flood plain–dominated fine-grained meandering river

Abbreviations: *GB* Gravel bars, *CH* Channels, *SB* Sandy bedforms, *DA* Downstream accretion, *LA* Lateral accretion, *CS* Crevasse-splay deposits, *LV* Levee deposits, *FF* Flood plain fines (Interpretation scheme after Miall 1977, 1985, 2000, 2006)

distance from the main channel caused a slowdown of the flow velocity due to which mud clasts were not transported for a long distance preventing it from further rework. 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 the overbank architectural elements suggests this facies association FA2 as the deposits of the flood-dominated overbank environment.

4.1.3 Facies association 3 (FA3)

4.1.3.1 Description This facies association shows the domination of sandstone facies with subordinate mudstone facies. 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. 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 facies Fl is observed in few beds.

Sandstone shows both amalgamated and non-amalgamated sandstone beds. Amalgamated sandstone beds occur intermittently with varying thickness ranging from 4 to ˃ 20 m (Fig. 4C) with dominant facies Sp. Each amalgamated sandstone beds consist of 1.0 to 3.0 m thick individual sedimentary succession with undulating amalgamation surface. In the lower portion of amalgamated sandstone beds, individual succession shows weakly developed fining-upward succession represented by basal coarse-grained sandstone grading upward into medium- to coarse-grained sandstone at the top (Fig. 3, Sc-5) (some time amalgamation surface is unclear due to identical grain size). Subangular to angular elongated (up to 20–30 cm in length) mud clasts (Fig. 4D) are sporadically observed at the base of these amalgamated beds. Towards the upper portion, individual fining-upward succession ranges from coarse- to fine-grained sandstone with a distinct amalgamation surface. Occasionally thin lenses of mudstone to siltstone are preserved at the top of the individual succession (Fig.3, Sc-8). Non-amalgamated sandstone beds are fine- to coarse-grained with thickness ranging from 0.2 to > 3.0 m. Facies Sp (Fig. 2F) is mainly observed in thick to very thick sandstone beds, though facies Sm (Fig. 2G) is also occasionally observed. These sandstone bears an occasional channel lags at the base composed of mud clast and coal fragments. These sandstones show a slightly erosive basal surface and lateral accretionary structures are also often observed (Fig. 4E). Thickly bedded (50–90 cm) fine- to medium-grained sandstone beds show sheet-like geometry and display both fining and coarsening-upward succession. Facies Sr is dominant with planar basal surfaces and sometimes associated with mud clast. Medium- to thickly bedded (25–50 cm) very fine- to fine-grained sandstones show facies Sh or Sr, but are mostly bioturbated. These sandstones are usually observed intercalated with mudstones. 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 analysis shows a frequent change in the flow direction with high dispersion (Fig. 1B). The FA3 facies association is preserved in the lower member of the Middle Siwalik sub-group.

4.1.3.2 Interpretation The occurrence of amalgamated sandstone beds suggests deposition by channel with a high deposition rate and high flow energy with a high erosive capacity (Zhang et al. 2017). Unclear

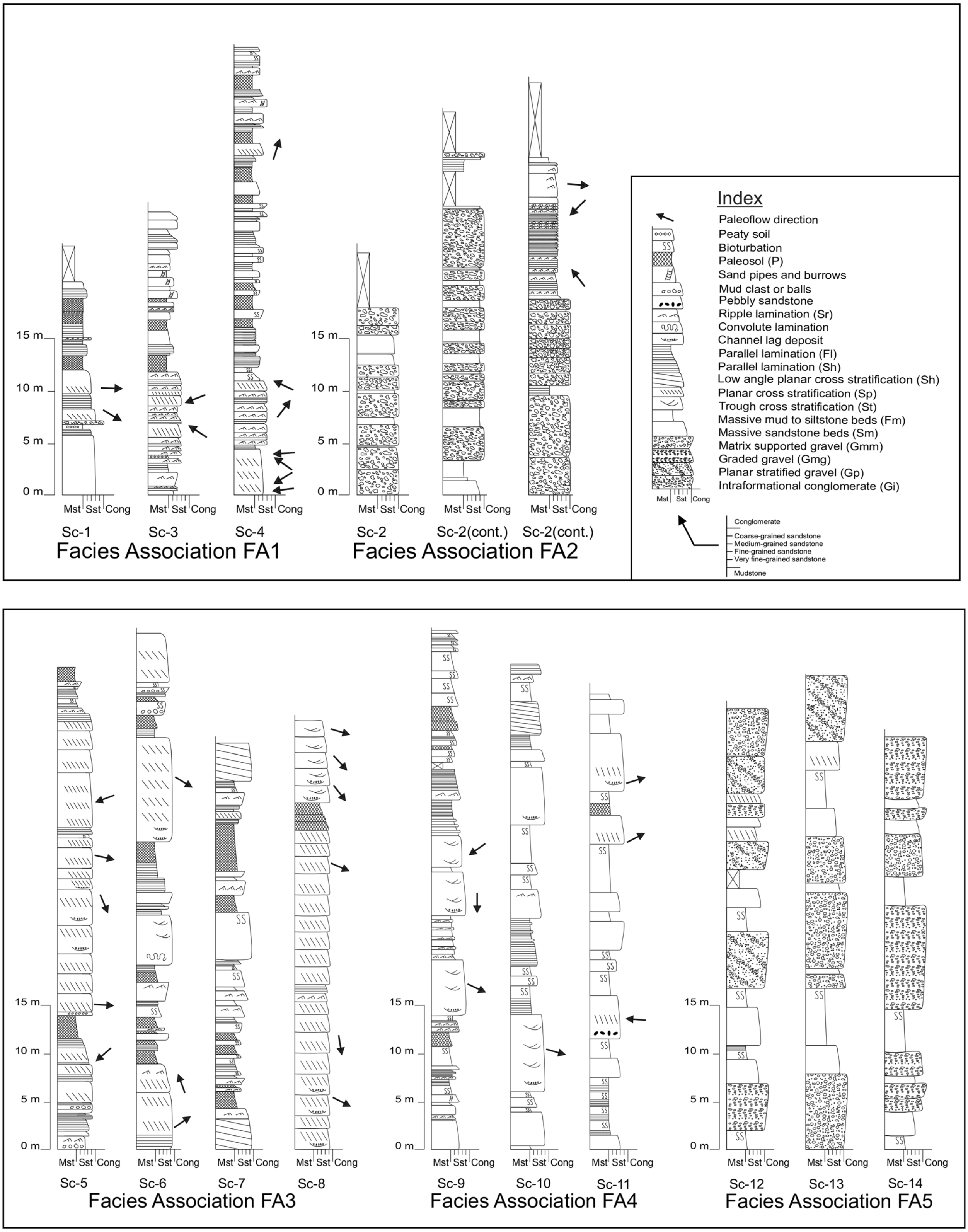


Fig. 3 Representative sedimentological log of the facies association of the Siwalik Group along the Muksar Khola section

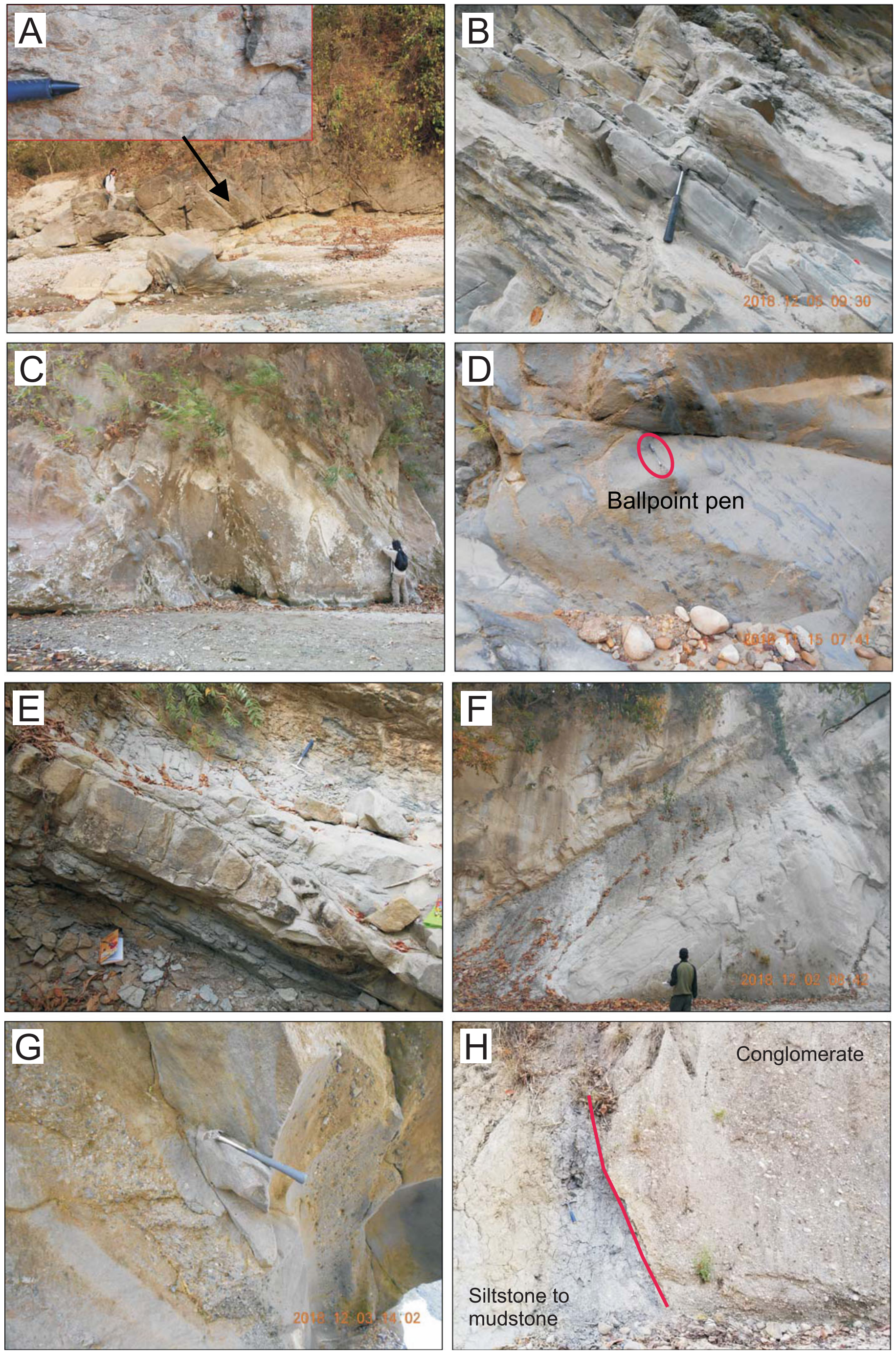


Fig. 4 Outcrop photographs of **A** intraformational conglomerate with mud clast observed in FA2, **B** fine-grained sandstone with parallel to ripple cross-lamination representing levee deposits of FA2, **C** amalgamated sandstone bed observed in FA3, **D** subangular to angular mud clast observed on the base of amalgamated sandstone of FA3, **E** lateral accretion observed in sandstone bed of FA3, **F** fining-upward sequence observed in a very thick bed of sandstone of FA4, **G** sandstone beds with channel lag deposits observed in FA4, **H** siltstone to mudstone bed and matrix-supported pebble to cobble conglomerate of FA5

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 succession with occasional unclear amalgamation surface in the lower section followed by the distinct amalgamation surface in the upper section suggests a shift of the channel. Thick to very thick sandstone beds showing fining-upward succession with channel lags and planer 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 ripple cross-lamination (Fig. 3, Sc-6 & 7) represents crevasse or sheet flow deposits. Very fine- to fine-grained sandstones intercalated with mudstone and showing parallel to ripple cross-laminations suggest levee deposits (Miall 2006). Thick bioturbated mudstone represents overbank deposits. Laminated mudstone represents the waning stage of river floods and swamp deposits. High dispersion of paleoflow direction, fining-upward succession of sandstone with lag and lateral accretion, and thick flood plain deposits with intermittent crevasse deposits resemble the meandering river deposits (Miall 2006). On these bases, FA3 is interpreted as the deposits of the sandy meandering river system.

4.1.4 Facies association 4 (FA4)

4.1.4.1 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. In this facies association, an increase in both the proportion and thickness of mudstones is observed. The overall thickness of mudstone is > 20 m with individual beds ranging from 0.3 to 3.0 m. Mudstones are mostly gleyed and bioturbated, but occasionally, facies Fl is also observed. Variegated mudstones and carbonaceous layers are rare and observed sporadically at the upper section of this facies association.

Sandstones are less indurated compared with sandstones of FA3 and lacks a "salt and pepper" texture. The thickness of sandstone beds ranges from 1.0 to ˃ 5.0 m with well-maintained fining-upward succession (Fig. 4F). Facies St (Fig. 2H) is abundant compared with facies Sp, with pebbly sandstone layers observed as a lens at the base with mostly sub-rounded quartzite clast (Fig. 4G). Very thickly bedded (> 1 m), fine- to coarse-grained sandstones are massive with faint traces of cross-stratification. In the upper portion of these facies association, downstream accretion is observed in these very thick sandstone beds. Thickly bedded medium- to coarse-grained sandstones show coarsening-upward succession with facies Sm or bioturbation. Similarly, fine-grained sandstones are medium- to thickly bedded (30–70 cm) with facies Sr or facies Sh (Fig. 2I) but are mostly bioturbated. These sandstones are associated or interlayered with mudstone beds. Paleocurrent shows the flow direction changed towards southeast from the southwest with high dispersion (Fig. 1B). This facies association FA4 is observed in the upper member of the Middle Siwalik sub-group.

4.1.4.2 Interpretation Coarse- to very coarse-grained sandstone with pebbly lags represents the channel deposits. Massive or bioturbated sandstone showing coarsening-upward succession within mudstone are crevasse or sheet flow deposits (Martin and Turner 1998) representing overbank deposits. Bioturbated fine-grained sandstone with occasional ripple cross-lamination interlayered with laminated or bioturbated mudstone suggests levee deposits. Such thick levee deposits may be the result of a comparatively stable channel. Glayed mudstone suggests the overbank deposits are influenced by a shallow or fluctuating groundwater table (Tabor et al. 2017). Such thick to very thick glayed mudstone may be the result of frequent overbank floods which accumulate fine sediments for long periods and rarely dry out completely (Sinha et al. 2005). Sporadically occurring variegated or carbonaceous layers suggest the long time exposure of flood plain. Crevasse deposits, high dispersion and repeated change in the paleoflow direction (Fig. 1B) show the sinuous nature of the channel. The well-developed fining-upward succession of sandstone beds, with a considerable proportion of flood plain deposits like crevasse or sheet flow, resembles a meandering river. Increase downstream accretion and absence of lateral accretion suggest bar deposits related to the braided river system (Almeida et al. 2016). 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), though the anastomosing river system is hard to demonstrate in the stratigraphic log (Makaske 2001), but Miall (2006) suggested anastomosing river shows channel deposits bounded by large flood plain deposits. In the modern fluvial environment, Sinha et al. (2005) remarked anastomosing rivers are characterized by variable discharge and frequent and widespread overbank flooding. Therefore, FA4 is interpreted as deposits of an anastomosing river system.

4.1.5 Facies association 5 (FA5)

4.1.5.1 Description This facies association is characterized by very thick beds of poorly sorted pebble to cobble conglomerate with very coarse-grained sand to granule matrix. These conglomerate beds are associated with coarse- to very coarse-grained sandstones and dull-yellowish-grey mudstones (Fig. 4H) and mostly show a flat non-erosional basal surface. The clasts are mostly sub-rounded and dominated by quartzite with moderate purple meta-sandstone and a few sandstone, mudstone and gneiss. These conglomerates show facies Gp (Fig. 2J), facies Gmg (Fig. 2K) and facies Gmm (Fig. 2L), but dominating facies are Gmg and Gmm. Facies Gp is rare and only 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 > 5.0 m thick succession. The thickness of sandstones range from 1.0 to 3.0 m (occasionally > 3.0 m) and are almost massive. Few beds showing slight fining-upward succession bears faint planar cross-stratification. Isolated pebbles are abundant in sandstone, sometimes up to pebbly sandstone. Mudstones are thickly bedded (> 4 m) and bioturbated without any pedogenic features. This facies association FA5 is observed in the Upper Siwalik sub-group.

4.1.5.2 Interpretation A 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 succession represents bar deposits of the braided river system (Nakayama and Ulak 1999). Thick bioturbated mudstone represents flood plain deposits (Miall 2006). Domination of poorly sorted conglomerate with inverse grading is observed in this facies association. Thus, FA5 is interpreted as a deposit of the debris flow-dominated gravelly braided river system. The presence of thick mudstone beds within the conglomerate beds will be further discussed in the Discussion section.

4.2 Depositional process

Facies analysis of sedimentary succession is a useful tool to understand the depositional environment. Based on this analysis, three fluvial systems namely the meandering river, the anastomosing river and the braided river are recognized, responsible for the deposition of the Siwalik Group of rocks in the Muksar Khola section (Fig. 5). Deposition began with flood plain-dominated fine-grained meandering river system (FA1). This river system encountered a large-scale flood depositing very thick successions of intraformational conglomerate at around 10.5 Ma as flood-dominated overbank environment (FA2). The magnetostratigraphy established by Ojha et al. (2009) does not cover the Lower Siwalik sub-group section deposited before 10.0 Ma. Therefore, using their oldest sedimentation rate of 0.33 mm/year and the thickness of 210 m from the sedimentological log of Rai and Yoshida (2020), a tentative age of 10.6 Ma is calculated. Although this age is quite speculative due to the lack of proper age data and uncertainties on the sedimentation rate, evidence from other studies (that are discussed later) suggests this age is comparable to 10.5 Ma. The dominance of the sandy beds in the meandering river system (FA3) 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. 5). 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 was excluded by various researchers (e.g., Quade et al. 1995; Robinson et al. 2001; Chirouze et al. 2012). As mentioned above, formation of an intraformational conglomerate is related to the collapse of the distal alluvial terraces. Alluvial terraces are developed as a result of cyclic deposition of sediments and incision of the plain (Oldknow and Hooke 2017). The cause of incision in the alluvial plain of the Himalayan foreland basin can be a complex issue because various factors like climate, tectonics and eustatic fluctuations govern such incision (Mukerji 1990; Miall 2006; Tandon et al. 2006; Oldknow and Hooke 2017). In the present study area, the occurrence of such a 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). Zaitlin et al. (1994) suggested rivers proximal to coastal areas undergo incision during the fall of sea level and aggradation as sea-level rises. If the deposition of the Lower Siwalik sub-group was proximal to the coastal area and affected by the sea-level fall and subsequent sea-level rise, then these sub-group sediments must have recoded some tidal effects (Simms et al. 2006; Guliotta et al. 2016). But, such tide-influenced deposits are not observed in the present study. Moreover, in the case of rapid sea level fall (Fig. 5), the resulting river incision is narrow and V-shaped valleys rather than terrace morphology (Simms et al. 2006).

On the other hand, incisions due to climatic effects are mediated through variations in fluvial transport capacity. When the discharge exceeds that needed for

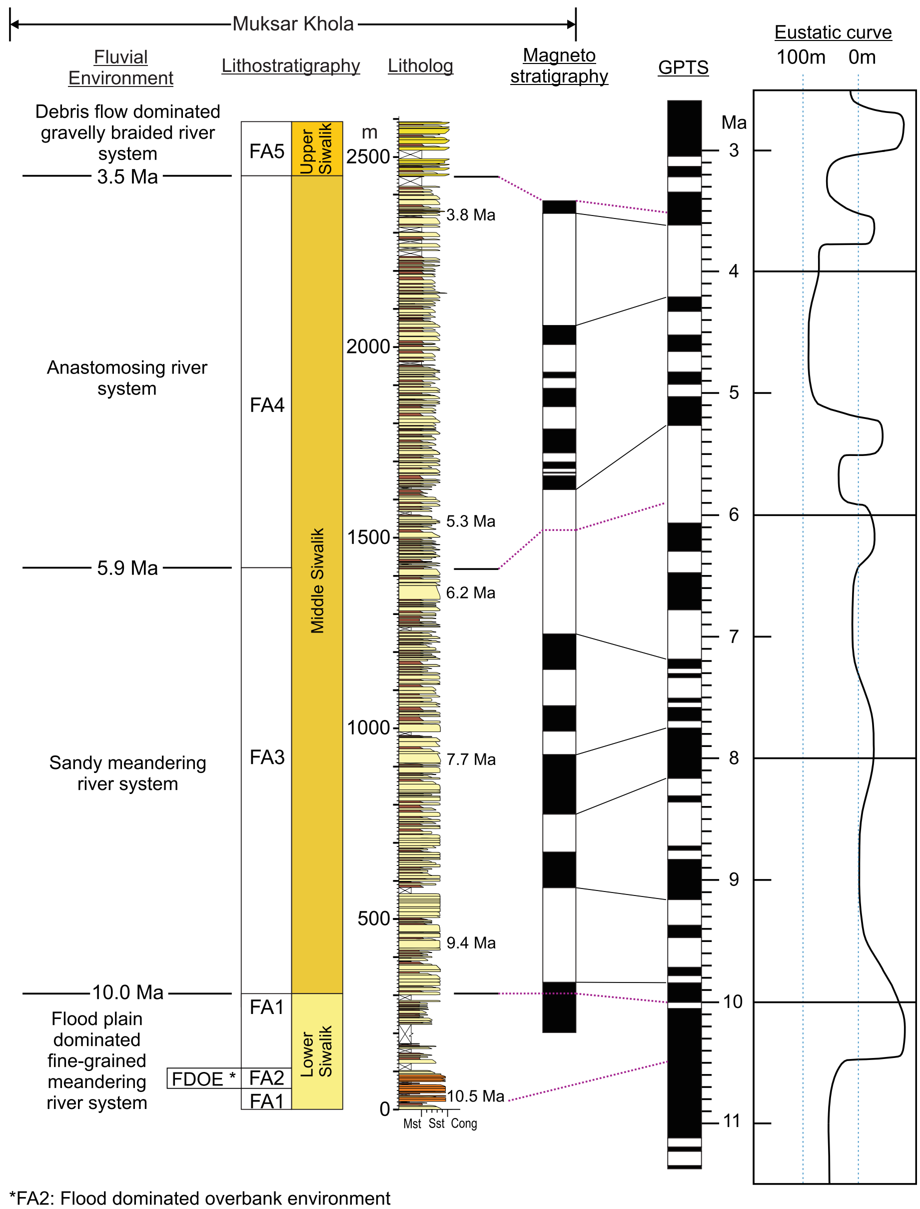


Fig. 5 Evolution of the fluvial style in the present study area based on a magnetostratigraphic time frame (modified from Ojha et al. 2009), GPTS (modified from Lourens et al. 2004) and the eustatic curve (modified from Haq et al. 1988)

transport of the available sediment, the river promotes incision, whereas large sediment pluses can overwhelm the transport capacity of the system and cause aggradation (Bogaart et al. 2003). Generally, an increase in water discharge or high-magnitude flood is triggered only during abnormal or strengthened monsoon season (Plink-Bjorklund 2015). In the western Ganga plains, increased precipitation with monsoon intensification was reported as the controlling factors for the river incisions developed around 10.0 to 5.0 ka (Tandon et al. 2006). The occurrence of massive coarse-grained sheet flow deposits within the intraformational conglomerate beds (Fig. 3, Sc-1) also suggest 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). Therefore, intensification of monsoon resulting in high discharge should have favoured the river incision on the foreland basin creating alluvial terraces. During the occasional high flood event when water level drastically rises, it submerse the overbank and undercut the distal alluvial terrace. This subjects to the collapse of the distal alluvial terrace. The dramatic increase in sediment proportion due to this terrace collapse as well as an increase in the distance from the main channel overwhelm the transport capacity of the river resulting in aggradation of the thick intraformational conglomerate. Therefore, the occurrence of this intraformational conglomerate in the present study area at around 10.5 Ma should be related to high-magnitude floods, suggesting the monsoon intensification in the eastern Nepal Himalaya. Though there is no evidence of tide-influenced deposits in the present study area, the effect of sea-level change cannot be denied considering the location of the present and Darjeeling-Sikkim area. The change in the sea level probably affected the regional base level of the foreland basin favouring incision.

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 Jr 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. 5). Therefore, the low gradient of the foreland basin due to sea-level rise and absence of the hinterland exhumation must be the reason for the meandering river system before 10.0 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 (Chirouze et al. 2012). 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). This fast exhumation of the hinterland in the eastern Nepal Himalaya could have increased the channel slope and the sediment supply, resulting in a domination of the braided river system similar to western and central Nepal. But, the tectonic history of eastern Nepal is quite different from central and western Nepal. In western and the central Nepal Himalaya, observed 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, this hinterland exhumation observed during the deposition of the lower member of the Middle Siwalik sub-group was due to the activation of the Sun Koshi Thrust (Rai et al. 2021). Therefore, the possible explanation may be asymmetric subsidence (Burbank 1992) of the foreland basin in the 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 with 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 the eastern Nepal Himalaya compared with western and the central Nepal Himalaya. Therefore, the activation of the out-of-sequence thrust and absence of duplex structure in the 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 episodic occurrence of a very thick succession of amalgamated sandstone beds within the sandy meandering river system (FA3) at ca. 9.4 Ma, 7.7 Ma and 6.2 Ma suggest 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 and consists of two processes: erosion of inter-sand mudstone barriers and amalgamation of sandstone beds which were previously separated by the mudstone barriers (Zhang et al. 2017). As discussed above, the gradual change in the amalgamation surface from bottom to top suggests lateral shifting of the channel. But such autogenetic effects like sinuosity changes, lateral migration, accretion, and erosion is controlled by seasonal fluctuations in discharge (Slingerland and Smith 2004; Durkin et al. 2017). The subangular to angular elongated mud clasts (up to 20–30 cm in length) observed on the base of the amalgamated sandstone (Fig. 4D) also suggest the erosive nature of the flow giving evidence of flood as discussed above. Other than this, the occurrence of these thick succession of amalgamated sandstone successions in the present study is coeval to the timing of sea-level fall and rise (Fig. 5). 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. Since the fluctuation of sea level should have a regional impact in the foreland basin, therefore such phenomena should be observed in the other Siwalik section. Previous studies along the Siwaliks in this time frame report domination of braided river system in the central and western Nepal Himalaya

Table 3 Comparison of the fluvial environment of present study area with the Surai Khola section and the Karnali River section

Age (Ma)	Karnali River Huyghe et al. (2005)	Karnali River Sigdel and Sakai (2016)	Surai Khola Nakayama and Ulak (1999)	Muksar Khola Present Study
1	Gravelly braided fluvial system	Debris flow dominated braided river system	Debris flow dominated braided river system	(grey)
2	~3.9 Ma	~2.0 Ma	1.0 Ma	Debris flow dominated gravelly braided river system
3	Anastomosed system	Gravelly braided river system	Gravelly braided river system	3.5 Ma
4	5.5-5.6Ma	~3.9 Ma	2.5 Ma	Anastomosing river system
5	SSBFS *	Shallow sandy braided river system	Anastomosed river system	5.9 Ma
6	6.4 Ma	6.0 Ma	4.0 Ma	Sandy meandering river system
7	Deep sandy braided fluvial system	Deep sandy braided river system	Shallow sandy braided river system	10.0 Ma
8	9.5 Ma	9.6 Ma	Deep sandy braided river system	FDOE ***
9	Sandy flood flow-dominated meandering fluvial system	Flood flow dominated meandering river system	6.5 Ma	Flood plain dominated fine-grained meandering river system
10	12.6-12.7 Ma	13.5 Ma	Flood flow dominated meandering river system	(grey)
11	FFDMFS **	Fine grained meandering river system	9.5 Ma	
12	13.1 Ma		Fine grained meandering river system	
13	Fine grained meandering river system with low discharge and relief		(grey)	
14				
15				

*Shallow sandy braided fluvial system
**Flood flow-dominated meandering fluvial system
***Flood dominated overbank environment

(Nakayama and Ulak 1999; Sigdel and Sakai 2016). Contrary to this, the Siwaliks in the eastern Himalaya were deposited under deltaic or open marine conditions till 5.0 Ma at Bhutan and 7.5 Ma at the Kameng River section of Arunachal Pradesh (Coutand et al. 2016; Taral et al. 2019). In the Tista valley of the Sikkim-Darjeeling area and the Kameng River sections, fluvial and deltaic environment transition is reported until the deposition of the lower part of the Upper Siwaliks (Taral et al. 2018, 2019). The present study lacks such direct evidence of deltaic or marine deposits to directly connect with sea-level change. But, the observed lithological variation in the present study which is synchronous to sea-level change suggests it should have some influence on the geometry of the foreland basin. Therefore, the occasional occurrence of very thick successions of the amalgamated sandstone should have resulted from the interplay of high discharge and sea-level rise in an asymmetrically subsidized foreland basin. 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 (Fig. 5) or the shift of depositional area more proximal to the hinterland. If we see the eustatic curve, the rate of sea-level fall around 8.4 Ma and 6.4 Ma is not as drastic as observed around 10.5 Ma. Also, the dominating grain size of FA3 is medium- to coarse-grained sandstone suggesting depositional area somewhere upstream to the depositional area of FA1, suggesting a shift of the depositional area more proximal to the hinterland.

Anastomosing of rivers are controlled by 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 an avulsion increases with an increase in the sedimentation rate (Bridge and Leeder 1979; Bryant et al. 1995) and the base level rise (Tornqvist 1994; Makaske 2001). The base level rise may be due to the rise in the sea level (Smith and Smith 1980) and the subsidence of the foreland basin (Smith 1986). Anastomosing rivers reported in the modern fluvial environment of the Himalaya foreland basin also suggest sedimentological readjustment and tectonic subsidence of the foreland basin as the major controlling factors (Jain and Sinha 2004; Sinha et al. 2005). The rise in the sea level (Fig. 5) and the subsidence of the foreland basin after ~ 5.5 Ma in eastern Nepal fulfil the conditions needed for the rise in the base level of the foreland basin. Regarding the sedimentological readjustment, an increase in seasonality observed as a shift of C3 plants to C4 plants can be considered. An increase in seasonality suggests strengthening of monsoon (Quade et al. 1989, 1995) and an arid to a semiarid climatic condition, where bankfull discharge rarely exceeds more than once a year (Gibling et al. 1998) which occurs during the high magnitude floods triggered by a strengthened monsoon. During normal conditions, deposition of the sediments takes place in-channel. Consequently, the channel loses the capacity to accommodate more sediments in the next flood and becomes 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). Therefore, the rise in the base level along with the strengthening of monsoon during the deposition of the upper member of the Middle Siwalik sub-group must have favoured anastomosing river system in the present study area.

The eustatic curve after 6.0 Ma shows three events of the sea-level change (Fig. 5). These are more precise than those observed during the deposition of FA3. Considering our previous discussion, the effects of sea-level change should have brought some lithological variation, but such variation as in FA3 is absent. The probable consideration might be the shift of the depositional area more proximal to the hinterland with an increase in the distance from the sea. The overall rise in the sea level from 6.0 to 3.0 Ma resulted in the base level rise of the foreland basin on the regional scale. But the possible effects of such sea-level change around 5.3 Ma, 3.6 Ma and after 3.0 Ma was overprinted due to the hinterland tectonics and climatic controls. 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 gravels were supplied mainly from the Lesser Himalaya Sequence. 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. Studies along the Siwalik section in central and western Nepal mention limited thickness or absence of such sandstone and mudstone beds in the Upper Siwalik sub-group (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 conglomerates are reported in both paleo and modern fluvial systems (Singh et al. 1993; Nakayama and Ulak 1999; 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 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 the large river systems. Willis (1993b) suggested small rivers exist in the fan and interfan areas that drain 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.

Such gravel progradation is also reported in the Nalad Khad and Jawalamukhi sections of the Himachal Pradesh (Brozovic and Burbank 2000). Brozovic and Burbank (2000) suggested three conditions for such progradation of gravels: (1) increase in the discharge and sediment flux of rivers due to climate change, (2) initiation of the MBT which 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 the 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. 2021), therefore there is no possibility for the development of the erosional relief. For the third condition, if we see the hinterland tectonics of the eastern Nepal Himalaya, formation of the duplex structure at the rear of the Himalaya was observed after 4.0 Ma (Rai et al. 2021). Therefore, this duplex structure should have slow down the thrusting along 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

From the above discussion, we came up with the following conclusions.

Five facies associations 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 evidence of a high-magnitude river flooding suggesting intensification of monsoon took place at 10.5 Ma in the eastern Nepal Himalaya as a result of uplift of the eastern Nepal Himalaya.

The present study shows the hinterland tectonics and climate and sea-level change have 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 asymmetric subsidence of the foreland basin due to the 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 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.

Acknowledgements
We thank Baburam Gyawali, Kshitiz Timsina and Manish K.C. for their assistance during fieldwork, and anonymous reviewers who significantly improved the manuscript and are gratefully acknowledged. We also acknowledge DMG (Nepal) for documentation of samples to bring to Japan. We also thank the Ministry of Education, Culture, Science and Technology of Japan for granting a Monbukagakusho (MEXT) Scholarship for PhD study to the first author.

Authors' contributions
The first author, LKR, 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, LKR, under the supervision of the second author, KY. Both authors read and approved the final manuscript.

Funding
This study is supported by the Japan Society for Promotion of Science (Nos. 18KK0096 and 17K05678). But, the authors declare it does not influence the results of this study.

Availability of data and materials
All data generated or analysed during this study are included in this manuscript.

Declaration

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Department of Science and Technology, Graduate School of Medicine, Science and Technology, Shinshu University, Matsumoto, Japan. [2]Institute of Science, School of Science and Technology, Shinshu University, Matsumoto, Japan.

Received: 20 January 2021 Accepted: 18 August 2021
Published online: 01 September 2021

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