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Lithostratigraphy of the Siwalik Group along the Muksar Khola section, Siraha-Udayapur districts, eastern Nepal Himalaya

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ABSTRACT

The Siwalik Group extending east to west co-linear to the main Himalayan range is well exposed along the Muksar Khola section, Siraha-Udayapur district, eastern Nepal Himalaya. The Siwalik Group in the present study area is divided into the Lower, Middle, and Upper Siwaliks based on the grain size and the proportion of sandstone-mudstone.The Lower Siwaliks is characterized by very fine- to fine-grained, light grey sandstone interbedded with dark grey to olive black mudstone. The Middle Siwaliks, is characterized by the domination of fine- to coarse-grained sandstone, and based on the lithology and bed thickness it is divided into two members. The lower member is dominated by fine- to medium-grained "salt and pepper" sandstone with dark greenish to olive-grey mudstone while, the upper member is dominated by light grey to white medium- to coarse-grained sandstone with grey, dark grey to black mudstone. An increase in the grain size and thickness of sandstone beds, an increase in the proportion of mudstone, a decrease in induration of sandstone and a decrease in the proportion of biotite grain in sandstone makes the upper member different from the lower member of the Middle Siwaliks. The Upper Siwaliks is characterized by very thick beds of clast supported conglomerate associated with coarse- to very coarse-grained, very thick bedded sandstone and dull yellowish-grey to grey mudstone. The boundary between the Lower and the Middle Siwaliks, lower and upper members of the Middle Siwaliks, and the Upper Siwaliks are 10.0 Ma, 5.7 Ma, and 3.5 Ma, respectively. The present study records the presence of a large succession of intra-formational conglomerate succession in the Lower Siwaliks.

Keywords: Siwalik group; Lithostratigraphy; Intra-formational conglomerate; Muksar khola; Eastern Nepal

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INTRODUCTION

The Siwalik Group consists of the molasses sediments derived from denudation of the tectonically uplifted Himalayan range (Gansser, 1964; Prakash et al., 1980; Corvinus, 1993: Baral et al., 2015, 2017; Neupane et al., 2016). These sediments were deposited by the fluvial systems, which show overall coarsening upward succession with individual beds showing fining upward succession (Tandon, 1976; Prakash et al., 1980; Tokuoka et al., 1990; Hisatomi and Tanaka, 1994; Willis, 1993b, Nakayama and Ulak, 1999). These molasses sediments were deposited during middle Miocene to early Pleistocene (Appel and Rosler, 1994; Gautam and Appel, 1994; Rosler et al., 1997; Gautam and Fujiwara, 2000; Ojha et al., 2009). The Siwalik groups of rocks form the southernmost hill range extending east to west are co-linear to the main Himalayan range with varying thickness (Dhital, 2015). This thickness is comparatively less towards the eastern part of the Himalayan range as compared to western counterpart, ranging from 20 km to the west to less than 1 km in the east (Dhital, 2015). Beds generally are north dipping with a decrease in dip amount towards younger succession (Dhital, 2015). Tectonically the Main Frontal Thrust (MFT) in the south and Main Boundary Thrust (MBT) in the north bounded these groups of rocks separating it from the Gangetic plain and the Lesser Himalayan rocks respectively (Gansser, 1964; Le Fort, 1975; Valdiya, 1980). This Siwalik Group is further divided into two belts by the Main Dun Thrust (MDT; Hérail and Mascle, 1980) or Central Churia Thrust (CCT; Tokuoka et al., 1986). Other thrust such as Kamala Tawa Thrust (KTT) is also reported in Siwalik section (Muksar Khola section) further duplicating the Siwalik Group into three belts (Shrestha and Sharma, 1996).

Lithostratigraphy of the Siwalik Group in the Nepal Himalaya has been established by various researchers (Glinnie and Ziggler, 1964; Tokuoka et al., 1990; Corvinus, 1993; Sah et al., 1994; Dhital et al., 1995; Ulak and Nakayama, 1998; Ulak, 2004; 2009; Sigdel et al., 2011; Adhikari and Sakai, 2015, Adhikari et al., 2018). These studies have resulted in two-fold to five-fold classification of the Siwalik Group. Different researchers studied the Siwalik Group along the Muskar Khola section (Quade et al., 1995; Shrestha and Sharma, 1996; Robinson et al., 2001; Ojha et al., 2009; DMG, 2011; Chirouze et al., 2012), but none of these studies described the lithostratigraphy in detail. Therefore, this study is focused on a detailed lithological description and a stratigraphic classification of Siwalik succession based on classical threefold classification, which was previously used in the study of the different Siwalik section (Pilgrim, 1908, Hagan, 1951; Shrestha and Sharma, 1996; Ulak, 2004; Ulak, 2009; Adhikari et al., 2018).

GEOLOGICAL SETTING

The study area lies in the eastern part of the Nepal Himalaya (Fig. 1). In this area, the MDT and the KTT divide Siwalik Group into three belts, namely: northern, middle and southern belt (Shrestha and Sharma, 1996). The northern belt bounded by the MBT to the north and the KTT to the south comprises the Lower Siwaliks and the Lower Middle Siwaliks. The middle belt bounded by the KTT to the north and the MDT to the south comprise Lower Siwaliks. All three litho units are observed in the southern belt, bounded by the MDT on the north and MFT on the south. This study is carried out on the southern belt (> 4 km thick) along the Muksar Khola section. Ojha et al., (2009) conducted the paleomagnetic dating in this section, which was limited to the Middle Siwaliks (~2500 m thick) indicating the deposition age between 10.0-3.5 Ma.

METHOD

Field data were acquired during the geological traverse along the Muksar Khola section. A route map and a detail sedimentological log of the entire section were prepared and precisely divide the lithological units. Rocks were classified into mudstone, sandstone and conglomerate based on grain size and composition. The colour of mudstone was determined using the Munsell colour chart**.** Variations in the lithological characteristics were taken as the basis for classification of rock units into member and litho units. The paleomagnetic data by Ojha et al. (2009) was used to determine the specific age for each litho units and the members, which was further used for regional correlation with the other sections of the Nepal Himalaya.

LITHOSTRATIGRAPHY

The present study describes the lithostratigraphy of the Siwalik Group of southern belt, south of the MDT along the Muksar Khola section. Three lithostratigraphic units i.e., Lower, Middle and Upper Siwaliks are recognized in the area. Figures 2 and 3 show the geological map, depositional age and figures 4, 5, 6 and 7 show the detailed sedimentological logs of each litho units respectively.

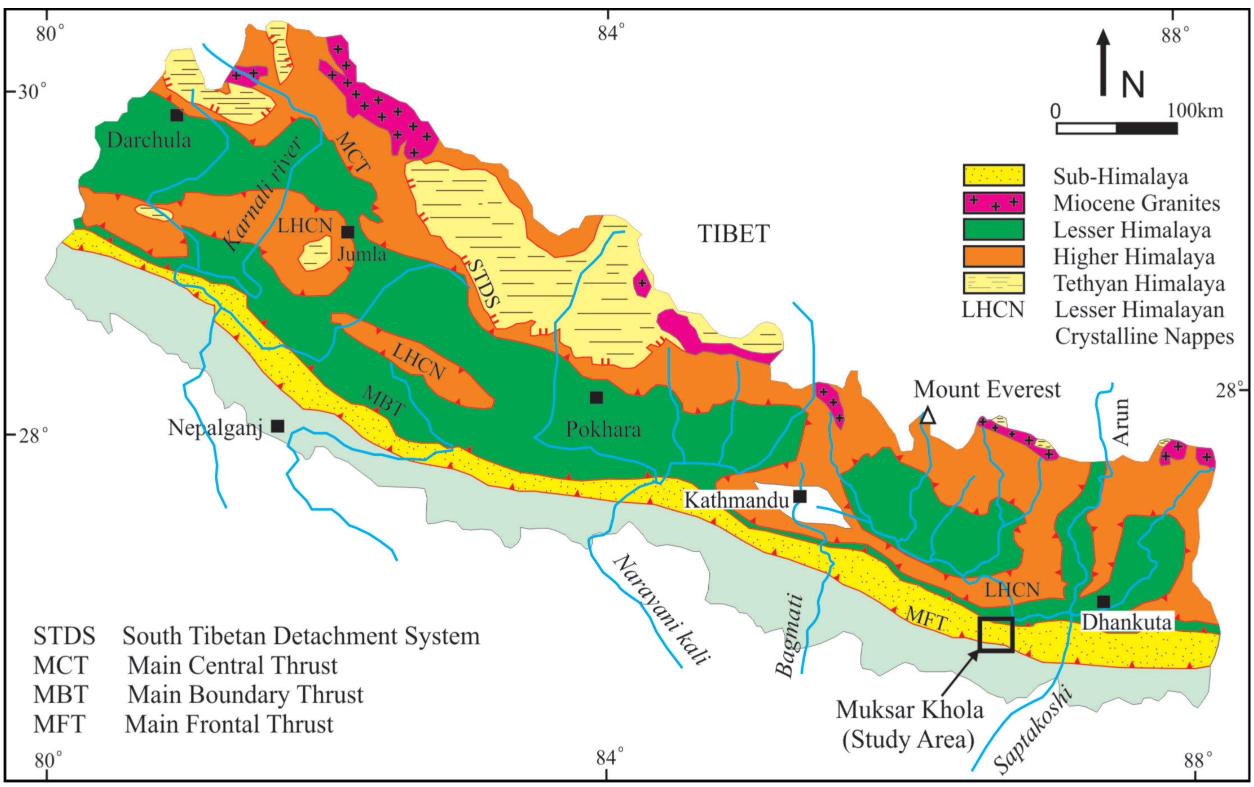


Fig. 1: Simplified geological map of Nepal (modified from Amatya and Jnawali, 1994), showing the location of the Muksar Khola section.

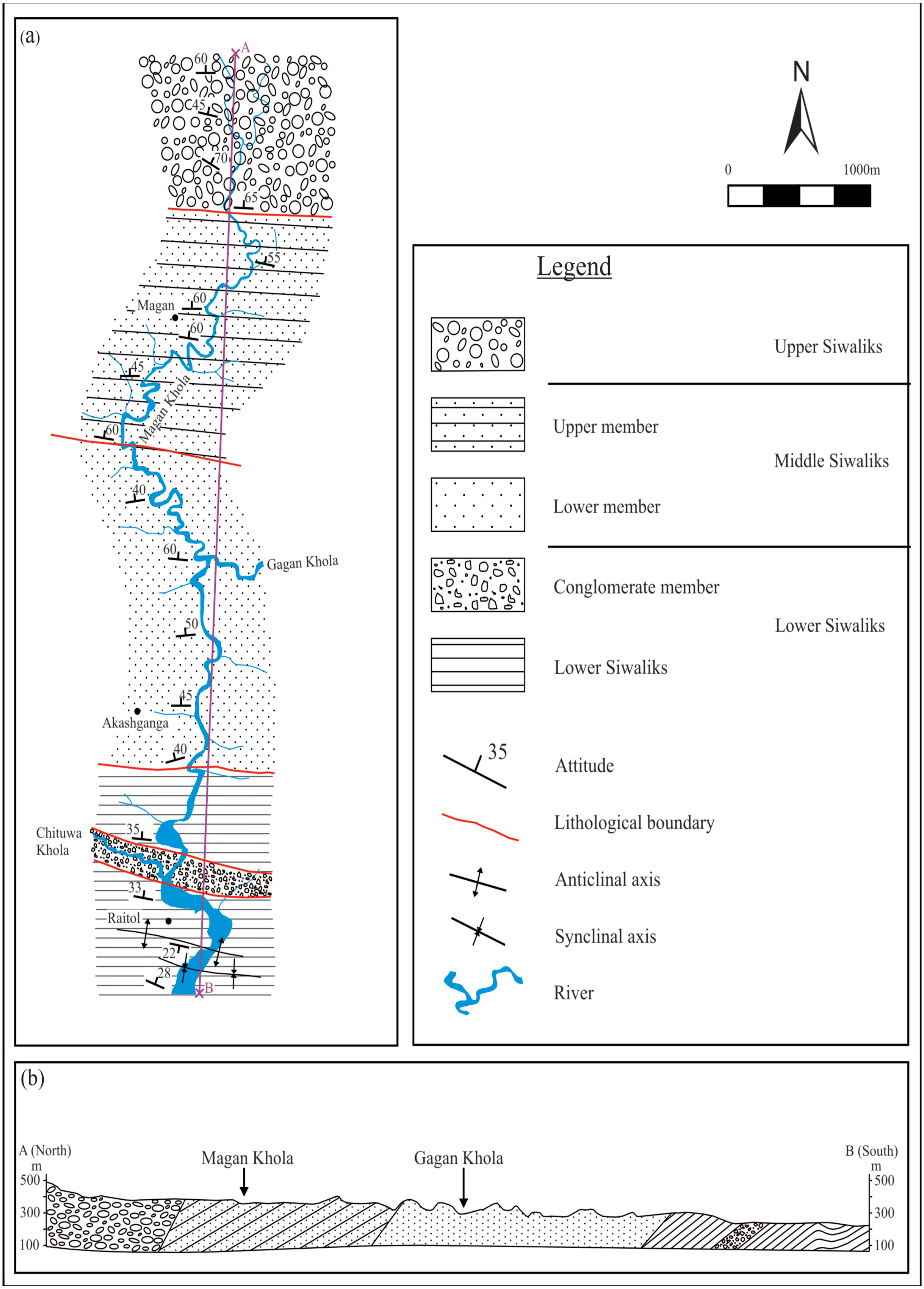


Fig. 2: (a) Geological Map along the Muksar Khola section (b) Cross-section along A-B.

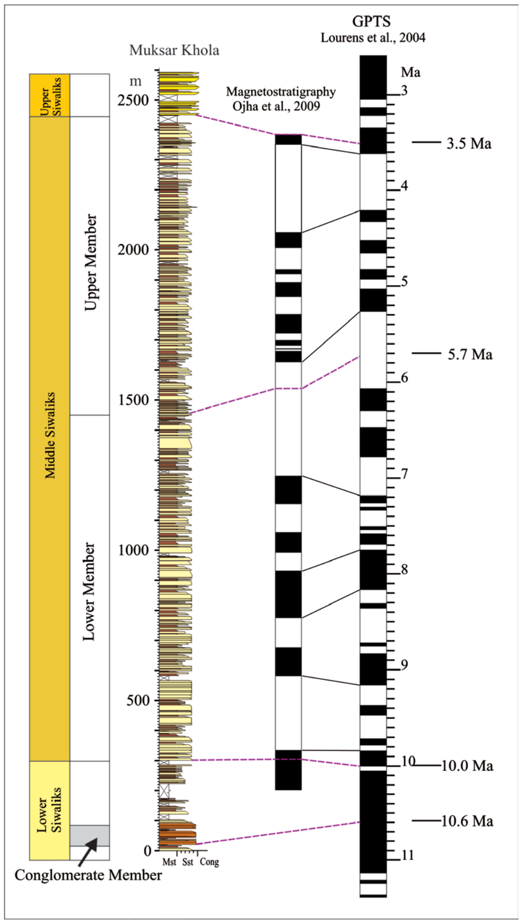


Fig. 3: Lithostratigraphic division of the Siwalik Group along the Muksar Khola section with respect to the magnetostratigraphic age data (modified after Ohja et al., 2009).

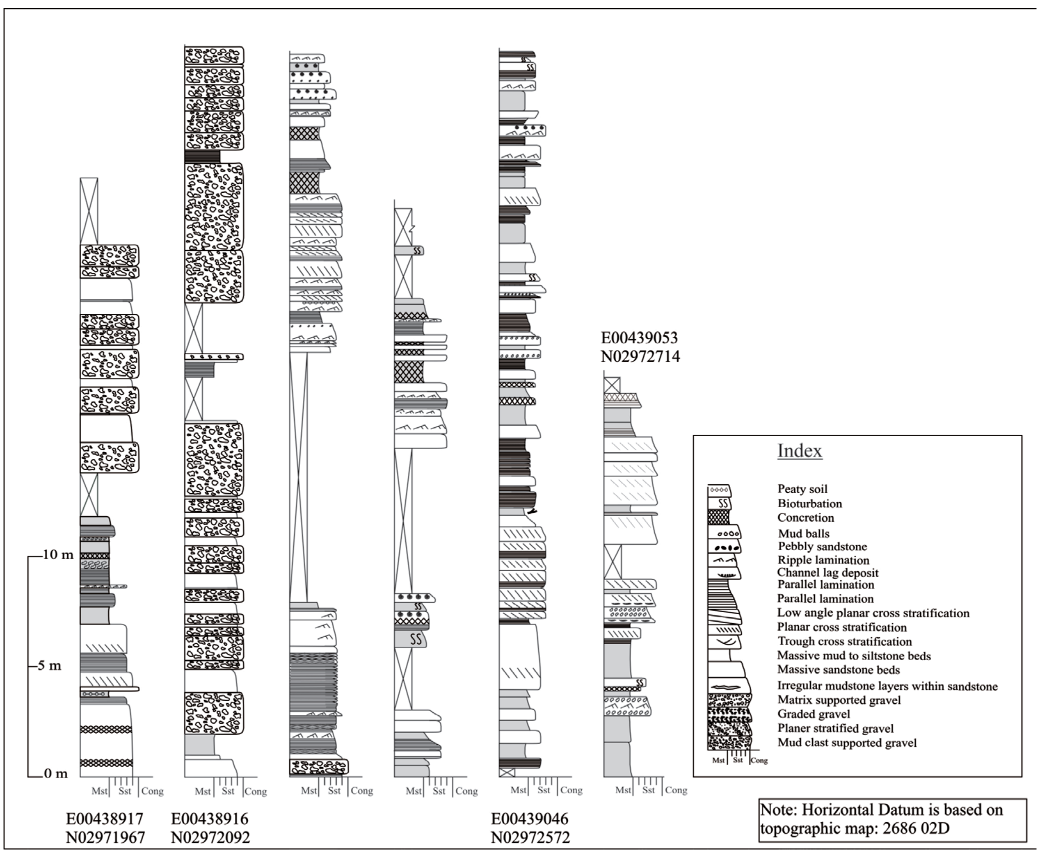


Fig. 4: Detailed sedimentological log (representative) of the Lower Siwaliks including the conglomerate member.

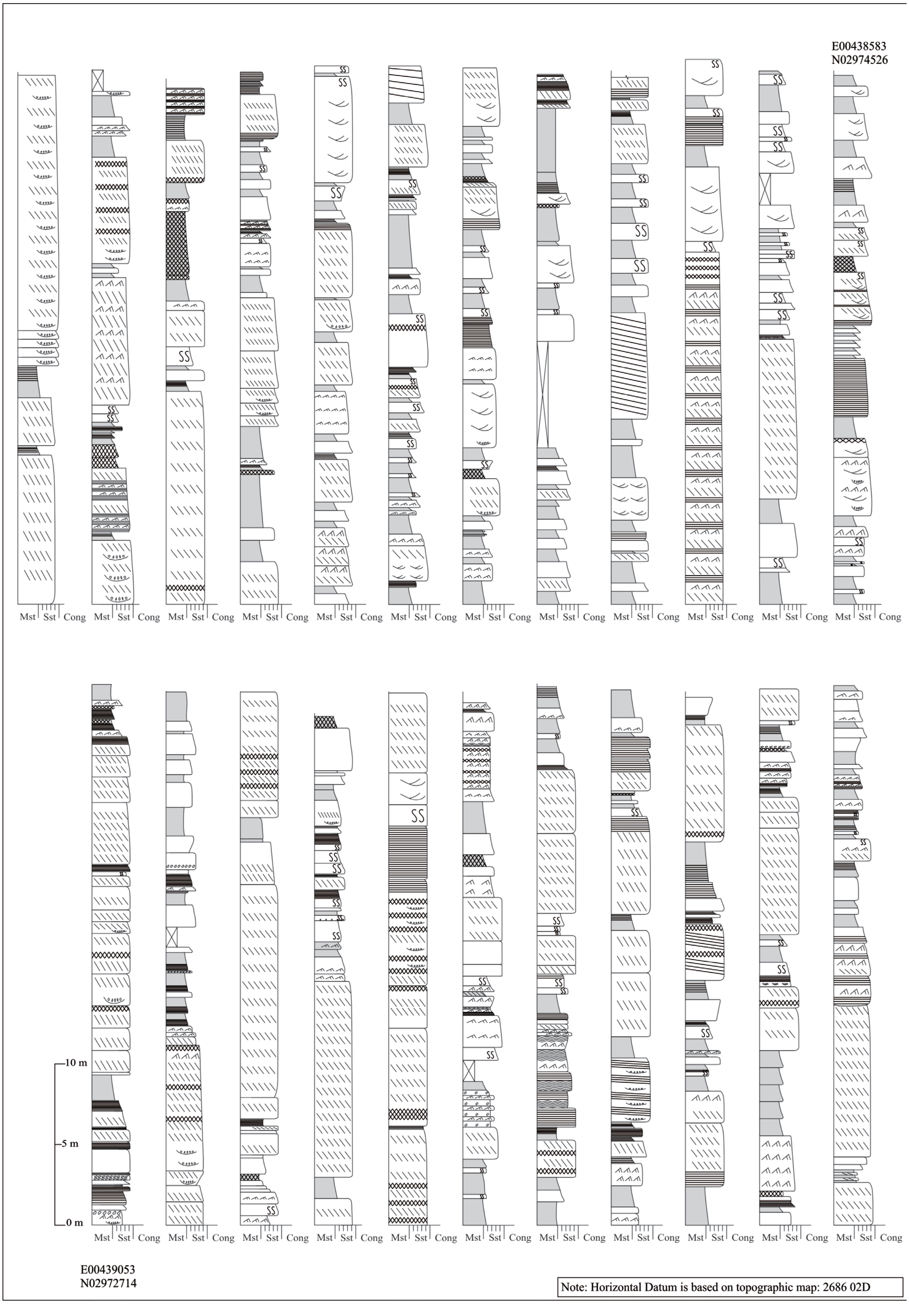


Fig. 5: Detailed sedimentological log (continuous) of the lower member of the Middle Siwaliks.

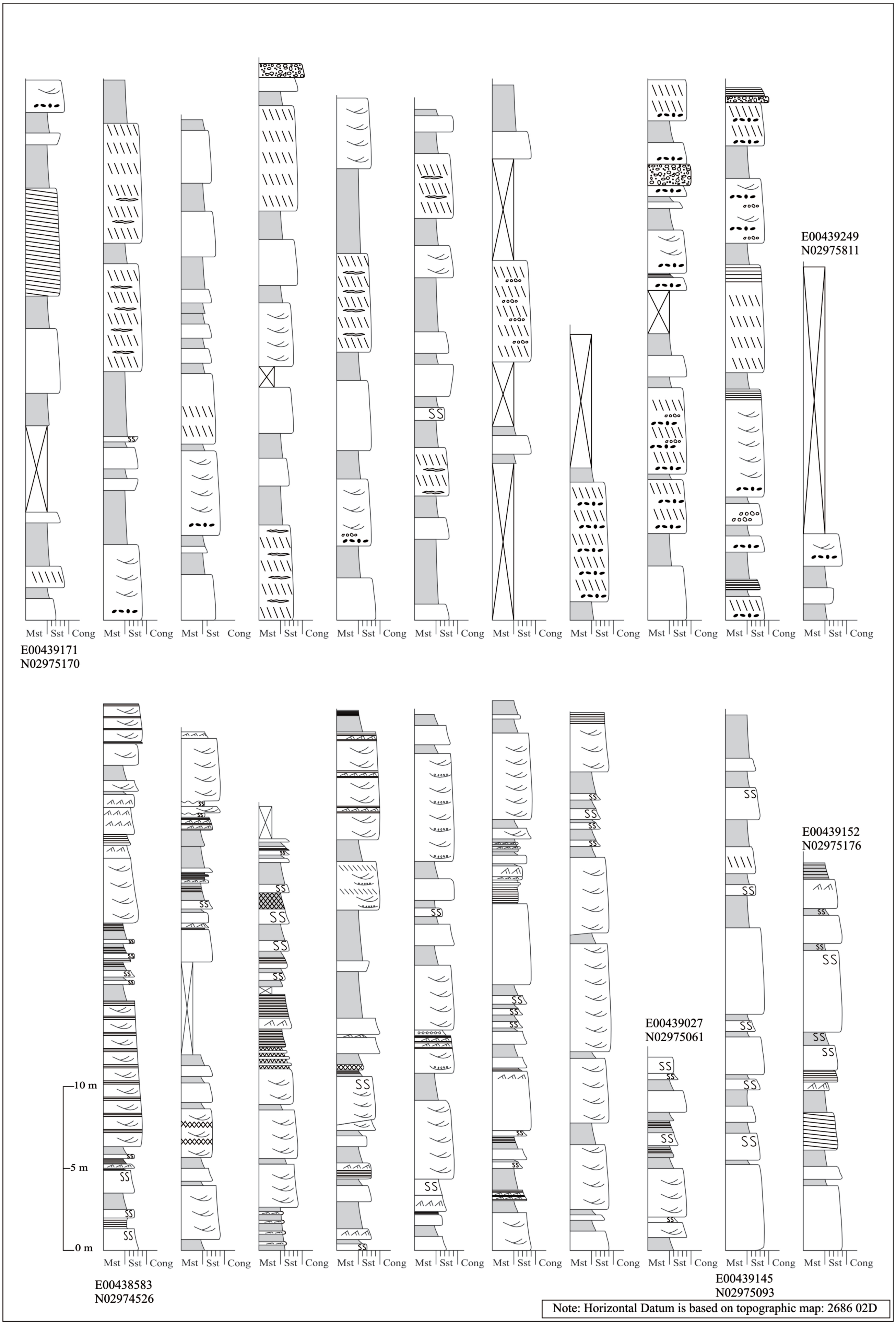


Fig. 6: Detailed sedimentological log (continuous) of the upper member of the Middle Siwaliks.

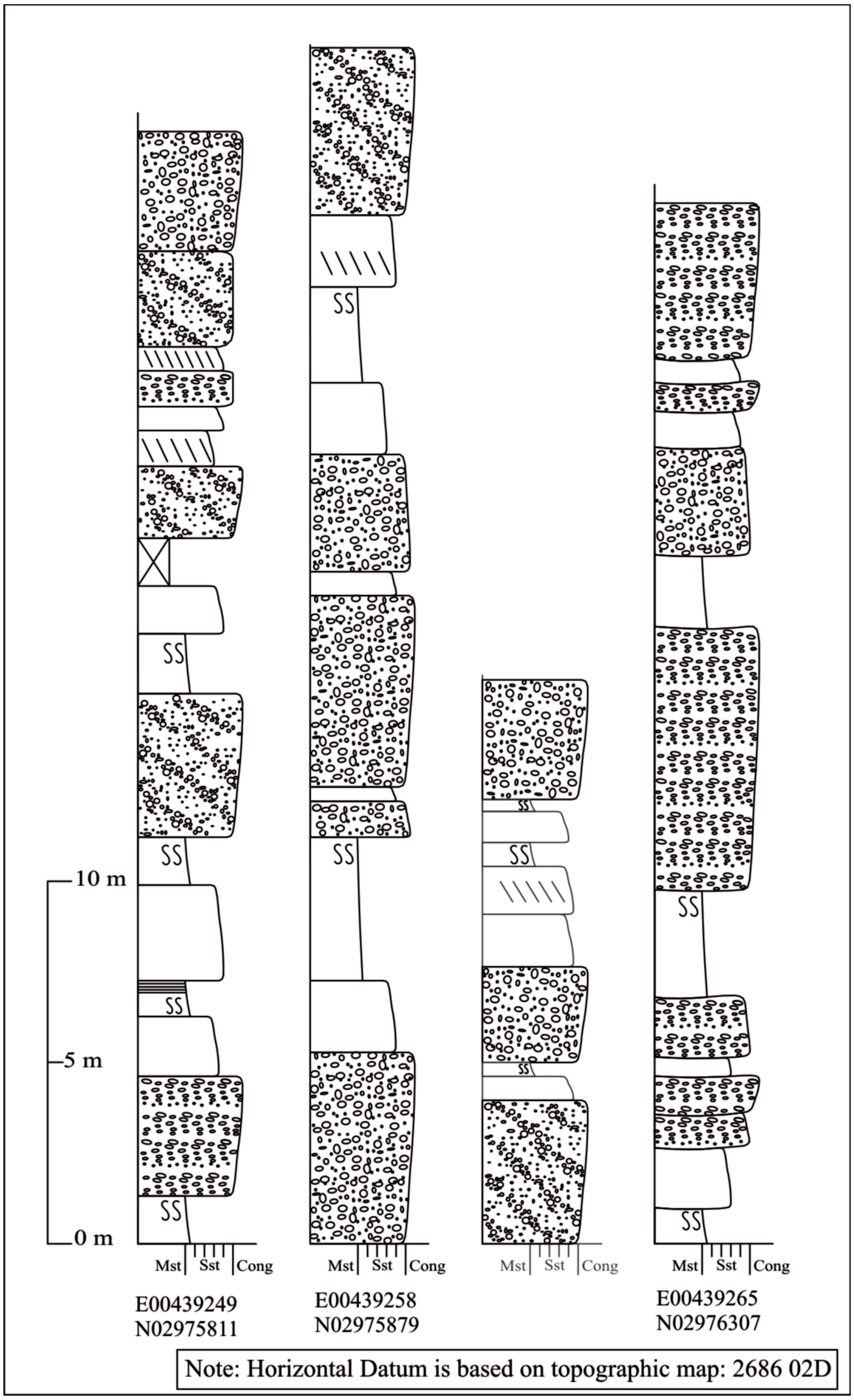


Fig. 7: Detailed sedimentological log (representative) of the Upper Siwaliks.

Lower Siwaliks

This litho unit is well exposed along the Muksar Khola near the Gola and Raitol villages (Fig. 2). The thickness of this unit attains > 400 m, with a distinctive conglomerate member at upper section. This unit is dominated by the mudstone and fine-grained sandstone (Fig. 8a) with intra-formational conglomerate (Fig. 8b). The unit was deposited before 10 Ma (Fig. 3; Ojha et al., 2009).

The main lithology of the Lower Siwaliks is characterized by very fine- to fine-grained, light-grey coloured sandstone interbedded with dark grey to olive black mudstone to siltstone (Fig. 4). Very fine-grained sandstone beds are 0.30-0.80 m thick, whereas fine-grained sandstone beds are average of 1.0 m thick. Fine- to medium-grained sandstone beds are 1.0 -1.5 m thick on average (occasionally ~4.0 m thick). In the lower section, around the axis of low angled anticline (Fig. 9a), "salt and pepper" texture, fine- to medium-

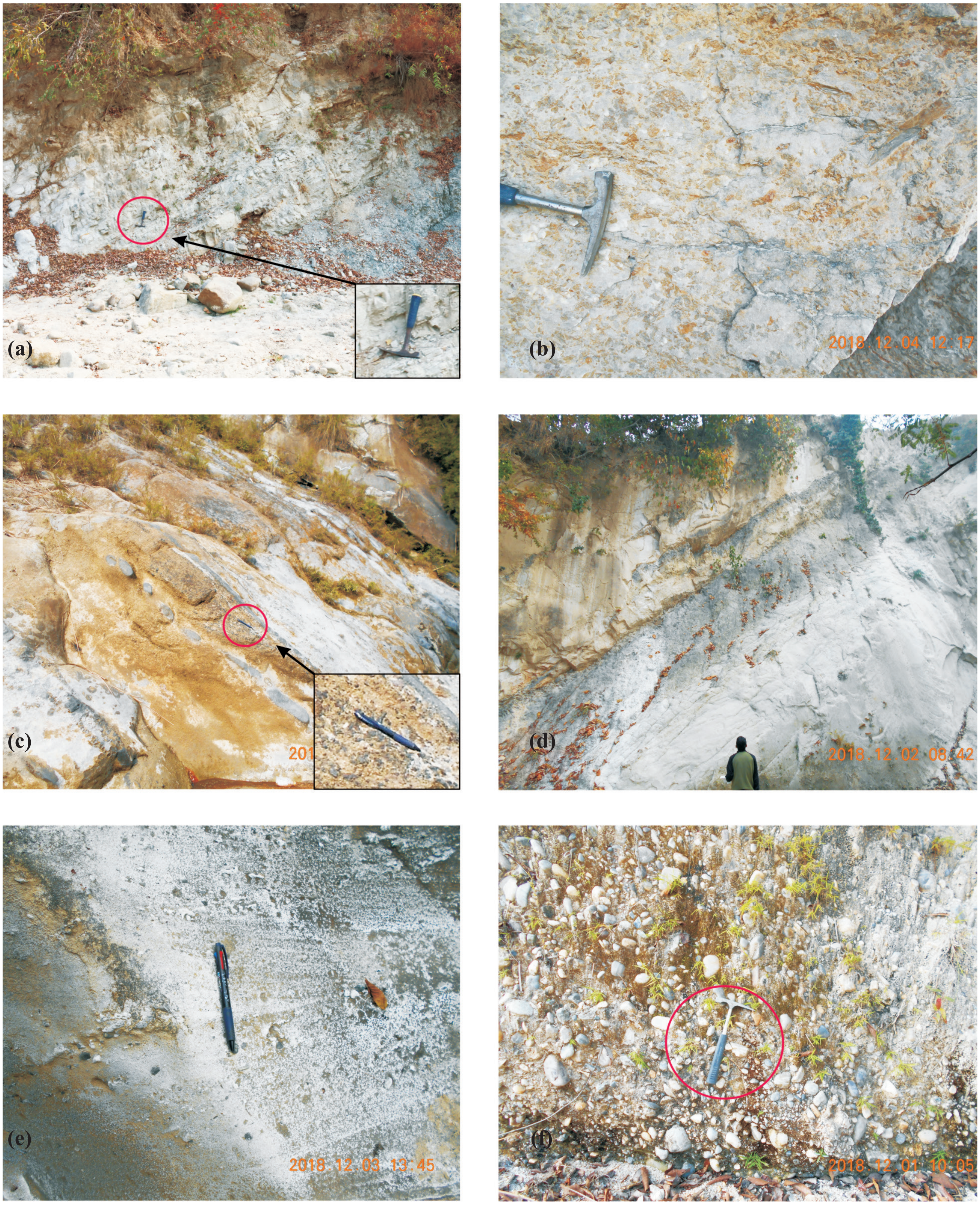


Fig. 8: Field photographs of (a) Inter-bedding of fine-grained sandstone and mudstone of the Lower Siwaliks (b) Intra-formational conglomerate of the Lower Siwaliks (conglomerate member) (c) Amalgamated sandstone of the Middle Siwaliks (lower member) (d) A typical fining upward sequence observed in very thickly bedded sandstone beds of the Middle Siwaliks (upper member) (e) pebbly sandstone with trough cross-stratification of the Middle Siwaliks (upper member) (f) Conglomerate of the Upper Siwaliks.

Fig. 9: Field photographs of (a) Anticline observed in the Lower Siwaliks (b) Variegated mudstone of the Lower Siwaliks (c) Concretion observed in siltstone to fine-grained sandstone of the Lower Siwalik (d) Calcium nodules observed in mudstone of the Middle Siwaliks (upper member) (e) Syn-tectonic deformation observed in the Middle Siwaliks (upper member) (f) Convolute lamination observed in the sandstone of the Middle Siwaliks.

Fig. 10: Field photographs of (a) Sandpipe observed in mud to siltstone of the Lower Siwaliks (b) Carbonized plant roots in siltstone of the Lower Siwaliks (c) Bioturbation in gleyed mudstone observed throughout the section (d) Bioturbated surface of sandstone in the Middle Siwaliks (e) Bivalve shell in the sandstone of the Middle Siwaliks (lower member) (f) Leaf imprints in siltstone of the Middle Siwaliks (lower member).

grained sandstone with thickness ranging 0.3-1.0 m are observed. Parallel lamination, ripple lamination and planer cross stratification are mostly common in sandstone beds. The colour of mudstone ranges from olive-grey to dark grey with few yellowish- to reddish-grey (Table 1). Mudstone are mostly bioturbated and the average thickness of 0.4-1.5 m, occasionally 2.0-3.5 m. Sandpipes (Fig. 10a) and carbonized roots (Fig. 10b) are observed mainly in siltstone. Mottled and variegated mudstones are abundant towards younger succession (Fig. 9b). Concretion is well developed in mudstone and siltstone (2-6 cm diameter) whereas fine- to medium-grained sandstone shows the larger concretion (sometimes 30 cm in diameter, Fig. 9c).

Conglomerate member of the Lower Siwaliks

This member is ~90 m thick, well exposed along the Muksar Khola around the confluence of the Muksar Khola and the Chituwa Khola (Fig. 2). This member is characterized by poorly sorted clast supported intra-formational conglomerate with medium- to coarse-grained massive sandstone and rare laminated olive-grey mudstone (Figs. 4 and 8b). Intra-formational conglomerate is composed of mud clast and medium- to very coarse-grained sandstone matrix with thickness ranging from 0.4 to>4.0 m. These mudstone clasts are reddish-brown and angular to sub-angular (soft deformation in mud clasts are also observed in considerable amounts) with an average diameter of 1-2 cm (some clasts are elongated up 10 cm). The average ratio of clast to matrix is about 70% to 30%, respectively. Sandstones are light-grey and massive (without clear fining-upward sequence) and thickness ranges from 0.1 to 0.8 m. Mudstones are dark-olive to bluish-grey with a thickness of 0.4 to 0.5 m (very rare occurrence). Although Ojha et al. (2009) conducted the paleomagnetic study, the age of this unit was not determined. Therefore, based on the thickness of sedimentological log of this study and oldest sedimentation rate of Ohja et al. (2009), the estimated age as 10.6 Ma.

Middle Siwaliks

The Middle Siwaliks is well exposed along the Muksar Khola around the Aakashganga Temple the Magan village with an overall thickness of ~2150 m (Fig. 2), deposited between 10.0-3.5 Ma (Fig. 3; Ojha et al., 2009). In the present study, the Middle Siwaliks is divided into the lower and upper member based on the proportion of biotite grain in sandstone, lithological variation and thickness and induration of sandstone beds. The proportion of mudstone and thickness of sandstone beds increased in the upper member as compared to that of a lower member (Figs. 11 and 12). Similarly, the colour of mudstone is greenish-grey to olive-grey in the lower member, whereas it is dark-grey to black in the upper member (Table 1)

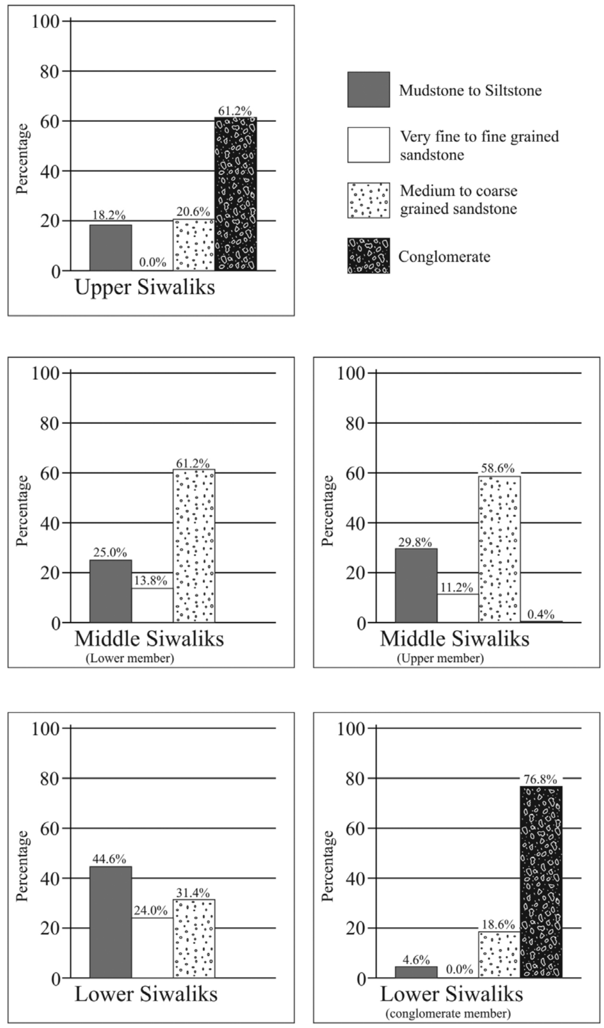


Fig. 11: Proportion of various rocks in the Muksar Khola area in different lithostratigraphic units.

Lower Member of the Middle Siwaliks

The main characteristic lithology of this member is "salt and pepper" appearance sandstone. These sandstones show distinct fining-upward succession and are dominantly medium-grained, sometimes medium- to coarse-grained (Fig. 5). There is a sporadic presence of thick amalgamated sandstone beds (>10 m thick) and the frequency of such beds decreases from the lower to the upper section (Fig. 8c). Majority of sandstone beds are medium- to thick bedded with thickness range from 26-100 cm (Fig. 12). Parallel and ripple lamination and planer cross-stratification are the dominating sedimentary structures in sandstone beds. Trough cross-stratification and channel lag deposits are also observed in amalgamated beds. Gleyed mudstone with dark greenish-grey to olive-grey and

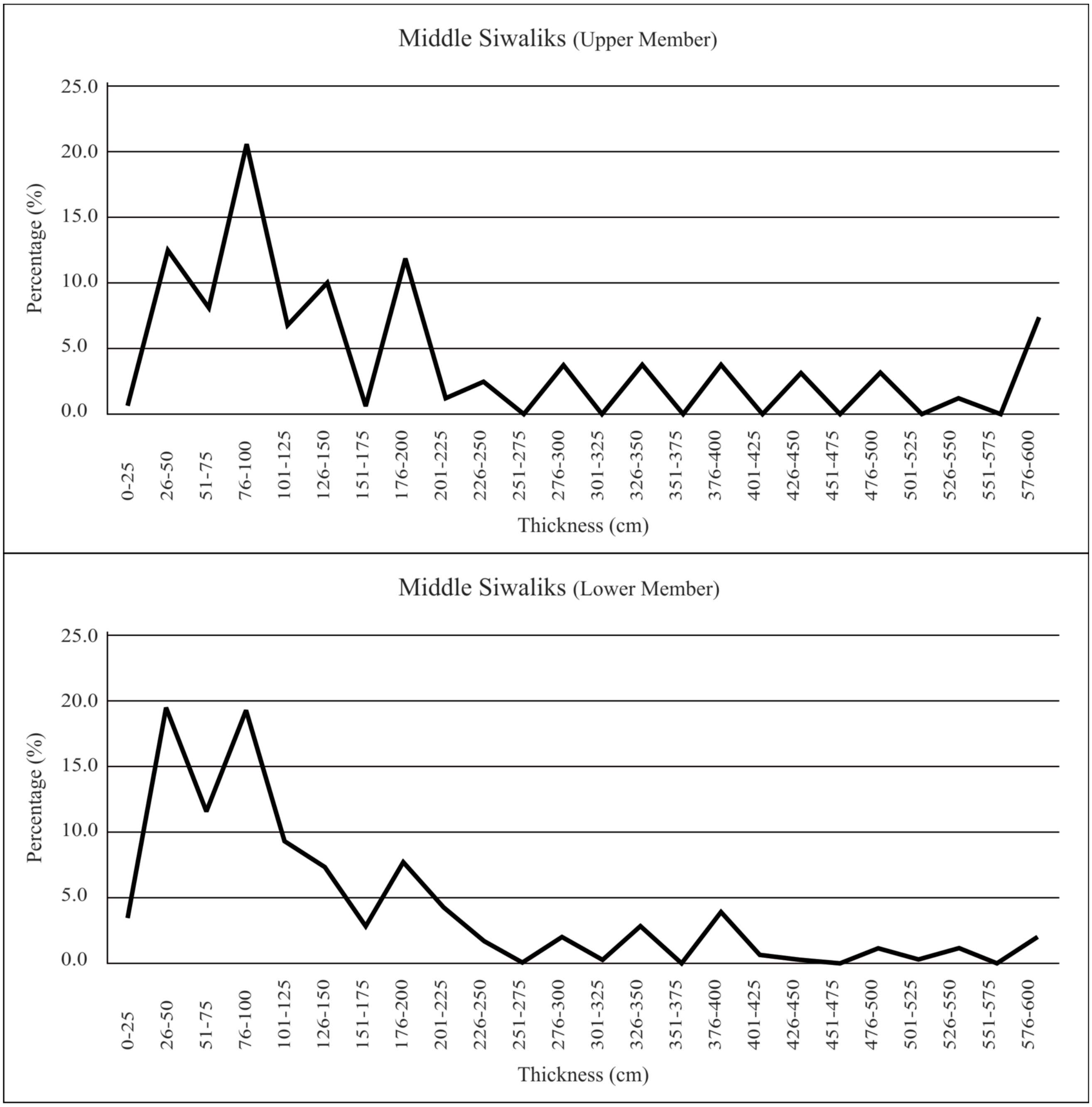


Fig. 12: Comparison of sandstone beds thickness of Lower and Upper member of the Middle Siwaliks. (Amalgamated sandstone beds with thickness more than 6 m were excluded).

black coloured dominates this member (Table 1). The thickness of mudstone to siltstone ranges from 0.3 to 1.0 m, occasionally up to 8 m. Bioturbation is abundant in mudstone (Fig. 10c) and even in some sandstone beds (Fig. 10d). Bivalve shells (Fig. 10e) are present in medium-grained sandstone and leaf fossils (Fig. 10f) are preserved in the fine-grained sandstone and mudstone. Concretion is observed both on sandstone and mudstone. The size of concretion is quite similar to the Lower Siwaliks, but numbers is less. The overall thickness of this member is around 1150m, which was deposited between 10 to 5.7 Ma (Fig. 3; Ojha et al., 2009).

Upper Member of the Middle Siwaliks

The main lithology of the upper member of the Middle Siwaliks is characterized by medium- to coarse-grained, light grey sandstone and dark-grey to black mudstone and siltstone (Fig. 6). Sandstone beds with thickness of 1.0-2.0 m dominates with a distinctive fining upward sequence (Figs. 8d and 12). The main difference of the sandstone of this member as compared to the lower member is the absence of "salt and pepper" sandstone. This "salt and pepper" sandstone beds are rare and limited to few beds in the lower portion of this member. Sandstones in

Table 1: Mudstone colour in the present study area based on the Munsell colour chart.

Formation	Munsell colour code Hue	Value/Chroma	Percentage	Colour Interpretation
Upper Siwaliks	2.5Y	6/1; 6/4	43.0%	Yellowish grey and dull yellow
	N	4; 5	43.0%	Grey
	2.5GY	4/1	14.0%	Dark olive grey
Middle Siwaliks (upper member)	7.5Y	3/1; 4/1; 4/2; 6/1	14.0%	Grey, greyish olive to olive black
	N	1.5; 2; 3; 4; 5; 6	54.5%	Grey, dark grey to black
	2.5GY	2/1; 3/1; 4/1; 5/1	14.5%	Olive grey, dark olive grey to black
	5B	3/1; 4/1; 5/1; 6/1	6.5%	Bluish grey to dark bluish black
	5BP	2/1; 3/1; 4/1	8.5%	Dark bluish grey to bluish black
	5P	1.7/1; 5/1	2.0%	Purplish grey to purplish black
Middle Siwaliks (lower member)	5Y	4/2; 4/3	3.5%	Dark olive
	7.5Y	3/1; 3/2; 4/2; 4/3	9.0%	Greyish olive to olive black
	10Y	2/1; 3/1; 3/2; 4/2	6.0%	Olive grey to olive black
	N	1.5; 2; 3; 4; 5	18.0%	Grey to black
	2.5GY	2/1; 3/1; 4/1	32.0%	Dark olive grey to black
	5GY	3/1; 4/1; 5/1; 6/1	10.0%	Olive grey to dark olive grey
	7.5GY	2/1; 3/1; 4/1	10.5%	Dark greenish grey
	5G	3/1; 4/1	6.5%	Dark greenish grey
	10G	3/1; 4/1	4.5%	Dark greenish grey
	10BG	3/1; 4/1	4.5%	Dark bluish grey
	5PB	2/1; 3/1	1.5%	Dark bluish grey to bluish black
	5P	1.7/1; 2/1; 3/1	3.0%	Dark purplish grey to purplish black
Lower Siwaliks	10R	3/1	6.5%	Dark reddish grey
	10YR	4/3	7.0%	Dull yellowish brown
	7.5Y	3/1; 4/1; 5/2; 5/3	33.5%	Grey, greyish olive to olive black
	10Y	5/1; 5/2	20.0%	Grey to dark grey
	N	3; 5	13.0%	Grey to dark grey
	2.5GY	4/1; 5/1	20.0%	Olive grey, dark olive grey

this member are less indurated as compared to the lower member of the Middle Siwaliks. The degree of induration decreases towards up section with the increased frequency of pebble occurrence in the sandstone beds. Trough cross-stratification and channel lag deposits are abundant and dominating sedimentary structure (Fig. 8e), with a minor amount of planer cross-stratification and ripple laminations on the lower section. In the upper section, the thickness of channel lag deposits drastically increases (up to 30-50 cm) resembling thin to medium beds of conglomerate. Gley mudstone with grey, dark-grey to black colour dominates this member (Table 1), but variegated and purple mudstone also occasionally observed. Bluish-grey to bluish-black mudstones are abundant in the lower section of this member whereas, dark greenish-grey and dark olive-grey to black colour mudstone dominates upper section. Mudstones are mostly bioturbated with the thickness of 0.4-2.0 m, but 2.0-6.0 m thick mudstone beds are also frequently observed. Concretion is occasionally observed and are limited to siltstone to mudstone (Fig. 9d). Syn-tectonic deformation and convolute lamination are well observed in this member (Figs. 9e and f). The overall thickness of this member is around 1000 m and the depositional age is estimated from 5.7 to 3.5 Ma (Fig. 3; Ojha et al., 2009).

Upper Siwaliks

This unit is observed around the Chure dada (local name) and the upper end of the Magan village along the Magan Khola. The thickness of this unit is more than 1000 m (MDT is inaccessible along this section). This unit is characterized by very thick-bedded clast supported conglomerate associated with very thick-bedded sandstone and mudstone (Figs. 7 and 8f).

Conglomerates are poorly-sorted and consist of pebble to cobble sized clasts with very coarse-grained sand to granules matrix. The clasts of the conglomerate are sub-rounded to sub-angular without any proper orientation. The dominant numbers of clasts are of Quartzite, while insignificantly there are presence of sandstones, mudstones and purple metasandstones. Parallel cross-stratifications (poorly developed) are observed in the lower section whereas inverse grading is dominant in the upper section. Sandstones are coarse- to very coarse-grained and very thick-bedded (1.0-3.0 m). Mostly these sandstone beds are massive, occasionally parallel cross-stratifications with slightly fining upward. Isolated pebbles are abundant in sandstone, sometimes its density increases resulting pebbly sandstones. Mudstones are dull yellowish-grey to grey colour (Table 1), mostly bioturbated and very thick-bedded (>4 m). Based on the paleomagnetic age established by Ojha et al. (2009), this unit was deposited after 3.5 Ma (Fig. 3).

DISCUSSION

Conglomerate member in the Lower Siwaliks

The presence of thick beds of intra-formational conglomerate in the Lower Siwaliks is unique in this section. The texture and composition of conglomerate as explained above makes it different from the conglomerate of the Upper Siwaliks. Such intra-formational conglomerate was also reported in the Lower Siwaliks (lower member) along the Tinau Khola section (Ulak and Nakayama, 2001) but their study lacks a detail description and its genesis. Intra-formational conglomerates (up to 3 m) are generally preserved in the scoured surface of typical sedimentary cycle (Prakash et al., 1980). However, such large succession of intra-formational conglomerate with the absence of sufficient sandstone and mudstone facies to complete the sedimentary cycle is quite unique. The composition and shape of the clast suggest that these sediments were probably derived from the near flood plains because mudstone cannot retain their angular to sub-angular shape when transported for long-distance. A case study of a modern Kosi and Brahmaputra River suggests, during the waning stage of a flood, adjacent banks are undercut developing shear cracks, which triggers bank slumps (Coleman, 1969; Gohain and Prakash, 1990; Singh et al., 1993). This bank failures initially form isolated scattered large blocks, that then develop into angular and then to rounded clasts, when broken into smaller pieces and rolled along the channel floor for some distance (Singh et al., 1993). Therefore, the presence of such large succession must be related to some flood activity during the deposition of Lower Siwaliks.

The occurrence of the conglomerate in the Lower Siwalik was also reported earlier. Shrestha and Sharma (1996) reported the presence of conglomerate in the Lower Siwaliks of northern belt bounded by the KTT and MBT (above the present study area). These conglomerate are observed at south of the Tintale Village and the confluence of the Tawa Khola and the Baijnath Khola. In the stratigraphic column, it appeared at the base of the Lower Siwaliks as basal conglomerate, which was separated by an unconformity from the underlying Tintale Formation (pre-Siwaliks). Their conglomerate consists of sub-rounded to rounded pebbles of grey to white dolomites, banded white grey quartzites, dark-grey to black cherts, purple and grey shales. Those clasts were derived from the underlying rock units of pre-Siwaliks Group separated by an unconformity (Shrestha and Sharma, 1996). The location of their basal conglomerate in the stratigraphic column and its texture and composition make our conglomerate different.

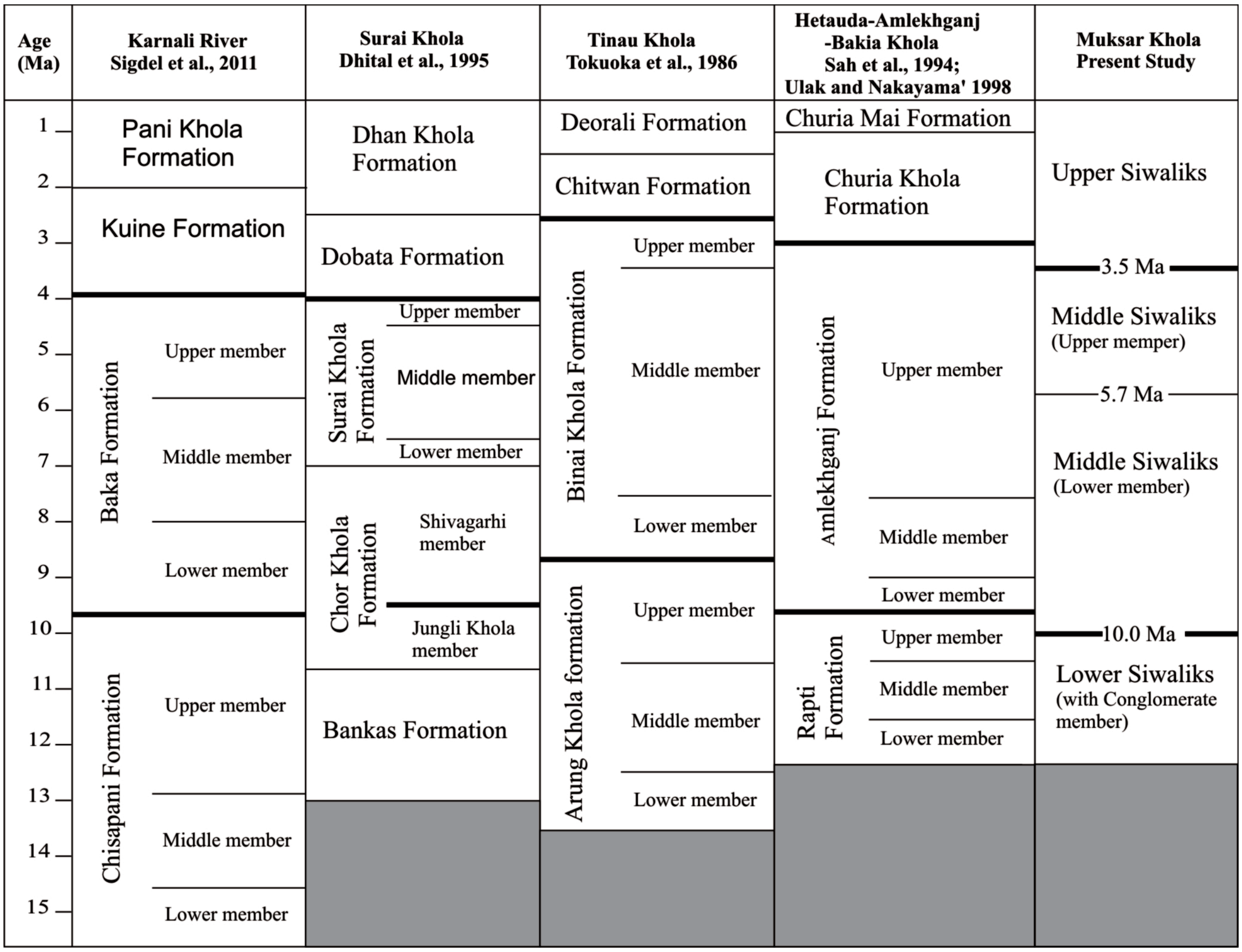
Comparison with previous work

Various studies have been carried out in the past along the Muksar Khola section and its vicinity (Quade et al., 1995; Shrestha and Sharma, 1996; Robinson et al., 2001; Ojha et al., 2009; DMG, 2011; Chirouze et al., 2012). Among these studies, to some extent, Shrestha and Sharma (1996) and DMG (2011) geological map deals with lithostratigraphy. In their map, the Siwaliks along the Muksar Khola section is divided into Lower Siwaliks, lower member and upper member of Middle Siwaliks and Upper Siwaliks. The present study also adopted a similar classification given by Shrestha and Sharma (1996); however, the boundary they mark between each units is not what we observed in the field. In previous study, the geological map was prepared on the broad scale; therefore exact boundary is not clear. The thickness of upper member of the Middle Siwalik is more than the lower member, but in the present study it is just opposite. Additionally, the existence of intra-formational conglomerate member mention above and a couple of folds in the Lower Siwaliks (Figs. 2 and 9a) observed in this study was not mentioned in the previous study.

Correlation

Siwalik sediments extend collinearly to the Himalaya from east to west (Dhital, 2015), deposited in a foreland basin by the fluvial system. The fluvial system in the foreland basin is controlled by the tectonics, climate and geomorphology of the hinterland (Willis 1993a; Zaleha, 1997; Nakayama and Ulak, 1999; Huyghe 2001; 2005). Change in this hinterland

Table 2: Lithostratigraphic classification and correlation of the present study with representing the Siwaliks section of central and western Nepal.



phenomena to time, resulted in lithological variations in the Siwalik group, i.e., the Lower, Middle and Upper Siwaliks (Huyghe et al., 2001). Numerous types of research show that the tectonic history and paleoclimate of the Himalaya was not synchronous from east to west (Robinson et al., 2001; Yin, 2006; Ojha et al., 2009; Vogeli et al., 2017). Therefore, the thickness in Siwaliks varies as it was deposited in fluvial system, and the sediments were eroded from the uprising Himalaya towards the north. Siwalik sediments were deposited by numerous river system, each with its characteristic hinterland phenomena in various period and it differ in each Siwalik section (Nakayama and Ulak, 1999; Ulak and Nakayama, 2001; Ulak, 2004; Ulak, 2009; Sigdel and Sakai, 2016). These arguments suggest that the lithology of the Siwaliks varies vertically as well as laterally. This might be the reason, some researchers used the local stratigraphic name to address these lateral and vertical variations from other Siwalik section and used 4-fold to 5-fold classification (Tokuoka et al., 1986; Willis 1993b; Dhital et al., 1995; Sah et al., 1995; Zaleha 1997; Sigdel et al., 2011). Therefore, the correlation of Siwaliks litho units based on the local stratigraphic name is quite complicated. However, the well-adopted classification (three-fold i.e., the Lower, Middle and Upper Siwaliks), where litho units are classified based on the grain size (Piligram, 1913; Auden 1935; Ulak, 2004; Ulak, 2009; Adhikari et al., 2018). The present study also adopted this classification (Table 2) and correlated the other section of the Siwalik Group. 2).

CONCLUSIONS

In the present study, the Lower Siwaliks is characterized by very fine- to fine-grained, light-grey sandstone interbedded with grey to olive-black mud to siltstone, deposited before 10 Ma. A large succession of intra-formational conglomerate is recorded in the Lower Siwaliks for the first time. Based on the lithological composition and the thickness of sandstone, the Middle Siwaliks is divided into two members and the boundary between these members is ~5.7 Ma. The lower member of the Middle Siwaliks is dominated by fine- to medium-grained “salt and pepper” sandstone with greenish-grey to olive-grey mudstone. In contrast, the upper member consists of light grey to white medium- to very coarsesandstone with a dominant volume of grey, dark grey to black mudstone. An increase in the grain size and the thickness of sandstone beds, an increase in the proportion of mudstone, a decrease in the induration of sandstone and a decrease in the proportion of biotite grain in sandstone makes upper member different from the lower member of the Middle Siwaliks. Very thick beds of clast characterize the Upper Siwaliks supported conglomerate associated with very thickly bedded coarse- to very coarse-grained sandstone and very thickly bedded dull yellowish-grey to grey colour mudstone.

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AUTHOR'S CONTRIBUTIONS

L.K. Rai conceptualized the research. The field study and data analysis were carried out by L. K. Rai. The manuscript was drafted by L. K. Rai under the supervision of K. Yoshida. L. K. Rai and K. Yoshida read and approved the final manuscript.

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