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Lithostratigraphy of the Siwalik Group from the Arjun Khola section, Dang district, Mid-western Nepal

***Anil Datta Chaudhary[1], Purushottam Adhikari[1,2] and Khum Narayan Paudayal[1]**

[1]Central Department of Geology, Tribhuvan University, Kritipur, Kathmandu, Nepal
[2]Department of Geology, Birendra Multiple Campus, Tribhuvan University, Bharatpur, Chitwan, Nepal
**Corresponding author's email: anildattachy@gmail.com*

ABSTRACT

The fluvial sedimentary succession of the Siwalik Group is well exposed along the Inner Churia Range, bounded by the Deukhuri Dun valley to the south and the Dang Dun valley to the north, in the Arjun Khola section, mid-western Nepal. The lithostratigraphy of the succession is divided into the mudstone dominated Lower Siwalik, the sandstone dominated Middle Siwalik and the conglomerate dominated Upper Siwalik based on the lithological variation between mudstone and sandstone, grain size, texture and the distribution of the Siwalik sediments in three belts, which separated by the Central Churia Thrust (CCT) and the Arjun Khola Thrust (AKT) along the section. The magnetostratigraphic data and lithological characters are correlated with the measured thickness, indicate the Lower Siwalik was deposited between 12.5 and 10.98 Ma in the central belt and 12.83-11.5 Ma in the northern belts. Similarly, the Middle Siwalik of central and northern belts were deposited in 10.98-8.36 Ma and 11.5-8.9 Ma respectively. The lithological variation of the study area with other parts of the Siwalik sediments indicates that the study area was deposited in a small river system and represent an interfluve setting of a major river system.

Keywords: Siwalik Group, Lithostratigraphy, Arjun Khola, Mid-western, Nepal

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INTRODUCTION

The Siwalik Basin is one of the largest foreland basins on the Earth (Szulc et al., 2006) and it is an active collisional basin in the South Asia (Lyon-Caen and Molnar, 1985). The Indian subcontinents bent and flexure as a result of the Eurasian continents being uplift and loaded onto it, causing a depression adjacent to the Himalayan Mountain range formed the Siwalik Foreland basin (Lyon-Caen and Molnar, 1985). In this basin, there was a deposition of ~ 6 km thick succession of molasse sediments derived from denudation of the upliftment of the Himalayan Range (Gansser, 1964; Valdiya, 2002). The sediments were deposited by fine-grained meandering to gravelly braided river system during the middle Miocene to early Pleistocene (Parkash et al., 1980; Hisatomi and Tanaka, 1994; Nakayama and Ulak, 1999; Rai and Yoshida, 2021). Regarding the grain size of this unit, the entire sequence shows coarsening upward while individual beds are fining upward sequences (Parkash et al., 1980; Nakayama and Ulak, 1999). Tectonically, these group are separated from the Indo-Gangetic Plain towards south by the Himalaya Frontal Thrust (HFT) and from the Lesser Himalaya in the north by the Main Boundary Thrust (MBT) (Dhital, 2015; Baral et al., 2017). This group is divided into two belts named as southern and northern belts, which separated by the Central Churia Thrust (CCT) in the Arung Khola-Binai Khola-Tinau Khola area (Tokuoka et al., 1986; 1988; 1990), Hetauda-Amalekhganj (Nakayama and Ulak, 1999), and Chatara-Barahakshetra area (Adhikari et al., 2018). Even in some places, the units are breakdown into three belts (Shrestha and Sharma, 1996; Kafle et al., 2019; Acharya et al., 2020).

The lithostratigraphy of the Siwalik Group has been established by various researchers (Auden, 1935; Tokuoka et al., 1986; Ulak, 2009; Sigdel et al., 2011; Adhikari et al., 2018; Rai and Yoshida, 2020). There are numbers of classification system in the Siwalik Group such as the well accepted three-fold classification (tripartite classification) system (Auden, 1935; Ulak, 2009; Adhikari et al., 2018; Rai and Yoshida, 2020) and/or other used two- fold to five- fold classification system (Tokuoka et al., 1986; 1988; 1990; Dhital et al., 1995; Nakayama and Ulak, 1999; Sigdel et al., 2011). Previous studies along the Arjun Khola have focused on various aspects of the Siwalik sediments, including regional geology, landforms, magnetic properties, and plant life (Yamanaka and Yagi, 1984; DMG, 1987; Rösler et al., 1997; Kimura, 1998; Pradhan et al., 2000; Prasad and Gautam, 2016; Prasad et al., 2016; 2019). However, none of these investigations provided a comprehensive description of the rock layers in the area. The large-scale detail geological mapping aids in highlighting the minute structural and lithological details that are still lacking in the region. Therefore, the present study mainly focused on the detail description of lithological characteristics and stratigraphic classification along the Arjun Khola section, mid-western Nepal (Fig.1) based on the classical tripartite classification system.

METHODS

Field data was collected along the Lamahi-Ghorahi road and Arjun Khola sections, which separate the Deukhuri and Dang Dun valleys. Detailed lithological logs and a 1:100 scale route map were created for all rock exposures and divided into distinct lithological units. Rocks were categorized as mudstone, siltstone, sandstone, or conglomerate based on their composition, texture, and grain size. The precise age of each lithological unit was determined using the magnetostratigraphic data for the Arjun Khola area, established by Rösler et al. (1997). These data were then used to correlate the local sequence with other parts of the Nepal Himalaya.

LITHOSTRATIGRAPHY

The present study area bounded between the Deukhuri Dun valley to south and Dang Dun valley to north and called the Inner Churia Range. In this study area, the rocks of Siwalik succession are distributed in three belts by the Central Churia Thrust (CCT) and Arjun Khola Thrust (AKT) (Fig. 2). The southern belt separated by the Deukhuri Dun valley to south and the CCT to north comprises the Upper Siwalik. The central belt separated by the CCT to south and the AKT to north and northern belt bounded by the Dang Dun valley to north and the AKT to south. However, two litho-units, the Lower Siwalik and the Middle Siwalik are observed in both central and northern belts (Fig. 2). Lithostratigraphically, the Siwalik Group of the Arjun Khola section is divided into three litho-units i.e., the Lower Siwalik, Middle Siwalik and Upper Siwalik in ascending order (Fig. 2).

Lower Siwalik

The Lower Siwalik is prominently exposed along the Arjun Khola near Khulmohar and Ghodebas villages, the Masot Khola near Rajkhutti village and the Lamahi–Gorahi road section. This litho-unit primarily consists of mudstone and siltstone, fine-grained sandstone (Fig. 3a). The total thickness of this unit exceeds 900 m in the central belt and 1275 m in the northern belt. The mudstone and siltstone are dominated in the lower part (Fig. 4a–c) and fine-grained sandstone is dominated in the upper part (Fig. 4d).

The Lower Siwalik is composed primarily of alternating layers of variegated mudstone and light grey siltstone, interbedded with fine-grained sandstone in various shades of grey. Mudstone and siltstone beds typically range in thickness from 35 to 640 cm and 15 to 475 cm, respectively, while fine-grained sandstone beds vary from 20 to 420 cm thick. Additionally, fine- to medium-grained, light grey sandstone beds averaging 30-370 cm thick are present. The middle portion includes medium-grained sandstone beds in shades of light grey and greenish grey, with thicknesses ranging from 12 to 85 cm. Coarse-grained, "pseudo-salt and pepper" sandstone beds, averaging 20-135 cm thick, occur sporadically in the upper part.

Mudstone beds are generally variegated and mottled, often containing bioturbation, burrows, nodules, and concretions, especially in the lower sections. Sandstone beds exhibit various sedimentary structures, including planar and trough cross stratification, parallel lamination, ripple cross stratification, and lateral accretion. A distinct fining-upward sequence with numerous erosional surfaces is observed. Calcretes are prominent within mudstone and siltstone beds (Fig. 3b). Evidence of organic activity, such as sandpipes, carbonized roots, and leaf fossils (primarily found in light to dark grey mudstone and siltstone) is abundant. Fine-grained, light grey sandstone beds occasionally contain light to dark grey, angular to sub-rounded mud clasts up to 2 cm in diameter.

Middle Siwalik

The Middle Siwalik is significantly exposed along the Arjun Khola near Ghodebas, Beldamar, and Maine villages, the Masot Khola near Rajbas and Chisapani villages, and the Lamahi-Gorahi road near Chaupatta village. This unit comprises primarily medium- to coarse-grained "salt and pepper" sandstone, along with mudstone and siltstone (Fig. 3d). The total thickness of this unit exceeds 625 meters in the central belt and 1375 meters in the northern belt (Fig. 2b). Fine- to medium-grained sandstones dominate the lower portion (Fig. 5a-b), while coarse-grained and pebbly sandstones predominate in the upper part (Fig. 5c-d).

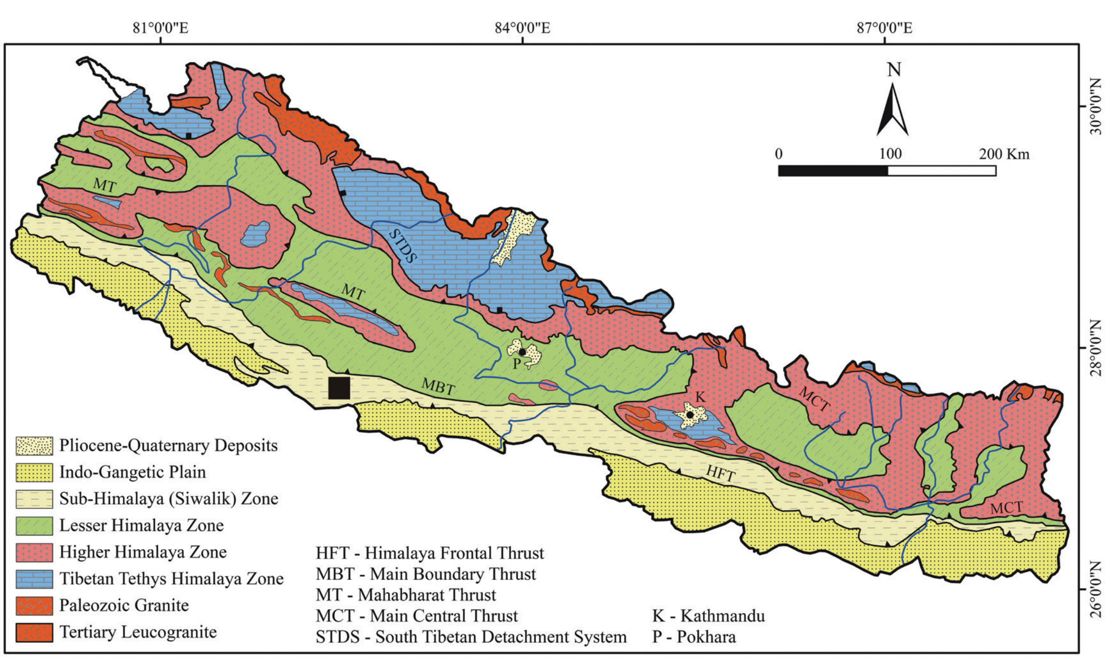


Fig. 1: Geology of the Nepal Himalaya (modified after Martin et al., 2005) showing Black rectangle indicates study area.

The main lithology of the Middle Siwalik consists of medium- to coarse-grained, "salt and pepper" texture appearance, light grey, light yellowish grey sandstone, pebbly sandstone, interbedded with fine-grained, light grey, greenish grey sandstone, light to dark grey mudstone and light grey, greenish grey siltstone. The thickness of medium- to coarse-grained, "salt and pepper" sandstone is 200−1150 cm. However, fine-grained sandstone beds are 15−600 cm thick. Light to dark grey mudstone with 10−400 cm and light grey to greenish grey siltstone beds with 12−290 cm average thick beds are observed. Coarse-grained, "salt and pepper" sandstone with rounded to well-rounded pebbles of sandstone, quartzite, limestone, dolomite etc. with average thickness ranging from 50−1135 cm are observed in middle and upper parts. Fining upward successions are commonly observed. Indurated sandstone beds are common in lower part and compared to upper parts are less indurated. Medium- to coarse-grained, amalgamated sandstone with up to 1230 m thick beds are common and show fining upward succession. Variegated mudstone beds are occasionally observed. Parallel lamination (Fig. 6a), ripple cross stratification (Fig. 6a), Planar cross stratification (Fig. 6b) and trough cross stratification are common in amalgamated

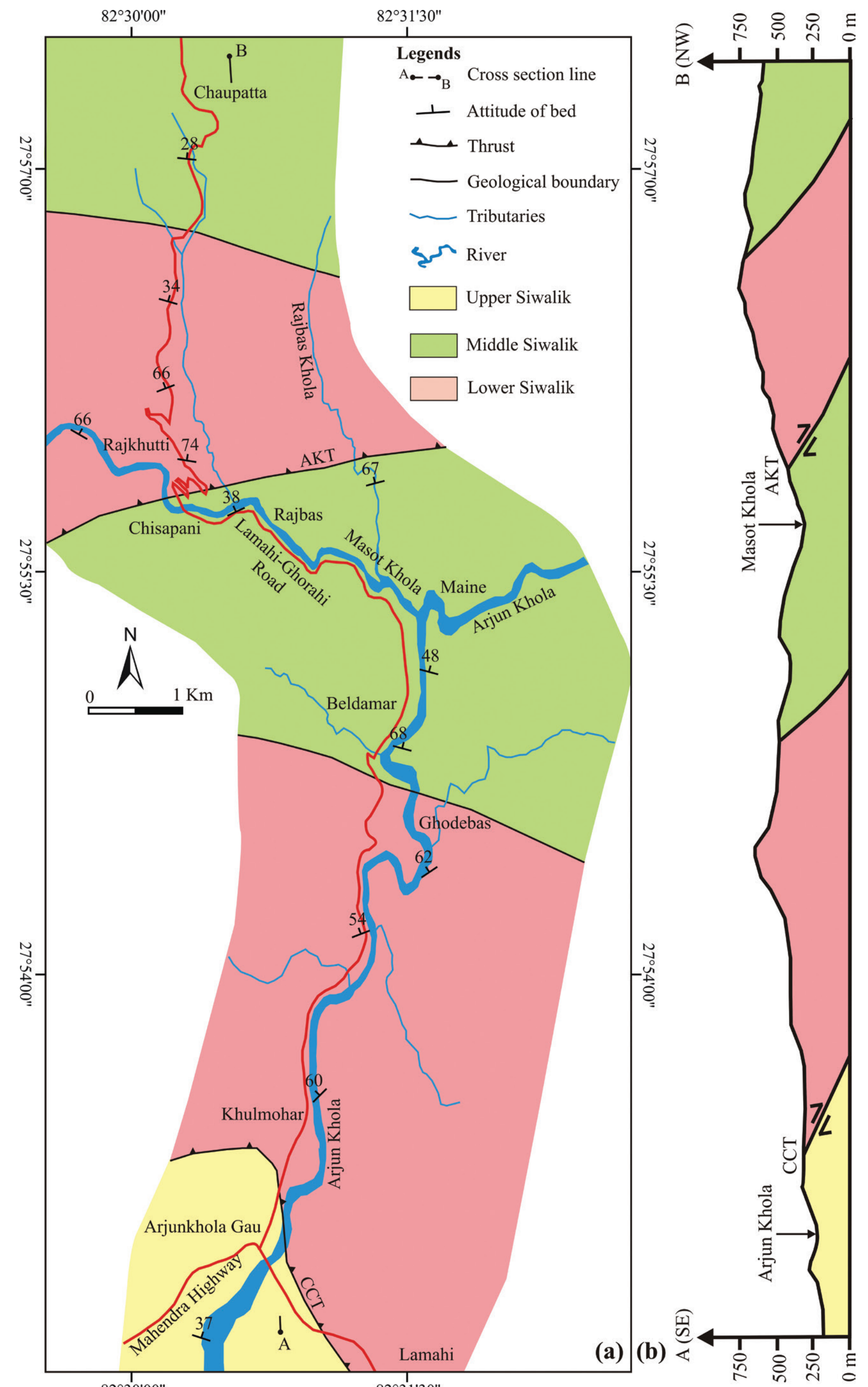


Fig. 2: (a) Geological map of the Siwalik Group along the Arjun Khola section (b) Cross-section along line A-B.

Fig. 3: Outcrop photographs of (a) Interbedding of mudstone, siltstone and fine-grained sandstone of the Lower Siwalik (b) Calcrete observed in siltstone beds of the Lower Siwalik (c) Trace of organic activity observed in siltstone beds of the Lower Siwalik (d) interbedding of the sandstone, mudstone and siltstone of the Middle Siwalik.

sandstone beds. The 10–35 cm thick of Channel lag deposits are also observed. In Upper parts, granules-cobble-pebble size, rounded to subrounded, well sorted, clast supported conglomerate with 20–500 cm thick are also frequently observed (Fig. 6f). Calcrete are most pronounced in siltstone beds but decrease in this litho-units as compared to the Lower Siwalik. Bioturbation (Fig. 7a), sandpipe (Fig. 6d), carbonized wood lens (Fig. 7c) are abundant in siltstone and sandstone beds. Leaf fossils (Fig. 7b) are most observed in light grey to dark grey mudstone and siltstone beds. Mud ball, sand ball and mud clast (Fig. 6d) are observed in sandstone beds, which are light to dark grey, sub-rounded–rounded to angular size with average diameter up to 15 cm. Convolute structure (Fig. 6c) and syn-tectonic deformation (Fig. 6e) are also observed in sandstone beds and concretion is infrequently observed in siltstone and mudstone beds.

Upper Siwalik

The Upper Siwalik is prominently exposed near the Arjunkhola Gau (gau means village) along the Arjun Khola. This unit is characterized by a thickness exceeding 1275 meters and is predominantly composed of conglomerates (Fig. 7d), with subordinate sandstones, mudstones, and siltstones. The lower part of the unit contains well-sorted conglomerates, while the upper part exhibits poorly sorted conglomerates (Fig. 8).

Conglomerates within the Upper Siwalik are thick- to very thick-bedded, clast-supported, and composed of cobbles and pebbles set in a medium- to coarse-grained sand matrix. Clasts are predominantly well-rounded to subrounded sandstone and quartzite, with minor carbonate and shale fragments. Conglomerate beds range from 6 to 16 meters in thickness and show an upward increase in clast size. Interbedded with the conglomerates are thinner beds of coarse-grained, light grey to yellowish grey, "salt and pepper" sandstones, along with minor mudstones and siltstones. Sedimentary structures are limited, with poorly developed planar cross-stratification in sandstones and occasional bioturbation in mudstones. Fining-upward sequences are indistinct due to frequent erosional surfaces.

DISCUSSION

Comparison with magnetostratigraphic data and previous works

Rösler et al. (1997) analyzed the magnetic polarity from the Lower to Middle Siwalik in the central and northern belts of the studied area and correlated with standard polarity time scale (Cande and Kent, 1995). The base point of the magnetic

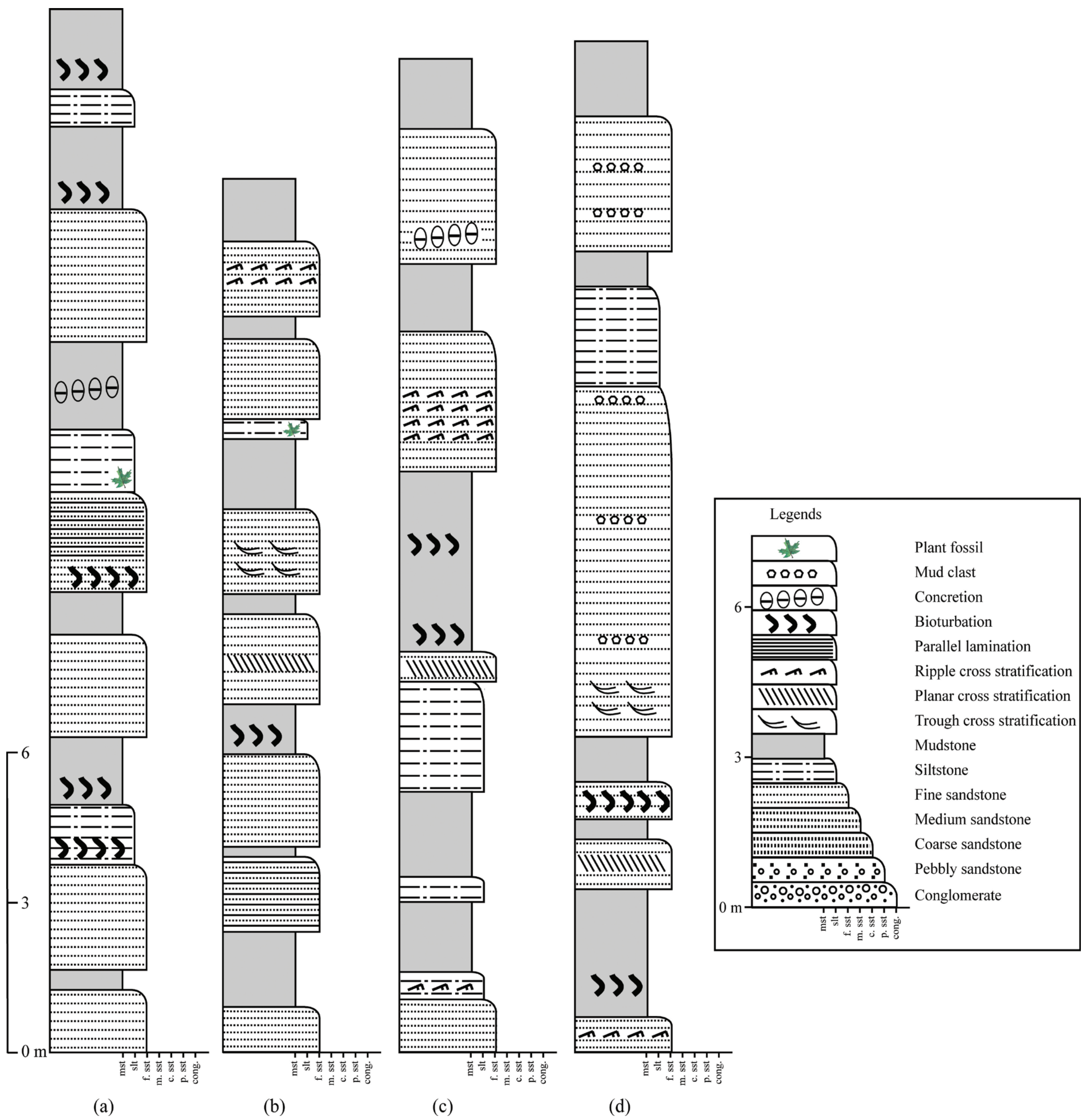


Fig. 4: Representing lithological logs of the Lower Siwalik (a-b) Lower parts of the Lower Siwalik (c-d) Upper parts of the Lower Siwalik.

polarity along the Lamahi-Ghorahi Road, near Khulmohar village and the northern belts of the Lower and Middle Siwalik stretches along the Lamahi-Ghorahi Road, near the Masot Khola bridge (Rösler et al., 1997) with same stratigraphic position of the present studied. So, the estimated age with comparing the standard polarity time scale of the study area ranges from ca. 12.5 to 8.36 Ma (Chron 5A to Chron 4r) in the central belt and ca. 12.83 to 8.9 Ma (Chron 5A to Chron 4An) in the northern belt. The age boundary between the Lower and Middle Siwalik of the central and the northern belts are 10.98 Ma (i.e. near base of the Chron 5n) and 11.05 Ma (i.e. near top of the Chron 5r) respectively (Fig. 9).

The Lower Siwalik sandstones are characterized by a low matrix content and moderately to well-sorted detrital grains. The most dominant grains are quartz with subordinate numbers of feldspar do present along with the lithic fragments. Lithic grains are dominant in sedimentary and metamorphic origin and extremely rare grains are of volcanic ones (Baral et al., 2016; 2017; Nakajima et al., 2022; Rai et al., 2021). However, the Middle Siwalik sandstone mainly composed of matrix well, moderately to well sorted detrital grains. The quartz grains are abundant whereas, subordinate numbers of feldspar grains do present but as compare to the Lower Siwalik these grains are higher in number. Lithic fragments are dominantly metamorphic and volcanic origin and sedimentary origin are extremely rare (Baral et al., 2016; 2017; Rai et al., 2021). It suggests that the Lower and Middle Siwalik sediments were dominantly sourced from the Himalayan units: Lesser, Higher and Tethys Himalayan Sequence (Baral et al., 2016, 2017;

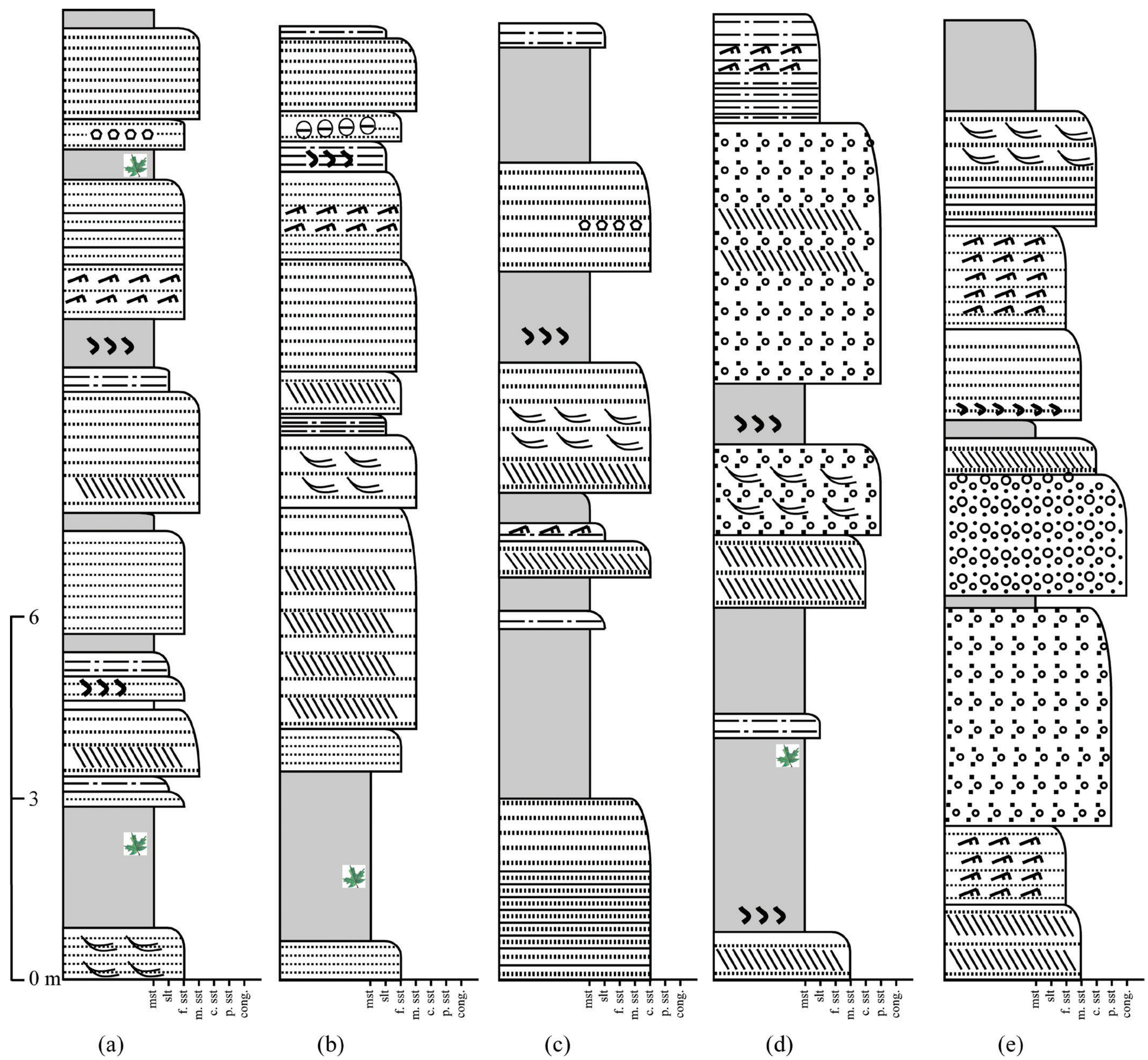


Fig. 5: Representing lithological logs of the Middle Siwalik (a-c). Lower parts of the Middle Siwalik (d-e) Upper parts of the Middle Siwalik.

Rai et al., 2021). However, the mineral assemblages of muscovite and biotite grains increase in the Middle Siwalik (Baral et al., 2015; 2017; Rai et al., 2021). Moreover, after the deposition of the Middle Siwalik there was an activation the Ramgarh Thrust (RT; DeCelles et al., 2001; Pearson and DeCelles, 2005; Baral et al., 2017) resulting the more input from the Lesser Himalayan detritus. The thrust sheets as the MBT and RT in the western Nepal were activated at ~10 and ~11 Ma that causes the exhumation and denudation pattern of the Lesser Himalayan Duplex in the western Nepal and the proportion of eroded materials from the Lesser Himalaya deposited in the Middle Siwalik (DeCelles et al., 2001; Pearson and DeCelles, 2005; Baral et al., 2017). The activation of the MBT and RT, the vegetation and floristic pattern of the Lower and Middle Siwalik has also affected. The floristic assemblages of the Lower and Middle Siwalik suggested a vegetation shift from the dominance of wet evergreen forest to moist deciduous forest from the Lower Siwalik to Middle Siwalik (Srivastava et al., 2018; Adhikari et al., 2024). This vegetation shift suggests a C_4 plant replaced C_3 plant during the deposition time of Middle Siwalik (Hoorn et al., 2000; Srivastava et al., 2018).

The geology and plant fossil has been conducted in the Arjun Khola section and its surrounding area (DMG, 1987; Pradhan et al., 2000; Prasad et al., 2016, 2019). Among these studied, DMG (1987) and Pradhan et al. (2000) deal with the lithostratigraphy of the vicinity of the study area. According to DMG (1987) and Pradhan et al. (2000), the study area is divided into three litho-

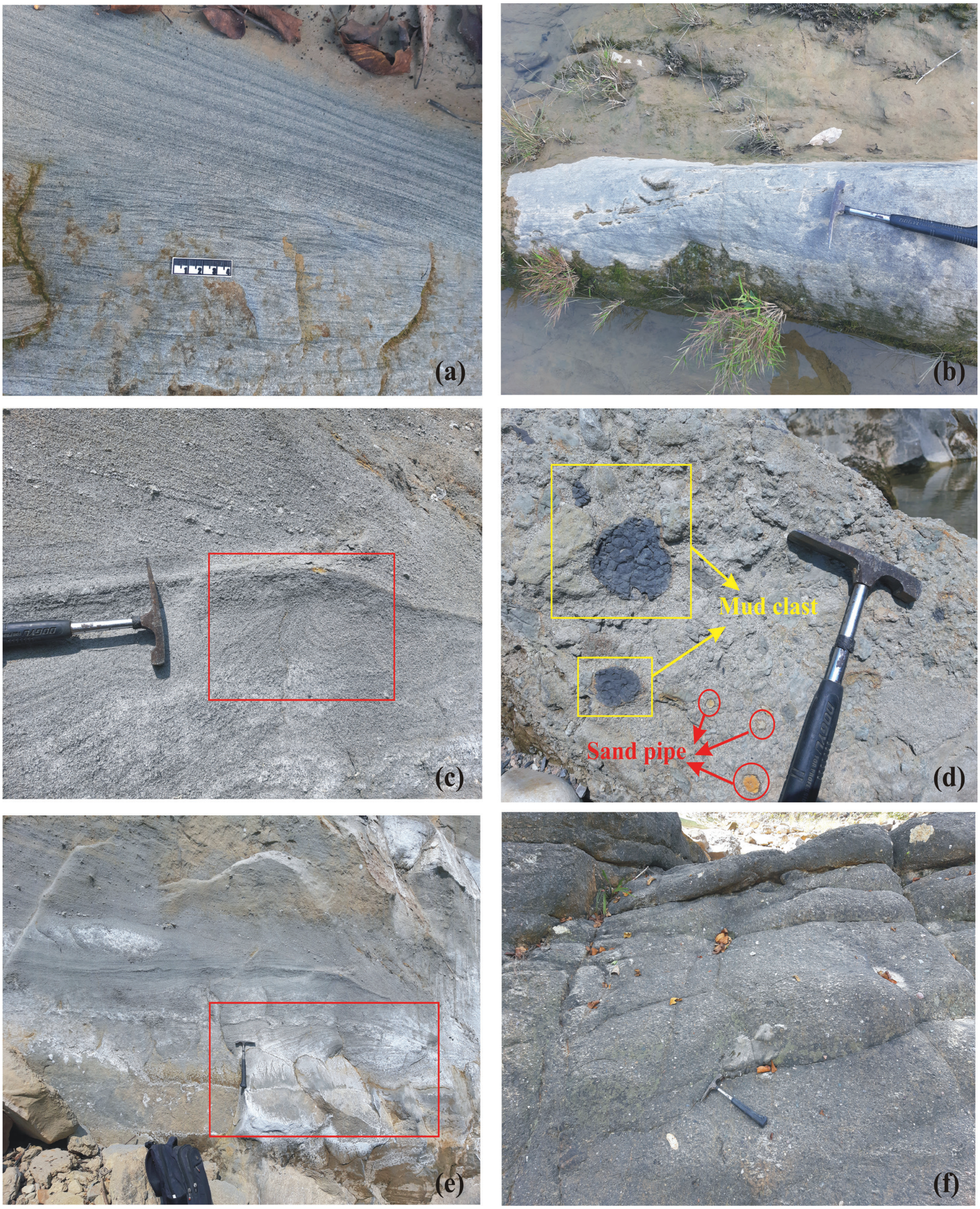


Fig. 6: Outcrop photographs of (a) Parallel lamination and ripple cross lamination observed in coarse-grained sandstone of the Middle Siwalik (b) planar cross stratification observed in coarse-grained sandstone of the Middle Siwalik (c) Convolute structure of the Middle Siwalik (d) Mud clast and sandpipe observed in fine-grained sandstone beds of the Middle Siwalik (e) Syn-tectonic deformation observed in coarse-grained sandstone beds of the Middle Siwalik (e) Clast supported conglomerate beds of the Middle Siwalik.

Fig. 7: Outcrop photographs of (a) Bioturbation surface observed in fine- to medium-grained sandstone beds of the Middle Siwalik (b) Leaf fossil observed in siltstone beds of the Middle Siwalik (c) Carbonized wood lens observed in fine-grained sandstone beds of the Middle Siwalik (d) Clast supported conglomerate beds of the Upper Siwalik.

units named as the Lower Siwalik, lower and upper member of the Middle Siwalik and Upper Siwalik. In their geological map was prepared on the regional scale. So, it is not clear the exact boundary between the each litho-units. DMG (1987) has not divided into the Siwalik succession and not placed any thrust in that succession but in the present study, the Siwalik succession is divided into three belts namely, southern, central, and northern belts. Pradhan et al. (2000) has divided into three belts such as southern (Lower Siwalik, lower and upper member of Middle Siwalik and Upper Siwalik), central (lower and upper member of Middle Siwalik and Upper Siwalik) and northern (Lower Siwalik). Also, in central parts of the study area placed in back thrust, but the present study it is just opposite. The present study, the study area is divided into three belts namely southern (Upper Siwalik), central (Lower Siwalik and Middle Siwalik) and northern (Lower Siwalik and Middle Siwalik) which is separated by the Central Churia Thrust (CCT) and the Arjun Khola Thrust (AKT) respectively. The various primary structures such as ripple cross stratifications, planar and trough cross stratifications show that all three belts of study area are normal sequences.

Correlation

The lithological correlations of the study area with other parts of the Siwalik sediments in the Nepal Himalaya is shown in Table 1. Lithological characters of the Lower Siwalik are mudstone, siltstone interbedded with fine-grained sandstone, which are correlated with the Chisapani Formation in the Karnali River section (Sigdel et al., 2011), the Bankas Formation and the Jungli Khola member of the Chor Khola Formation in the Surai Khola section (Dhital et al., 1995), the Arung Khola Formation in the Arung Khola–Tinau Khola section (Tokuoka et al., 1986; 1988), the Rapti Formation in Hetauda–Bakaiya Khola section (Nakayama and Ulak, 1999), Lower Siwalik in Muksar Khola section (Rai and Yoshida, 2020). Similarly, the lithological characters of the Middle Siwalik are medium- to coarse-grained ‘salt and pepper’ sandstone interbedded with mudstone, siltstone and fine-grained sandstone and this litho-unit has lithological similarity with the Baka Formation in the Karnali River section (Sigdel et al., 2011), the Shivaghari member of the Chor Khola Formation and the Surai Khola Formation in the Surai Khola section (Dhital et al., 1995), the Binai Khola Formation in the Arung Khola–Tinau Khola section (Tokuoka et al., 1986; 1988), the Amalekhganj Formation in Hetauda–Bakaiya Khola section (Nakayama and Ulak 1999), Middle Siwalik in Muksar Khola section (Rai and Yoshida, 2020). However, the lithological character of the Upper Siwalik are matrix-supported, poorly to well sorted, cobble-pebble conglomerate interbedded mudstone and siltstone and it has similarity with the Kuine Formation in the Karnali River section (Sigdel et al., 2011), the Dobata

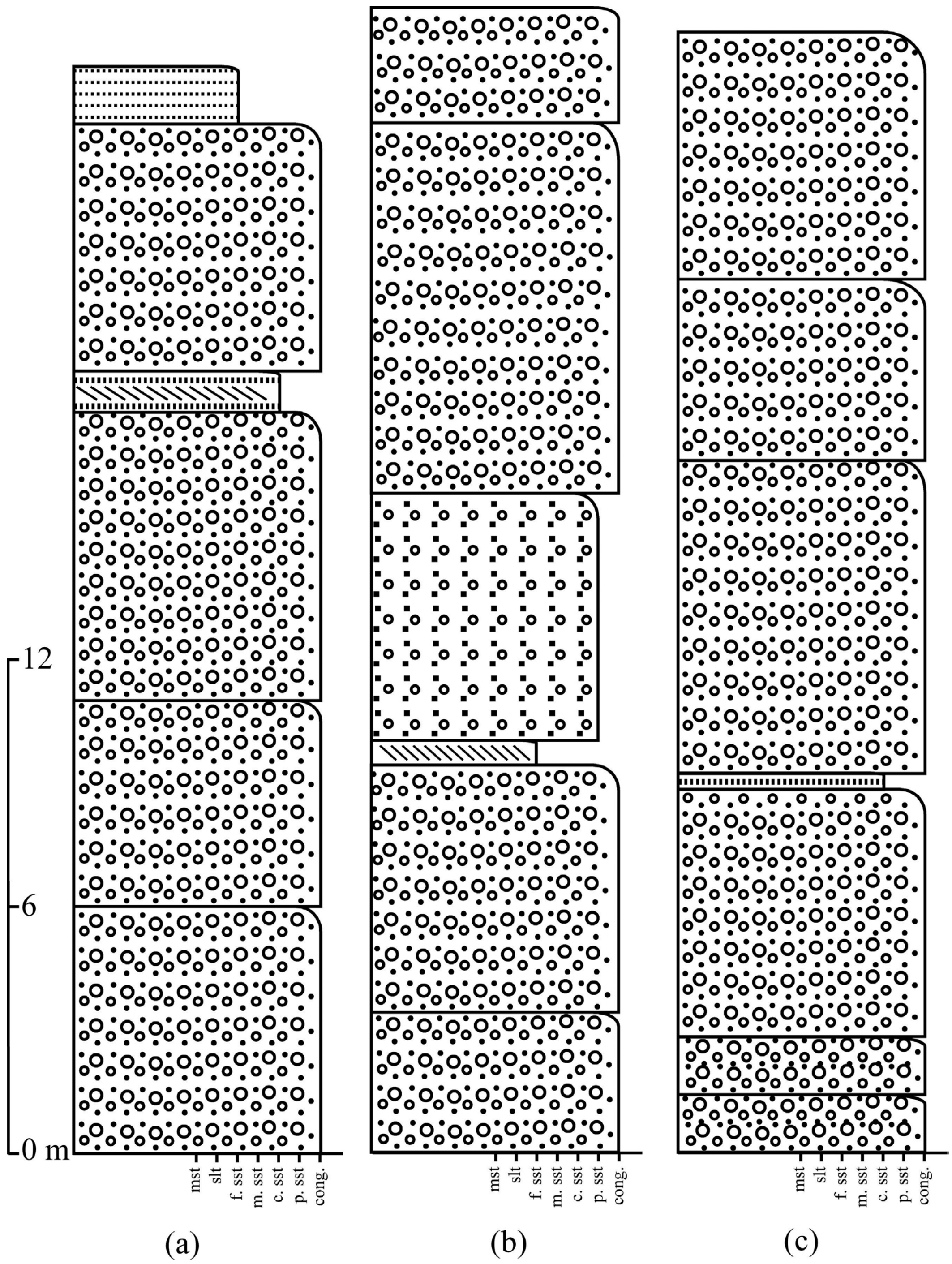


Fig. 8: Representing lithological logs of the Upper Siwalik (a-b) Lower parts of the Upper Siwalik (c) Upper parts of the Upper Siwalik Siwalik.

Formation in the Surai Khola section (Dhital et al., 1995), the Chitwan Formation in the Arung Khola–Tinau Khola section (Tokuoka et al., 1986; 1988), the Churia Khola Formation in Hetauda–Bakaiya Khola section (Nakayama and Ulak, 1999), Upper Siwalik in Muksar Khola section (Rai and Yoshida, 2020).

The Siwalik foreland basin, shaped by diverse river systems, was influenced by the climate, tectonics, and topography of the Himalayas (Nakayama and Ulak, 1999). Consequently, the basin exhibits significant lithological variations. However, the basin's tectonic and climatic history was not uniform (Yin, 2006). The varying thickness of Siwalik sediments, deposited by different river systems originating from the Himalayas, resulted in both vertical and lateral lithological changes (Nakayama and Ulak, 1999).

While various classification systems have been proposed for the Siwalik succession, three- fold to five- fold classification system, this study adopts a widely accepted three-fold division (Table 1; (Tokuoka et al., 1986; Nakayama and Ulak, 1999; Sigdel et al., 2011). The Lower Siwalik, dominated by

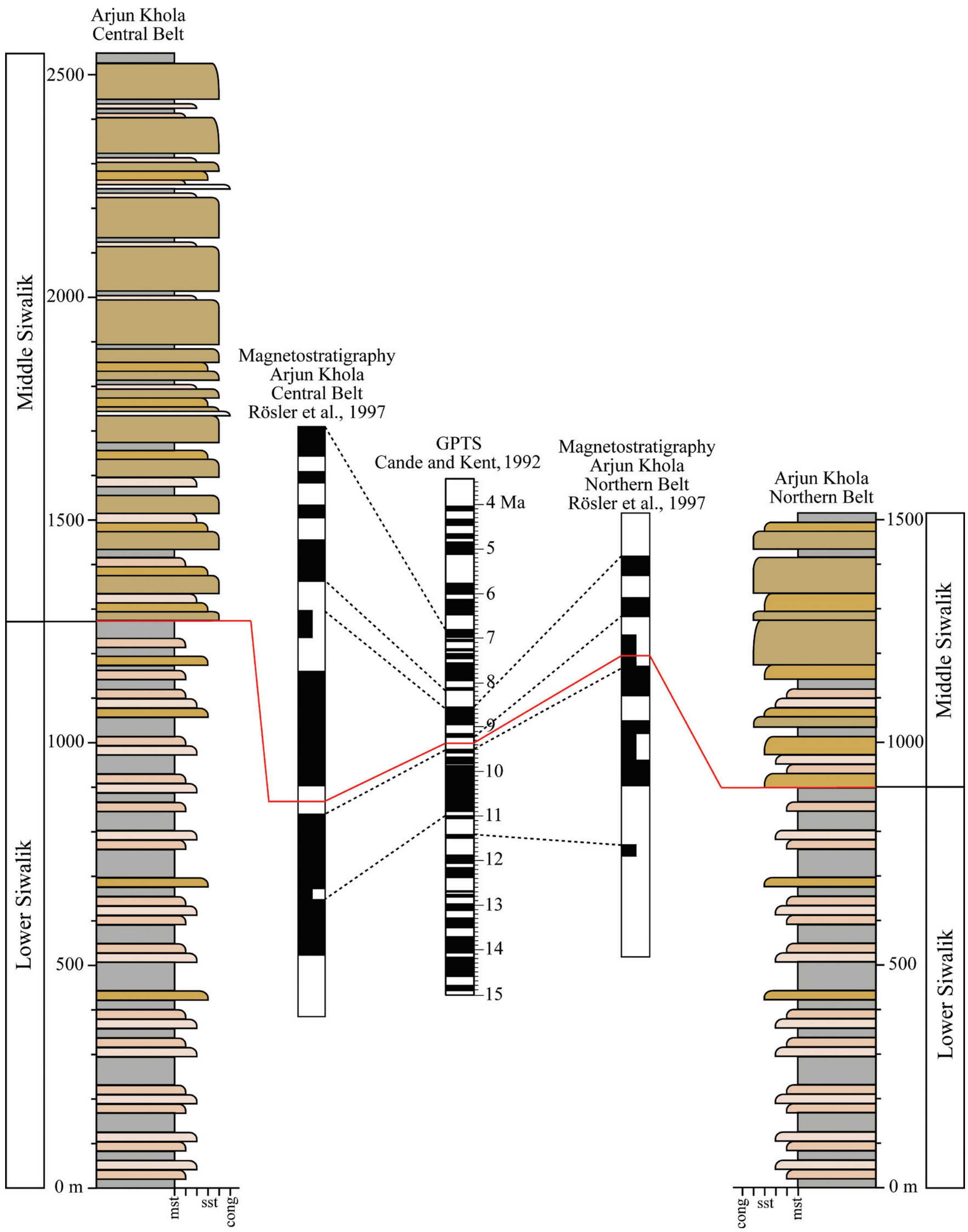
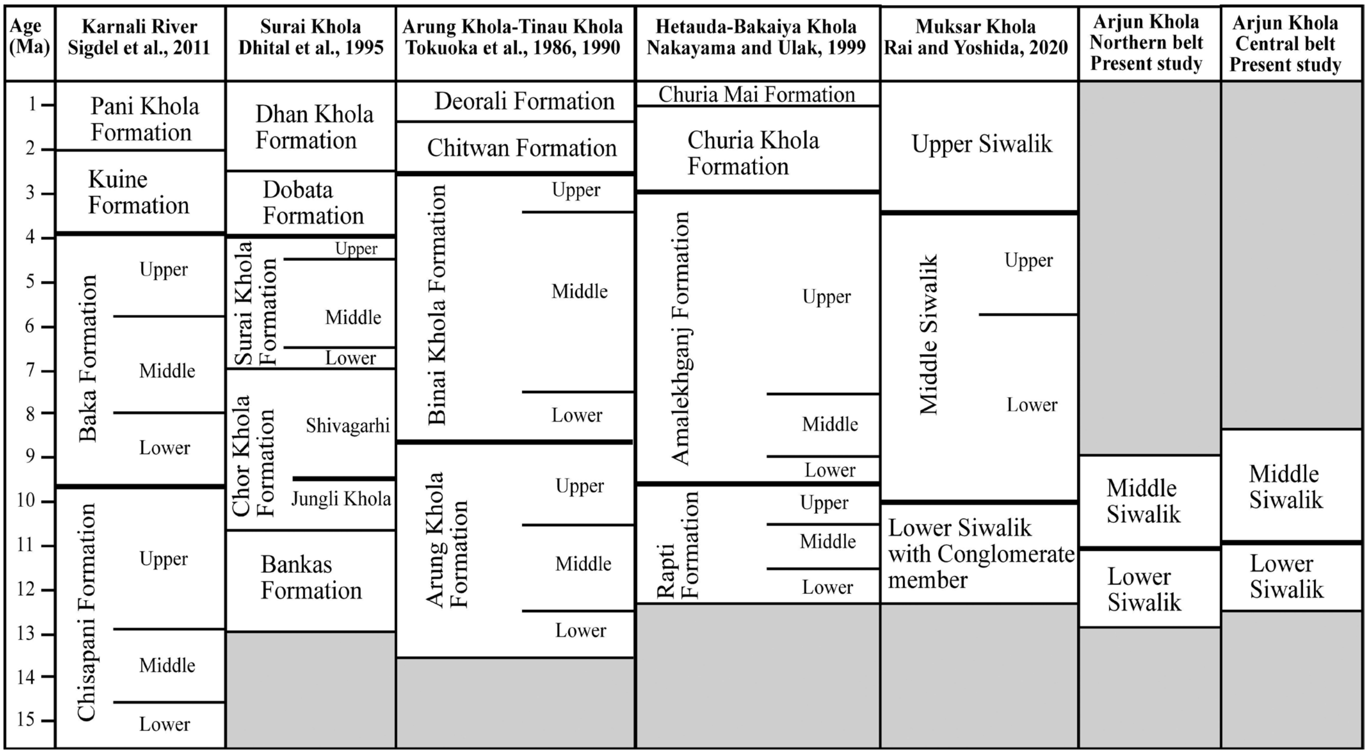


Fig. 9: Lithostratigraphic division of the Siwalik Group along the Arjun Khola with respect to the magnetostratigraphic age data.

mudstones, represents a meandering river environment. The sandstone-rich Middle Siwalik reflects a sandy braided river system, whereas the conglomerate-dominated Upper Siwalik indicates a gravelly braided river setting.

Comparative analysis of the Arjun Khola and Surai Khola sections reveals lithological differences despite their proximity. The Lower Siwalik is dominated by mudstone facies and were deposited in meandering river system, the Middle Siwalik is dominated sandstone facies and were deposited in sandy braided river. However, the conglomerate facies are dominated in the Upper Siwalik and were deposited in gravelly braided river (Nakayama and Ulak, 1998; Sigdel et al., 2011; Rai and Yoshida, 2021). The Arjun Khola section's predominance of mudstones, siltstones, and thin sandstones contrasts with the Surai Khola's mudstones, siltstones, and thicker sandstones (Corvinus and Nanda, 1994; Dhital et al., 1995). These variations suggest that the Arjun Khola area represents a smaller river system within a larger drainage basin.

Table 1: Lithostratigraphic correlation of the present study with representing the Siwalik section of Nepal.



CONCLUSION

The Siwalik Group in the study area is divided into the Lower, Middle, and Upper Siwaliks based on lithological variations, grain size, and texture. The Lower Siwalik comprises predominantly mudstones and siltstones with interbedded fine-grained sandstones. The Middle Siwalik is characterized by medium- to coarse-grained "salt and pepper" sandstones, often with pebbles, interbedded with finer-grained sandstones, mudstones, and siltstones. The Upper Siwalik is dominated by poorly to moderately sorted, clast-supported conglomerates with pebbles and cobbles, along with interbedded sandstones, mudstones, and siltstones.

Magnetostratigraphic data, correlated with lithological characteristics and thickness measurements, indicate that the Lower Siwalik was deposited between 12.5 and 10.98 Ma in the central belt and between 12.83 and 11.5 Ma in the northern belt. The Middle Siwalik was deposited between 10.98 and 8.36 Ma in the central belt and between 11.5 and 8.9 Ma in the northern belt. Lithological comparisons with other Siwalik regions suggest that the study area represents a smaller river system within a larger drainage basin.

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