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Geological study of Pattharkot-Thada area, Arghakhachi district, western Nepal

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Abstract
A comprehensive geological study was carried out in the Siwalik succession of the Pattharkot–Thada region, western Nepal. Structurally, the study area is divided into southern and northern belts, demarcated by the Central Churia Thrust (CCT). Stratigraphically, the succession is classified into three distinct litho-units, such as the mudstone-dominated Lower, sandstone-dominated Middle, and conglomerate-dominated Upper Siwalik, based on their lithological variations. Magnetostratigraphic evidence from the nearby Siwalik regions suggests the deposits in this area to be a transition from Lower to Middle Siwalik that occurred before or around 8.5 million years ago, while the shift from the Middle to Upper Siwalik was established approximately 2.5 million years ago. Additionally, the deposition the Siwalik succession was laid down by localized fluvial systems, representing an interfluve zone within a broader fluvial network.

Keywords Lithostratigraphy, Correlation, Siwalik Group, Pattharkot−Thada

1. Introduction

Around 50 million years ago, the Indian and Eurasian plates collided, resulting in extensive crustal thickening and shortening that facilitated the formation of the Great Himalayan Mountains Belt (Valdiya, 2002). The southern flank of the Himalayan belt accumulates huge piles of molasse sediments (~ 6 km thick) as muds, silts, sands and gravels, which are derived from the rising Himalaya in the north and got accumulated in the Himalayan Foreland Basin (HFB) covering a longitudinal distance of about 2400 km from the Potwar basin, Pakistan in the west to Arunachal Pradesh, India in the east covering parts of Nepal (Gansser, 1996; DeCelles et al., 1998; Mugnier et al., 1999; Valdiya, 2002). This infill foreland basin is known as the Siwalik Group (Gansser, 1964; Valdiya, 2002), and in Nepal, the group is also termed as the Churia Group (Tokuoka and Yoshida, 1984). Tectonically, the group is bounded between the Himalayan Frontal Thrust (HFT) to its south and the Main Boundary Thrust (MBT) to its north (Gansser, 1964; Valdiya, 2002). The age of the sediment ranges from the middle Miocene–early Pleistocene (Rösler et al., 1997; Gautam and Fujiwara, 2000; Ojha et al., 2009) and were deposited by a fine-grained meandering river to gravelly braided river system (Nakayama and Ulak, 1999; Sigdel and Sakai, 2016; Rai and Yoshida, 2021). This unit's grain size displays an overall upward coarsening trend across the entire sequence, with each individual bed exhibiting a fining-upward sequence (Parkash et al., 1980; Nakayama and Ulak, 1999). This group is divided into two belts namely, the southern and northern belts, and separated by the Central Churia Thrust (CCT) or the Main Dun Thrust (MDT) in Nepal (Hérail and Mascle, 1980; Tokuoka et al., 1986, 1990; Nakayama and Ulak, 1999; Adhikari et al., 2018). However, in the Bagmati River and Triyuga-Katari area, the group is repeated across three distinct belts named as southern, central, and northern belts (Schelling, 1992; Shrestha and Sharma, 1996).

The lithostratigraphy of the Siwalik Group has been established by numerous researchers (Tokuoka et al., 1986; 1990; Nakayama and Ulak, 1999; Sigdel et al., 2011; Adhikari et al., 2018; Chaudhary et al., 2024). Several classification systems have been developed for the Siwalik Group, including the widely accepted three-fold (tripartite) classification system namely Lower, Middle, and Upper Siwalik (Adhikari et al., 2018; Rai and Yoshida, 2020; Chaudhary et al., 2024). Additionally, other studies have applied classifications ranging from two-fold to five-fold systems (Tokuoka et al., 1986; 1990; Dhital et al., 1995; Nakayama and Ulak, 1999; Sigdel et al., 2011; Adhikari and Sakai, 2015). Previous studies in the study area have primarily concentrated on tectonics and regional geology (Pradhan et al., 2000; DMG, 2020). However, these studies do not offer a detailed description of the stratigraphic succession within the region. Detailed geological mapping at a large scale can reveal the finer structural and lithological details that remain undocumented. Therefore, the present study aims to provide a detailed description of the lithological characteristics and stratigraphic classification of the Pattharkot–Thada area in western Nepal, using the widely accepted classical tripartite (three-fold) classification system (Figure 1).

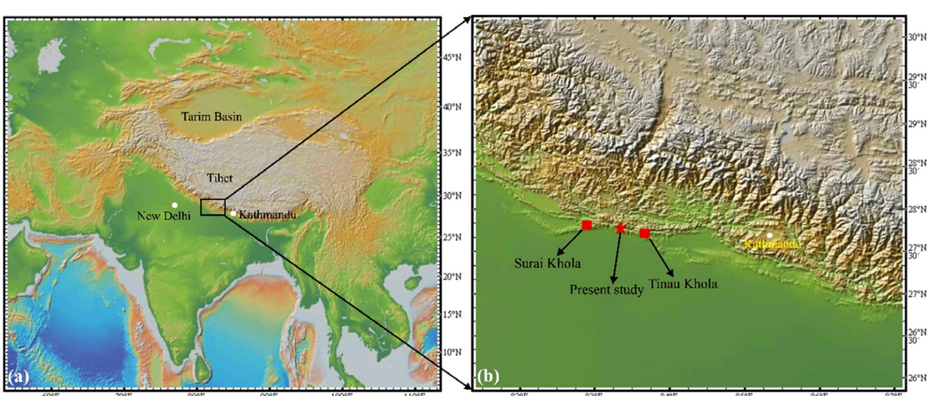


Figure 1. Locality map of the study area. (Source: www.geomapapp.org).

2. Methods

This research is mainly based on the field study of the Gorusinge–Sandhikharka road section. Detailed lithological logs on a 1:100 scale and a geological route map on a 1:500 scale of the entire rock exposures were prepared. Bed-by-bed lithological data were collected systematically to distinguish and classify rock units based on their texture, grain size, and composition. Depending on their composition, texture, and grain size, rocks were classified as conglomerate, sandstone, siltstone and mudstone. The data gathered from the Pattharkot–Thada section were compared and correlated with the well-documented Siwalik sections of the Tinau Khola and Surai Khola areas in western Nepal. These comparisons were used to infer the relative chronological positions of lithological units and establish regional correlations.

3. Result

The study area is situated in western Nepal and lies between the Indo-Gangetic Plain to the south and the Lesser Himalaya to the north (Figure 2). Structurally, it is divided into two primary tectonic belts, as the southern and northern belts and separated by the Central Churia Thrust (CCT). In the southern belt, which extends between the Himalayan Frontal Thrust (HFT) to the south and the CCT to the north, the Siwalik succession comprises three distinct litho-units namely, the Lower, Middle, and Upper Siwalik. The northern belt lies between the CCT, and the Main Boundary Thrust (MBT) to the north and south, respectively and includes the Lower and Middle Siwalik units.

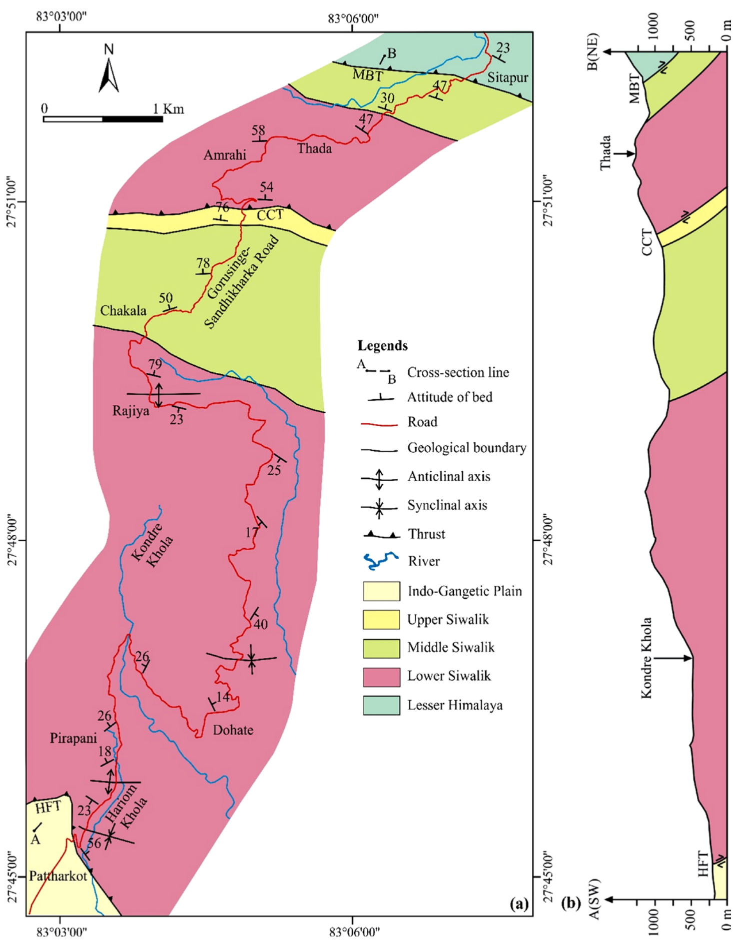


Figure 2. (a) Geological map of the study area, (b) Cross-section along A–B.

These litho-units were classified based on variations in lithology observed across the stratigraphic succession (Figure 2).

3.1 Lower Siwalik

This unit is predominantly exposed along the Gorusinge–Sandhikharka road near Pattharkot, Pirapani, Dohate, Rajiya, Amarahi and Thada villages. It is mainly composed of variegated mudstone, siltstone, and fine-grained sandstone (Figure 3a). The Lower Siwalik has an approximate thickness of 3545 m in the southern belt and about 1075 m in the northern belt (Figure 2b). The proportion of mudstone and siltstone beds is greater than sandstone beds (Figure 4a). Moreover, the lower part of the unit predominantly contains mudstone and siltstone (Figure 5), while the upper sections show an increased presence of fine-grained sandstone (Figure 6).

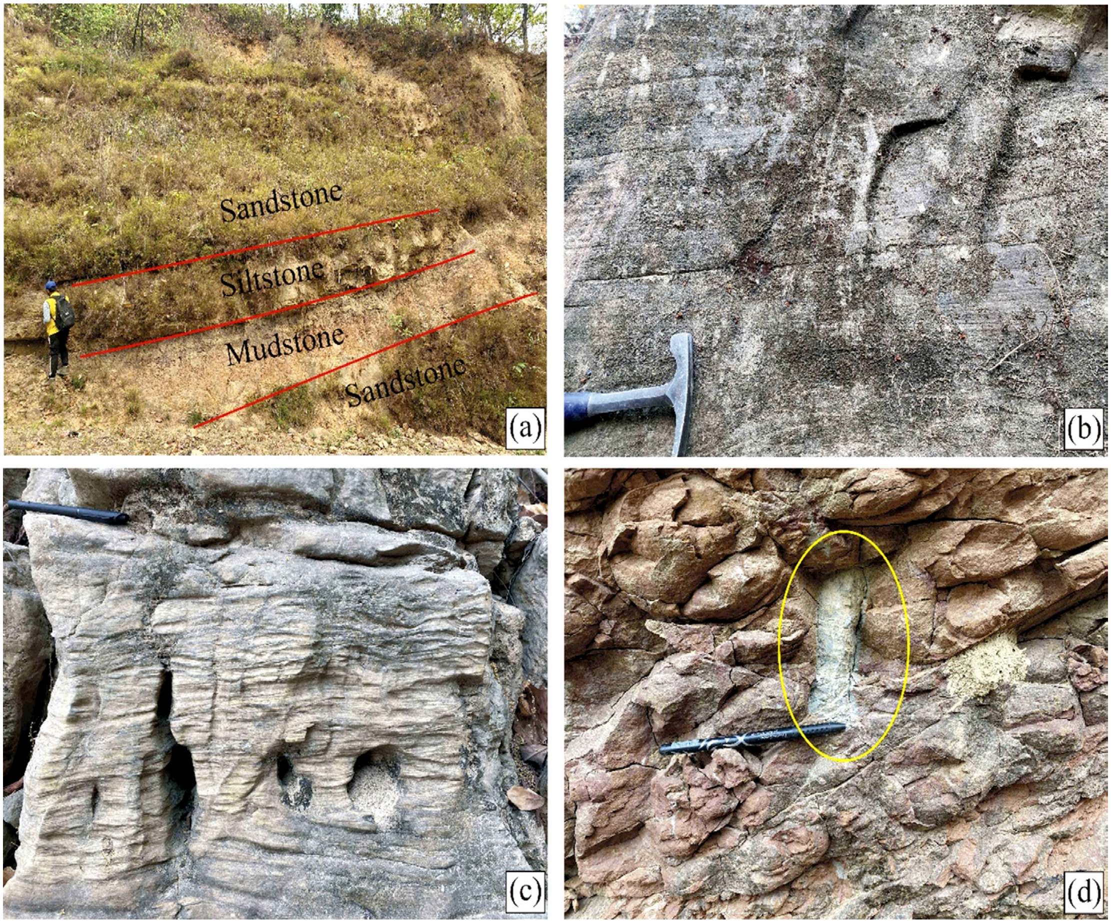


Figure 3. Outcrop photographs of the Lower Siwalik, (a) Mudstone bed interbedded with siltstone bed, fine-grained sandstone bed, (b) Parallel lamination in fine-grained sandstone bed, (c) Ripple cross lamination in siltstone bed, (d) Concretion in mudstone bed.

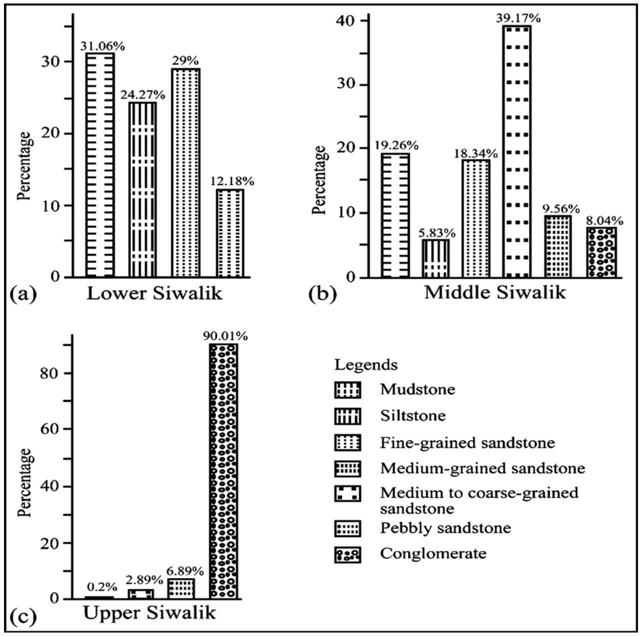


Figure 4. Rock distribution in the Siwalik succession of the study area. (a) Lower Siwalik, (b) Middle Siwalik, (c) Upper Siwalik.

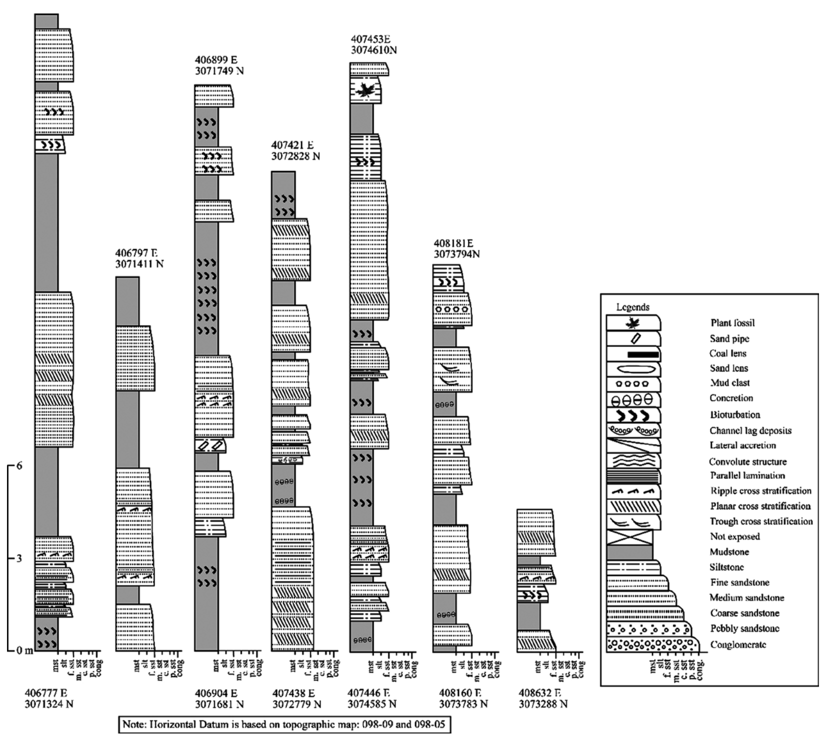


Figure 5. Lithological details of the lower part of Lower Siwalik.

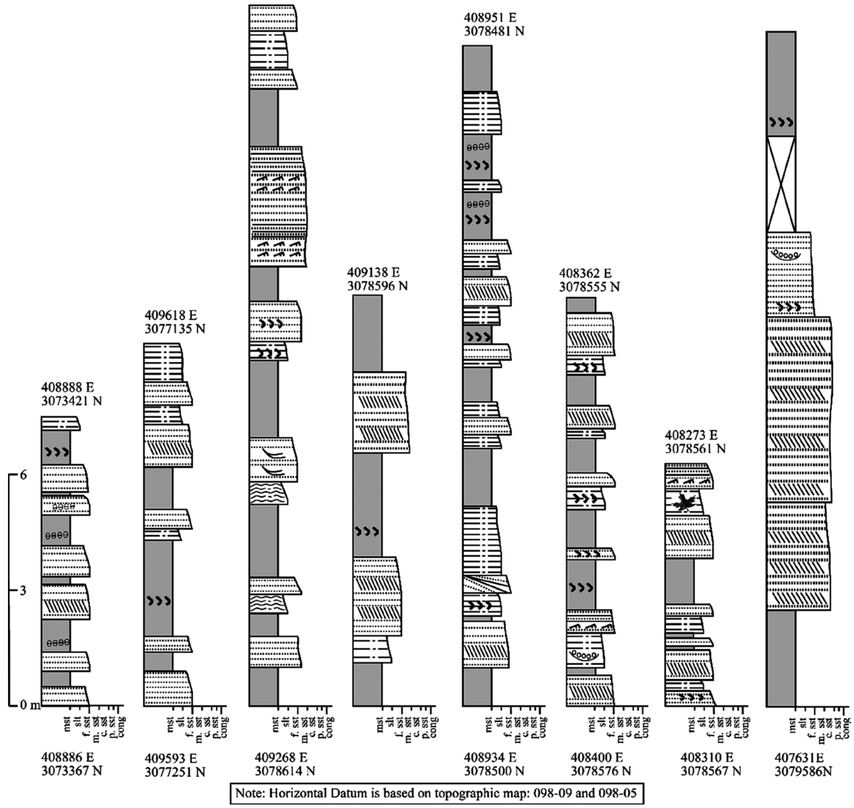


Figure 6. Lithological details of the upper part of Lower Siwalik.

The main characteristics of the Lower Siwalik are light grey to greenish grey, fine-grained sandstone beds with the grey to variegated mudstone beds as well as grey to greenish grey siltstone beds (Figure 3a). The thickness of mudstone and siltstone beds varies between 20 and 470 cm and 5 to 242 cm, respectively, whereas fine-grained sandstone beds range from 12 to 380 cm in thickness. The light to dark grey, yellowish grey medium-grained sandstone beds ranging from 15 to 205 cm thick, and "pseudo-salt and pepper", medium-grained sandstone beds with 30 to 80 cm thick, are observed in the upper part.

There are two low-angled anticline and syncline folds observed in these litho-units, whereas most of the sedimentary structures are likely lateral accretion, planar and trough cross stratification, parallel lamination (Figure 3b), and ripple cross stratification (Figure 3c) are observed in siltstone and sandstone beds. Variegated and mottled mudstone is common throughout the section. The mudstone and siltstone beds generally featured in bioturbation, burrows, ferruginous nodules, and concretions (up to 4 cm in diameters; Figure 3d). A distinct fining-upward succession, ranging up to 917 cm thick are observed, with numerous erosional and planar surfaces. Calcrete and calcareous formations are most pronounced in all the rock bodies. Sandpipes (up to

5 mm diameter), carbonized roots, leaf and freshwater molluscan fossils in siltstone beds and vertebrated bone fragments are observed in the fine-grained sandstone beds. Dark grey, angular to sub-rounded, with an average diameter up to 4.5 cm of mud and silt clasts are observed within fine-grained sandstone beds. Channel lag deposits are occasionally observed in the upper part of the litho-units.

3.2 Middle Siwalik

The Middle Siwalik is exposed in the Gorusinge–Sandhikharka road near Chakla, Amarahi, Badachaur and Sitapur villages. This litho-unit consists predominantly of medium to coarse-grained, "pepper and salt" sandstone, matrix supported conglomerate, pebbly sandstone, fine-grained sandstone, mudstone, and siltstone (Figure 7a–c). The thickness of the litho-unit is about 1275 m in southern belt and about 385 m in northern belt (Figure 2b). The proportion of mudstone and siltstone beds is less than sandstone beds (Figure 4b). Moreover, the lower part is dominated by medium to very coarse-grained, "pepper and salt" sandstone beds (Figure 8), while the upper part is abundance of pebbly sandstone and conglomerate beds (Figure 9).

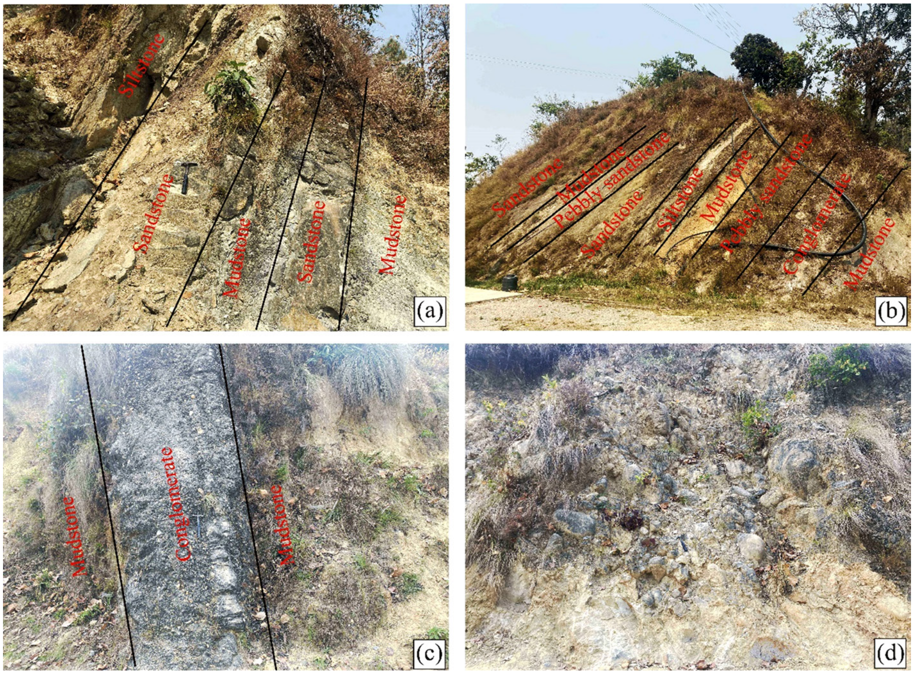


Figure 7. Outcrop photographs of the Middle and Upper Siwalik. (a). Coarse-grained, sandstone bed interbedded with mudstone and siltstone beds in the Middle Siwalik. (b). Coarse-grained, sandstone bed, pebbly sandstone bed interbedded with matrix supported conglomerate and mudstone beds in the Middle Siwalik. (c). Matrix supported conglomerate and mudstone beds in the Middle Siwalik. (d). Cobble- to boulder conglomerate bed in the Upper Siwalik.

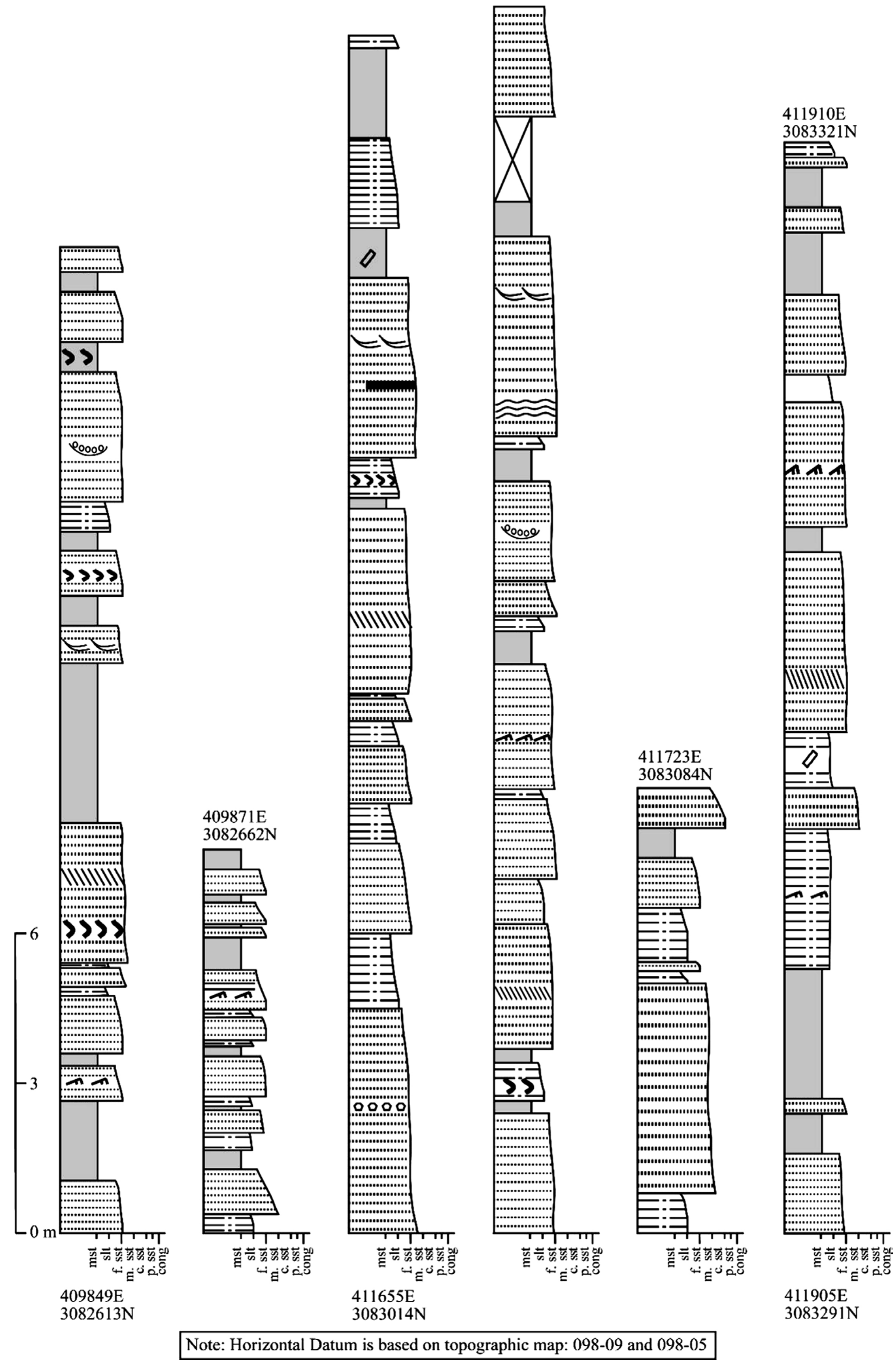


Figure 8. Lithological details of the lower part of Middle Siwalik.

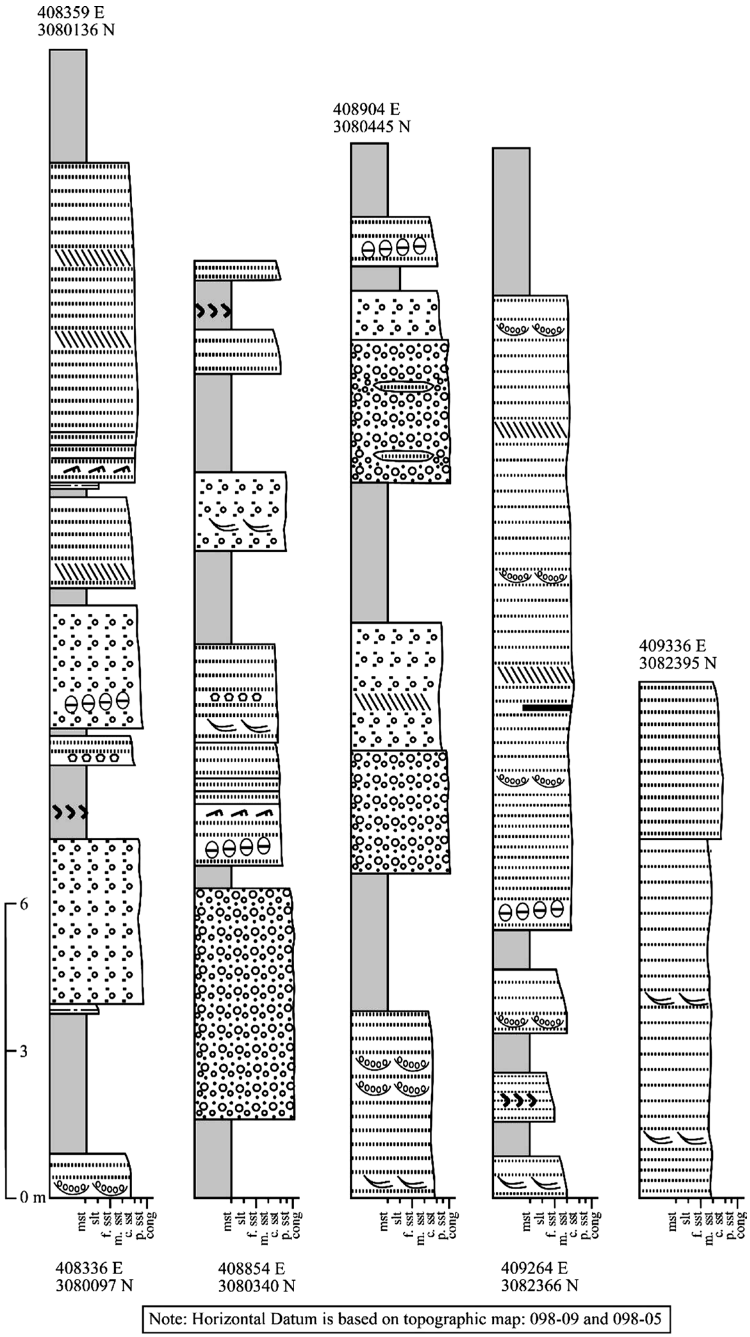


Figure 9. Lithological details of the upper part of Middle Siwalik.

The main lithological characteristics of these litho-units are medium- to very coarse-grained, light grey, "salt and pepper" sandstone beds, pebbly sandstone beds interbedded with grey to greenish grey mudstone beds as well as greenish to yellowish grey, grey siltstone beds (Figure 7a–c). Sandstone beds exhibiting a "salt and pepper" appearance are more commonly observed in the lower part of the sequence than in the upper part, while the grain size of sandstone beds shows an increasing trend from the lower to upper parts. Medium- to very coarse-grained, "pepper and salt" sandstone beds vary from 10 to 675 cm in thickness, while fine-grained sandstone beds range from 15 to 275 cm. Mudstone and siltstone beds range in thickness from 10 to 285 cm and 13 to 87 cm, respectively. In the upper part, medium- to coarse-grained, "pepper and salt" sandstone beds contain rounded to subrounded pebbles (referred to as pebbly sandstone beds) composed of quartzite, limestone, dolomite, sandstone etc. with pebble diameters reaching up to 5 cm. The pebbly sandstone beds exhibit thicknesses ranging from 20 to 250 cm. Well- to poorly sorted, clast- to matrix-supported, subangular to rounded, granule-cobble-pebble sized conglomerate beds are also frequently observed in the upper parts, with thickness ranging from 20 to 470 cm. The clasts of conglomerate are mainly composed of quartzite and sandstone with minor limestone, dolomite, phyllite, and gneiss fragments with an average diameter up to 6 cm, while silt and fine- to coarse-grained sands matrix can be observed in conglomerate beds. Medium- to coarse-grained, amalgamated sandstone beds reaching an average thickness of up to 1300 cm are most pronounced and show fining upward sequences. Fining-upward successions are commonly observed within these units. The sandstone beds exhibit greater induration in the lower sections, which progressively decreases toward the upper parts.

Planar cross stratification, trough cross stratification, parallel lamination, and ripple cross stratification are observed in amalgamated sandstone and siltstone beds. Variegated and mottled mudstone is rarely found. The mudstone and siltstone beds generally exhibit bioturbation, burrows, ferruginous nodules, and concretions, though these features show a decreasing trend in these litho-units compared to the Lower Siwalik. Also, bioturbation and bioturbation surfaces are exhibited in fine-grained sandstone beds. Calcrete and calcareous formations are less pronounced then compared of the Lower Siwalik. Sandpipes, convolute structure and carbonized wood lens (up to 16 cm in length) are observed in siltstone and sandstone beds. Raindrop prints and traces of organic activity are observed in siltstone beds. Dark to light grey, angular to rounded, with an average diameter up to 10 cm of mud and silt clasts, mud and silt ball are observed within fine- to medium grained sandstone beds. Channel lag deposits with thicknesses ranging from 10 to 30 cm are also observed (Figures 8 and 9).

3.3 Upper Siwalik

The Upper Siwalik is exposed in the Gorusinge–Sandhikharka road near Amarahi villages. This litho-unit is composed of matrix-supported conglomerate with medium- to coarse-grained, "pepper and salt" sandstone, fine-grained sandstone, pebbly sandstone, as well as mudstone (Figures 7d and 10). The thickness of the litho-unit is about 175 m (Figure 2b). The proportion of matrix-supported conglomerate beds is prominent in these units (Figure 4c).

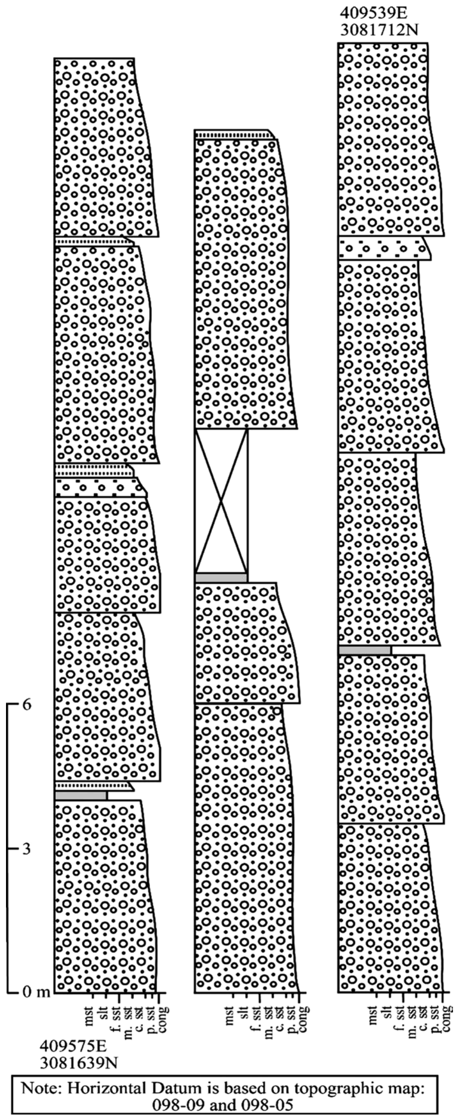


Figure 10. Lithological details of the Upper Siwalik.

The cobble-pebble-boulder- sized conglomerate layers are matrix- to clast-supported, poorly sorted, and contain rounded to subrounded clasts, including quartzite, sandstone, marble, slate, dolomite, limestone, and gneiss, with clast diameters reaching up to 25 cm. These beds are interbedded with "pepper and salt" appearance medium- to very coarse-grained, grey sandstone beds, fine-grained greenish, brownish to yellowish grey sandstone beds, as well as greenish to light grey, purple mudstone. The matrix of the conglomerate beds consists of very coarse-grained sand and granule-sized particles. Medium- to coarse-grained "pepper and salt" sandstone beds contain angular to subrounded pebbles, composed of quartzite and sandstone and minor of carbonate fragments with pebbles diameters reaching up to 3 cm. Conglomerate beds vary from 20 to 800 cm in thickness, while medium- to very coarse-grained, sandstone beds vary from 10 to 675 cm, and pebbly sandstone beds range from 17 to 28 cm in thick. Fine-grained sandstone and mudstone beds varying from 9 to 110 cm and 10 to 25 cm in thick respectively. Sand lenses ranging from 20 to 35 cm in thick are frequently observed in conglomerate beds. Sedimentary structures are very sparse, characterized by poorly developed planar cross stratification and trough cross stratification in sandstone beds and occasional bioturbation surface in mudstone and sandstone beds. Fining-upward successions are often challenging to identify because of the frequent erosional surfaces present in these litho-units.

4. Discussion

4.1 Comparison with previous work

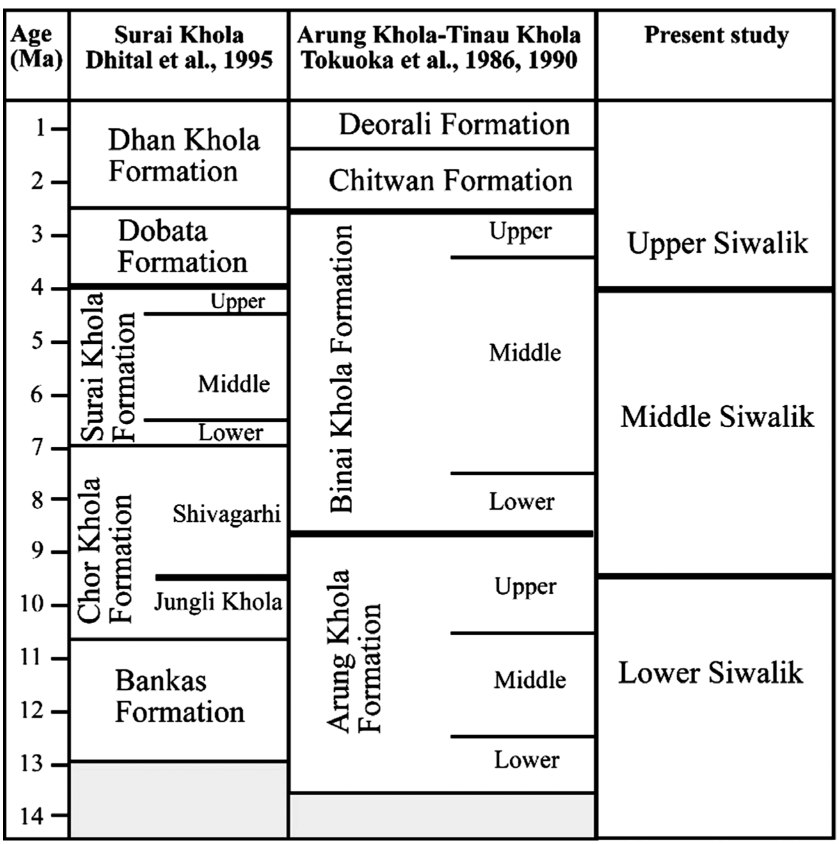
Previously, some studies dealing with regional geology have been carried out in the study area and nearby regions (Pradhan et al., 2000; DMG, 2020). Among these studies, the Siwalik Group along the Pattharkot–Thada area has been classified into the southern and northern belts, separated by a thrust. The litho-units in the study area are divided into the Lower Siwalik and Middle Siwalik (lower and upper members) in the southern belt, while the northern belt consists of the lower member of the Middle Siwalik (Pradhan et al., 2000; DMG, 2020). However, their geological map was prepared at a regional scale of 1:250000, making the exact boundaries between each litho-unit unclear and not placing any thrust name between the northern and southern belts. During the present study, the present study is clearly divided into two belts named as southern and northern belts, which are separated by the CCT. The lithostratigraphy in the study area is divided into three mappable litho-units as the Lower, Middle, and Upper Siwalik in southern belt and two mappable litho-units as the Lower and Middle Siwalik in northern belt (Figure 2). The numerous sedimentary structures likewise planar, ripple cross and trough cross stratifications indicate that the study area represents normal sequences. Additionally, previous studies in the area reported that a single anticline fold in the Lower Siwalik (Pradhan et al., 2000; DMG, 2020). However, the present study observed a couple of low-angle syncline and anticline folds in the Lower Siwalik (Figure 2).

4.2 Correlation and age of the Lower–Middle Siwalik and Middle–Upper Siwalik boundaries

The Siwalik succession runs parallel to the Himalaya from Arunachal Pradesh, India in the east to Pakistan in the west (Gansser, 1996; Valdiya, 2002) and was deposited in the foreland by numerous rivers flowing from the hinterland into a long, narrow depression, which is in front of the rising mountains (DeCelles et al., 1998; Mugnier et al., 1999).

The changing phenomenon of the hinterland resulted in lithological variations within the Siwalik basin (Nakayama and Ulak, 1999), while this implies that the tectonic evolution of the basin was not synchronous (Yin, 2006). These reasons imply that the lithology of the Siwalik sediments varies vertically as well as laterally (Nakayama and Ulak, 1999; Rai et al., 2021) and some researchers have used local stratigraphic names (three-to five-fold classification) to describe these lateral and vertical variations in other Siwalik sections (Tokuoka et al., 1986; Nakayama and Ulak, 1999; Sigdel et al., 2011). However, the correlation of the Siwalik succession is quite challenging because various research has proposed a three- to five-fold classification system. Therefore, the present study followed a well-accepted three-fold classification system and correlated to the Surai Khola in the west and the Tinau Khola in the east of the study area (Table 1).

Table 1. Lithostratigraphic classification of the Siwalik sediments and their correlation. Note: The bold lines indicate that the boundaries between the Lower-Middle and Middle-Upper Siwalik.



The Lower Siwalik consists of variegated mudstone, siltstone, and fine-grained sandstone, which are correlated with the Bankas Formation and Jungli Khola member of Chor Khola Formation of the Surai Khola section (Dhital et al., 1995) and the Arung Khola Formation of the Arung Khola–Tinau Khola section (Tokuoka et al., 1986; 1990) (Table 1). However, the Middle Siwalik represents of medium to coarse-grained, "salt and pepper" sandstone, pebbly sandstone, matrix-supported conglomerate, fine-grained sandstone, mudstone, and siltstone and this litho-unit has maximum similarity with the Shivgarhi member of Chor Khola Formation and Surai Khola Formation of the Surai Khola section (Dhital et al., 1995) and Binai Khola Formation of the Arung Khola–Tinau Khola section (Tokuoka et al., 1986; 1990) (Table 1). Similarly, the Upper Siwalik is mainly composed of matrix-supported conglomerate with medium to coarse-grained, "salt and pepper" sandstone, pebbly sandstone, fine- to medium-grained sandstone and mudstone and it has compared with the Dobata Formation of the Surai Khola section (Dhital et al., 1995) and Deorali Formation of the Arung Khola–Tinau Khola section (Tokuoka et al., 1986; 1990) (Table 1).

The age of the Siwalik sediments in the Nepal Himalaya has been established using the magnetostratigraphic data (Appel et al., 1991; Gautam and Appel, 1994; Rösler et al., 1997; Gautam and Fujiwara, 2000; Ojha et al., 2009). Moreover, we used magnetostratigraphic data to determine the relative age of the study area in comparison to the neighboring areas of the Surai Khola to the west and the Tinau Khola to the east (Appel et al., 1991; Tokuoka et al., 1990; Gautam and Appel, 1994). The boundary between the Lower and Middle Siwalik is defined by the top of the Jungli Khola member of Chor Khola Formation from the Surai Khola section (~9.5 Ma) and the top of the Arung Khola Formation from the Arung Khola–Tinau Khola section (~8.5 Ma) (Table 1). However, the development of the boundary between the Middle and Upper Siwalik has also varied (Table 1). It is dated to ~4 Ma at the top of the Surai Khola Formation in the Surai Khola section, and to ~2.5 Ma at the top of the Binai Khola Formation in the Arung Khola–Tinau Khola section (Table 1). So, the development of the boundary between the Lower–Middle Siwalik and Middle–Upper Siwalik in the study area occurred before or around 8.5 Ma and 2.5 Ma, respectively.

The fluvial analysis on the Siwalik sediments reveals that the mudstone-dominated Lower Siwalik was deposited in a meandering river system, sandstone-dominated Middle Siwalik was deposited in a sandy braided river system and conglomerate-dominated Upper Siwalik deposited in a gravelly braided river system (Tokuoka et al., 1986; 1990; Dhital et al., 1995; Nakayama and Ulak, 1999; Ulak and Nakayama, 2001; Huyghe et al., 2005; Sigdel and Sakai, 2016; Rai and Yoshida, 2021). The Siwalik sediments of the study are dominated by mudstone, siltstone and fine-grained sandstone and a thinner succession of sandstone beds. In the well-studied sections of the Surai Khola in the west and the Arung Khola–Tinau Khola in the east of the study area, which are very close to our study area represented by mudstone, siltstone, very fine- to medium-grained sandstone and a thicker succession of sandstone beds (Tokuoka et al., 1986; 1990; Corvinus and Nanda, 1994; Dhital et al., 1995; Ulak and Nakayama, 2001).

These lithological variations suggest that the Siwalik Group in the Pattharkot–Thada area was deposited within a small river system and represents an interfluve setting of a larger fluvial system.

5. Conclusion

Lithostratigraphically, the Siwalik Group of the study area is divided into three mappable litho-units such as the mudstone-dominated Lower Siwalik, sandstone-dominated Middle Siwalik and conglomerate-dominated Upper Siwalik based on the lithological variation. We have used magnetostratigraphic data to determine the relative age of the development of boundary between the Lower–Middle Siwalik and Middle–Upper Siwalik of the study area occurred before or around 8.5 Ma and 2.5 Ma, respectively. Moreover, the lithological variations with the neighboring area of the Siwalik Group suggest that the deposits in the Pattharkot–Thada area were formed by a smaller river system. This indicates an interfluve setting within a larger river system, where finer sediments accumulated in a lower-energy environment, distinct from the main river channels.

Declaration of Competing Interest: The authors declare no competing interests.

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