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Geological study of the Khutti Khola Watershed, Siraha District, eastern Nepal

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ABSTRACT

This study presents a detailed geological mapping at a 1:25,000 scale, aiming to establish the stratigraphy and geological structures of Khutti Khola Watershed, Lahan and Dhangadhi Municipalities, Siraha district. The Sub-Himalayan rock sequence of the study area is divided into the Lower Siwalik, Middle Siwalik, and Upper Siwalik units. The Middle Siwalik is further subdivided into the Middle Siwalik 1 and the Middle Siwalik 2. Structurally, the Main Frontal Thrust (MFT) divides the Terai Plain to the southern section and the Siwalik Group to the northern section. The Terai plain is subdivided into the Bhabar Zone and the Middle Terai in the studied section. Lithologically, the study area is characterized by sedimentary rocks, including siltstone, variegated mudstone, and fine-to coarse-grained sandstone. Features like the slickensides on sandstone, shear zones with many landslides, fault breccias, and sudden topographic breakages are field evidence to locate the MFT in the field. The sandstone in the Lower and the Middle Siwalik are classified as Feldspathic Wacke while those in the Upper Siwalik are as Lithic Arenite.

Keywords: Khutti Khola watershed; Geological mapping; Sub-Himalaya; Terai plain

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INTRODUCTION

The Siwalik Group comprises Middle Miocene to Early Pleistocene fluvial molasse sediments, forming Nepal's southernmost Churia hills which are bounded by the Main Boundary Thrust (MBT) to the north and the Main Frontal Thrust (MFT) to the south, constituting a key facet of the Himalayan foreland basin (Gansser 1964; Gautam and Appel, 1994; Ojha et al., 2009). Geologically, the Siwalik Group (Sub-Himalaya) of the Nepal Himalaya is subdivided into the Lower Siwalik, Middle Siwalik, and Upper Siwalik by various researchers (Auden 1935; Hagen 1969; Yoshida and Arita 1982; Dhital 2015; Rai and Yoshida 2020).

The Siwalik range serves as an important water catchment area with numerous rivers and streams. The Khutti Khola watershed represents the catchment areas of rivers originating from the Siwalik. The Siwalik Group characterized by its fragile lithological composition is prone to landslides and flooding during the rainy season due to the instability of loose sedimentary rocks (Tamrakar et al., 2002; Upreti, 2001; Dolidar, 2013; Dhakal 2014; Neupane and Paudyal, 2021; Dahal and Paudyal, 2022, Neupane et al, 2023). Pradhan et al. (2004) prepared a regional-scale geological map of the Khutti Khola watershed on a 1:250,000 scale and divided the study area into the Siwalik Group and the Terai Plain. The Siwalik Group is further subdivided into the Lower, Middle, and Upper Siwalik units, and the Middle Siwalik is further classified into the Lower and Upper Members (Ulak 2009). The sandstone in the Lower Siwalik and the Middle Siwalik are classified as Feldspathic Wacke and those in the Upper Siwalik as Lithic Arenite (Pettijohn et al. 1987). This study presents a detailed geological map and cross-section at a scale of 1:25,000, and a petrographic analysis of representative rocks from each geological unit.

LOCATION AND ACCESSIBILITY

The Khutti Khola watershed area lies between 26° 42' 20" to 26° 55' 0" north of latitude and 86° 23' 30" to 86° 31' 10" east of longitude, spans across the Lahan municipality and Dhangadhimai municipality within the Siraha district of the Madhesh province (Fig. 1). The Khutti Khola watershed is characterized by major tributaries such as the Khutti Khola, Sarre Khola, Ambule Khola, Maini Khola, Maina Khola, Raini Khola, Raydhar Khola, Dalame Khola, Mahajani Khola, and Madhyan Khola, exhibits a dendritic to parallel drainage pattern. The topography of the study area ranges from gentle to steep hills in the northern part to flat plains in the southern section. The area is accessible via the East-West Highway, Mahendra Highway, and B. P. Highway.

METHODOLOGY

The research methodology adopted for this research involves four steps, starting with a comprehensive review of relevant literature concerning the region's geology, and then pinpointing specific geological challenges for further investigation. Four topographical maps namely Risku (2686 02B), Dhangadhimai (2686 02 D), Lahan (2686 06 B), and Kadarbona (2686 07A) each at a 1:25,000 scale have been used as base maps to facilitate the geological mapping process during fieldwork. Furthermore, the study involved analyzing Google Maps and aerial photographs to accurately delineate the watershed boundary on the base map. During the initial phase, stratigraphy was established through fieldwork involving numerous

reconnaissance traverses along existing foot trails, where columnar sections were prepared at key locations. Optimal routes were carefully chosen to maximize the efficiency of detailed geological fieldwork within a constrained time frame. The geological traverses were specifically aimed at evaluating lithology, measuring rock orientation and thickness, assessing grain size variation, examining weathering conditions, and identifying primary sedimentary structures to determine the stratigraphic sequence. The nomenclature of the stratigraphic units was adopted from (PEPP, 2006), Pradhan et al. (2004), and Dhital (2015). Various geological features such as topographic breakage, spring line development, landslides, slickensides, shear zones, fault gouges, fault breccias, and quartz veins were observed as the field evidence of thrusts and field photographs were taken to show the field conditions. The geological data was carefully analyzed in a structured manner to ensure that all aspects of the research were connected smoothly. Thin sections of each representative rock sample were prepared and Dott's classification by Pettijohn et al. (1987) was adopted for the classification of sandstones based on mineral percentage. Additionally, mineral texture and microscopic structures were studied to classify the rock types. Ultimately, the columnar sections, geological maps, and cross-sections were prepared, and petrographic analysis, analyzing geological structures such as folds were analyzed with the aid of software including Geographic Information System (GIS), Adobe Illustrator, Adobe Photoshop CS, Dips 6.0, and Google Earth Pro.

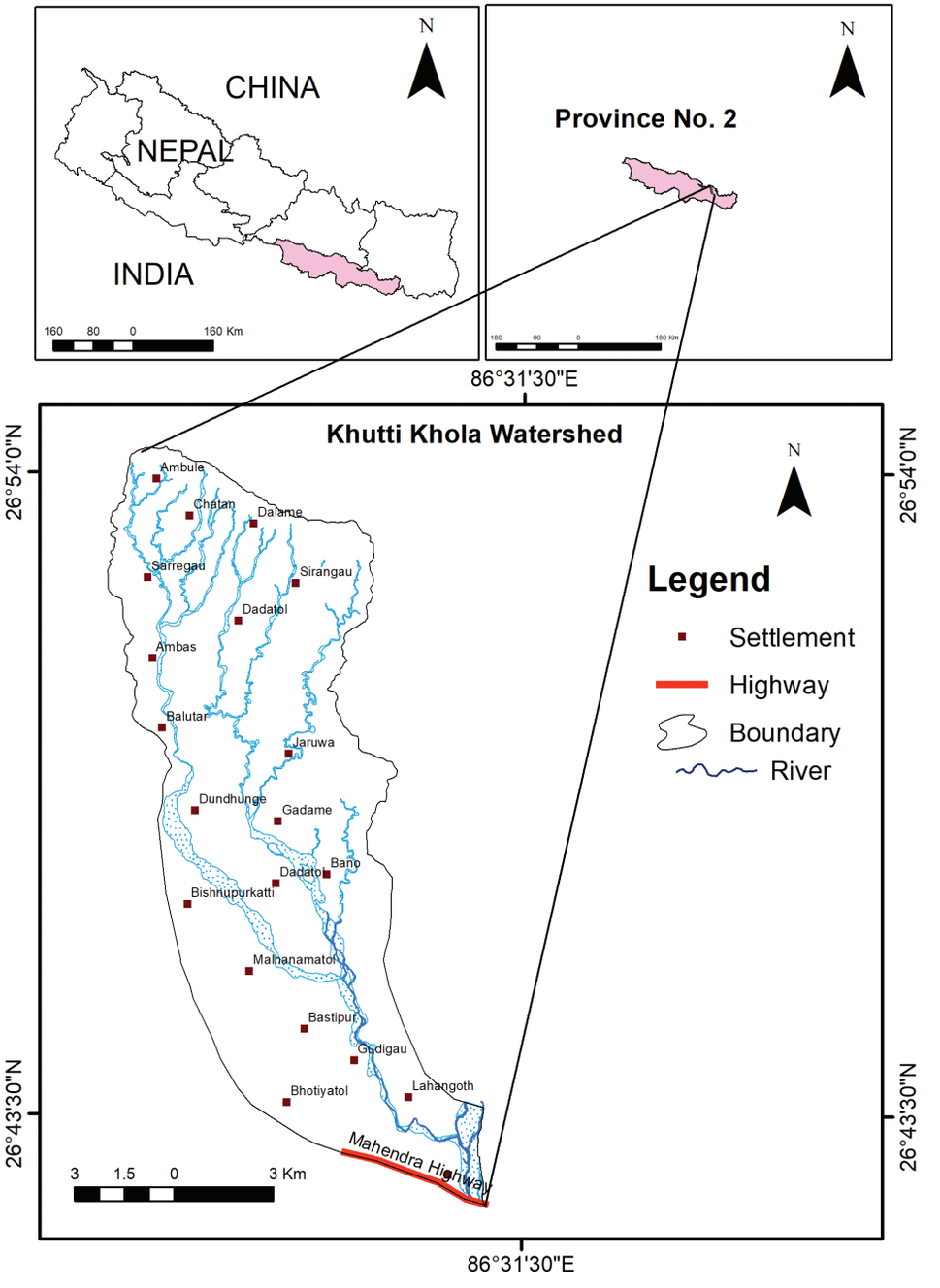

Fig. 1: Location map of the Khutti Khola watershed area.

RESULTS

Stratigraphy

The Khutti Khola watershed area can be divided into the Sub-Himalaya and the Terai plain. The Recent Riverbed Deposits cover some parts of the study area along the river course (Fig. 2 and Fig. 3). The Sub-Himalaya and the Terai plain are separated by the Main Frontal Thrust. The rock sequence of the Sub-Himalaya is divided into the Lower Siwalik, Middle Siwalik, and Upper Siwalik. The Middle Siwalik can further be subdivided into the Middle Siwalik 1 and the Middle Siwalik 2. The Terai Plain is subdivided into the Bhabar Zone and the Middle Terai.

Lower Siwalik

The Lower Siwalik consists of purple, light yellow, ash to greenish grey variegated mudstone, black shale, and ash grey, fine-medium-grained sandstone with coal lenses. The spheroidal weathering in the mudstone bed is fairly common. Interbedding of mudstone (3 cm to 5 m) and sandstone (20 cm to 3 m thick) is in a ratio of 3:1 (Fig. 4). This unit is well exposed in the Ambas, Bhotetar, Bhalutar, Aahle, and Gadame areas (Fig. 5).

Middle Siwalik

The Middle Siwalik comprises interbedding of pale yellow to dark grey, fine- to coarse-grained, thin- to thick-bedded sandstone, and pale yellow to ash grey, thinly bedded mudstone (Fig. 6). The Middle Siwalik is further subdivided into the Middle Siwalik 1 and the Middle Siwalik 2.

The Middle Siwalik 1 unit consists of greenish-grey to light yellow mudstone and pale yellow, fine- to medium-grained, quartz, plagioclase, and biotite, tourmaline containing salt and pepper type sandstone in the lower portion at the Khutti Khola near Aahle. Interbedding of dark grey, pale yellow, medium-grained, thick-bedded sandstone (0.2 m to 8 m thick) and pale

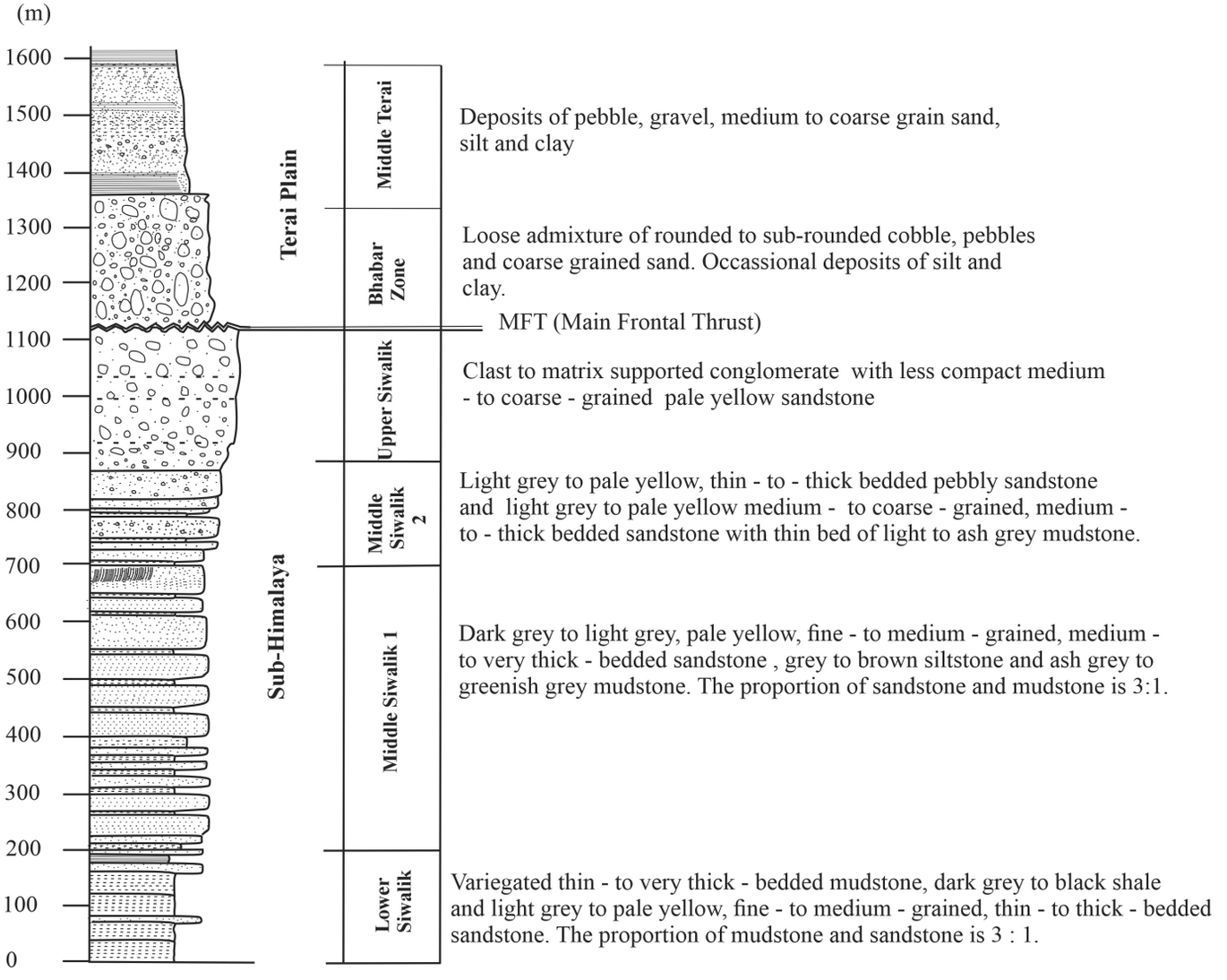

Fig. 2: A generalized columnar section of the rocks observed in the Khutti Khola watershed.

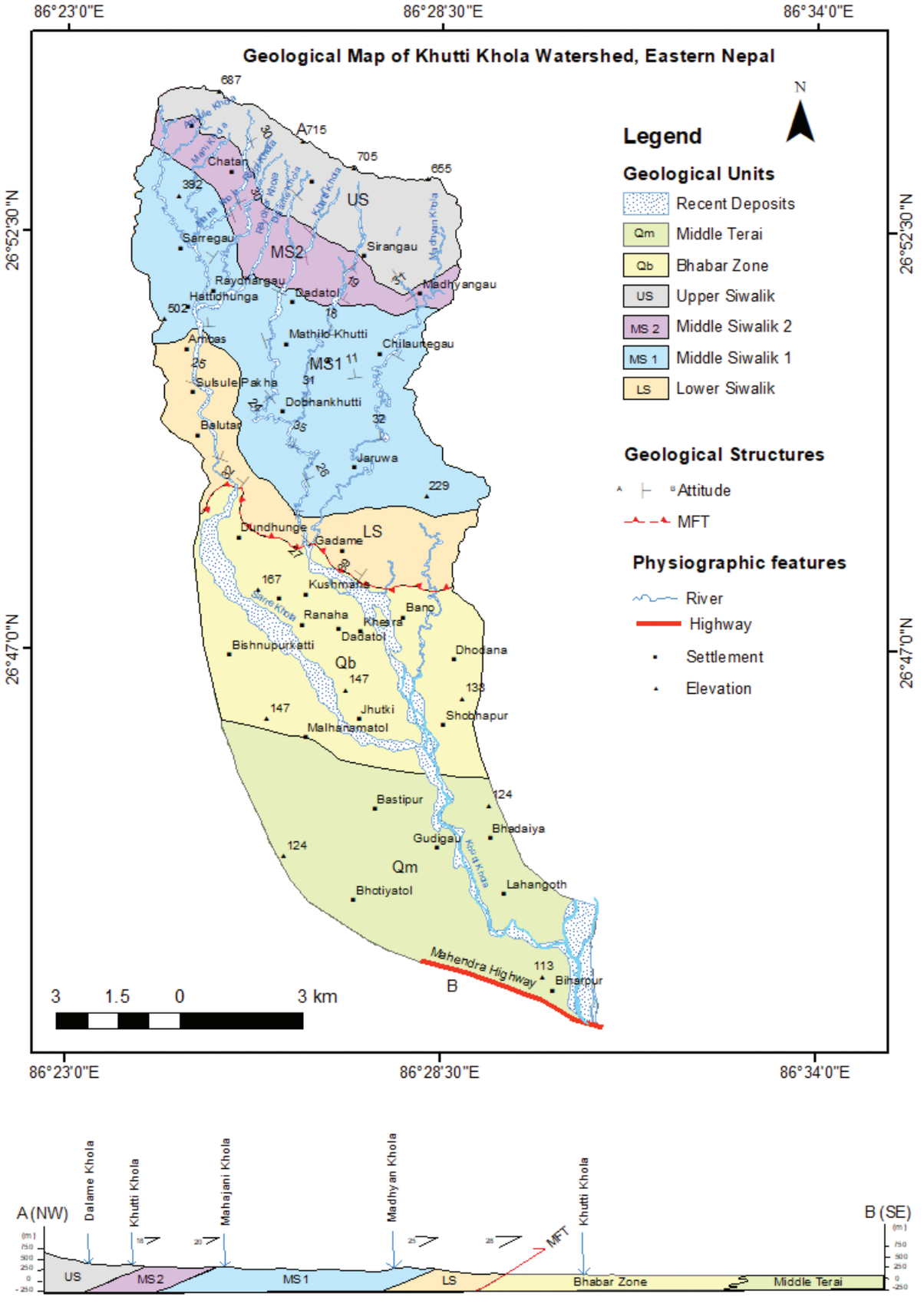

Fig. 3: Geological map and cross-section of the Khutti Khola watershed.

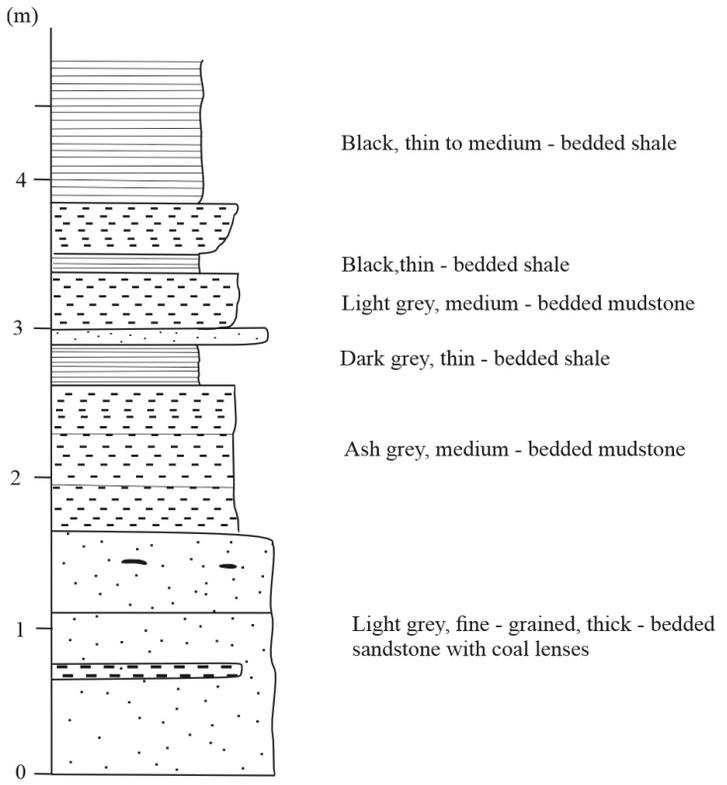

Fig. 4: Cyclic deposits of rocks in the Lower Siwalik succession near the Sulsulepakha area [GPS: 441733 E, 2969116 N].

Fig. 5: Succession of mudstone and sandstone beds at the left bank of the Sarre Khola, ≈ 900 m upstream from the Bhotetar area [attitude: 290º/ 20º NE; GPS 442002 E, 2968900 N].

yellow to grey, thin- to thick-bedded mudstone (0.1 m to 2.5 m thick) is observed along the Madhya Khola, Dhobhankhutti, and Mathillo Mahajani area (Fig. 7). The proportion of sandstone increases in the upper portion and the proportion of sandstone and mudstone is in a ratio of 3:1.

The Middle Siwalik 2 unit consists of thick-bedded, medium- to coarse-grained, salt and pepper appearance sandstone with thin-bedded pebbly sandstone at the lower portion along the Dalame Khola. The proportion of pebbly sandstone increases toward the upper portion (Fig. 8). Pale yellow, coarse-grained, salt and pepper appearance sandstone (0.2 m to 2 m thick) with thick-bedded pebbly sandstone bed (0.05 m to 3 m thick) is interbedded with mudstone bed (0.1 m to 0.5 m thick) at the upper portion (Fig. 9). The Middle Siwalik 2 unit is well exposed in the Madhyangaun, Sirangaun, and Dalame areas.

Upper Siwalik

The Upper Siwalik comprises a thick-bedded conglomerate with loose sandstone and mudstone. Poorly sorted, clast-supported, less compacted conglomerate in the lower part of the Upper Siwalik is followed by poorly sorted, matrix-supported conglomerate bed towards the stratigraphic up section (Fig. 10). This unit is well-exposed near the Madhyangaun, Sirangaun, and Dalame village.

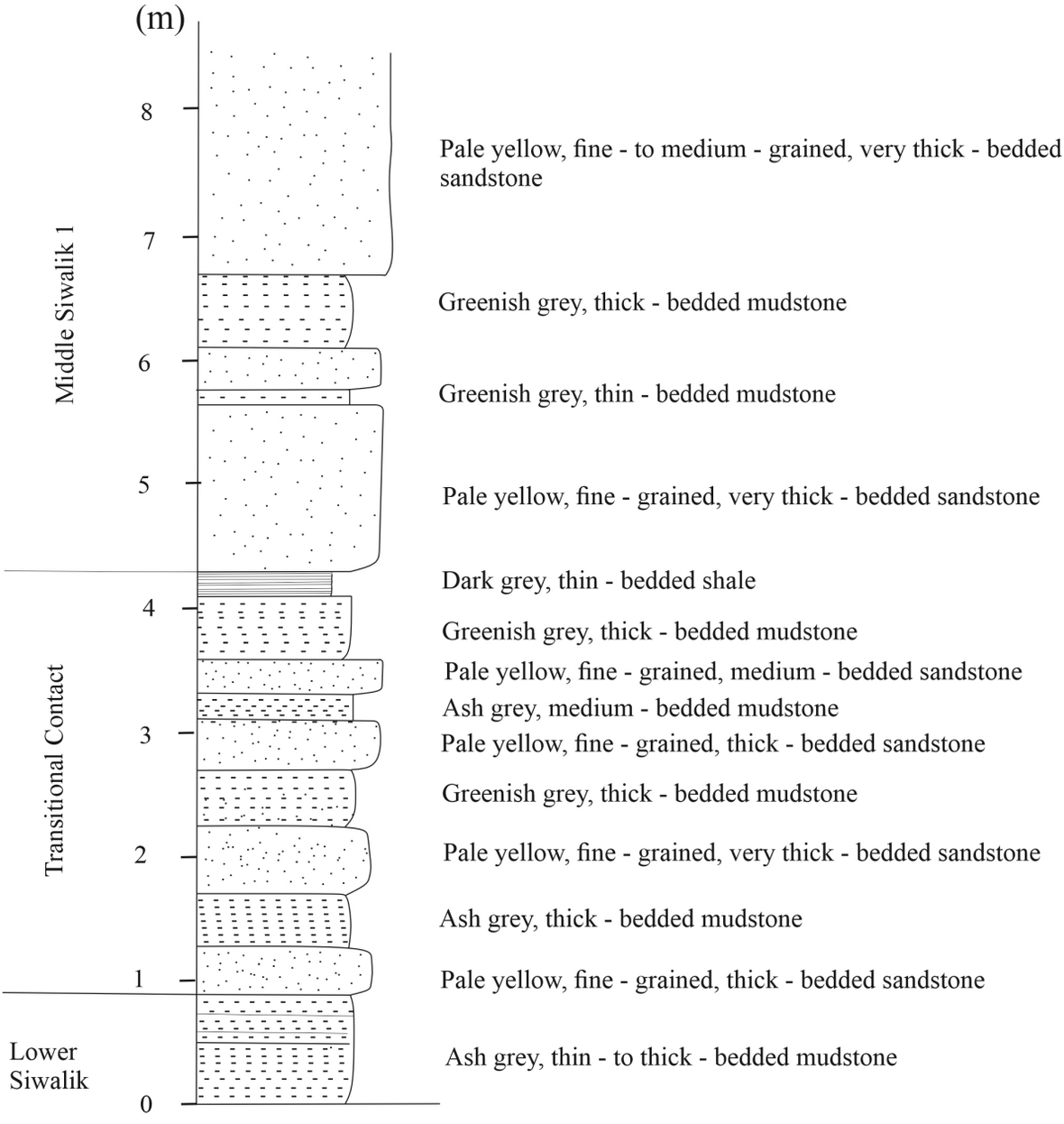

Fig. 6: Contact between the Lower Siwalik and the Middle Siwalik, ≈ 500 m upstream from the Aahale village [GPS 444068 E, 2966708 N].

Fig. 7: Thick-bedded sandstone of the Middle Siwalik 1 succession at the left bank of the Khutti Khola, ≈ 1 km upstream from the confluence of the Khutti Khola and the Madhyan Khola [attitude: 44º/ 34º SE; GPS 444138 E, 2966440 N].

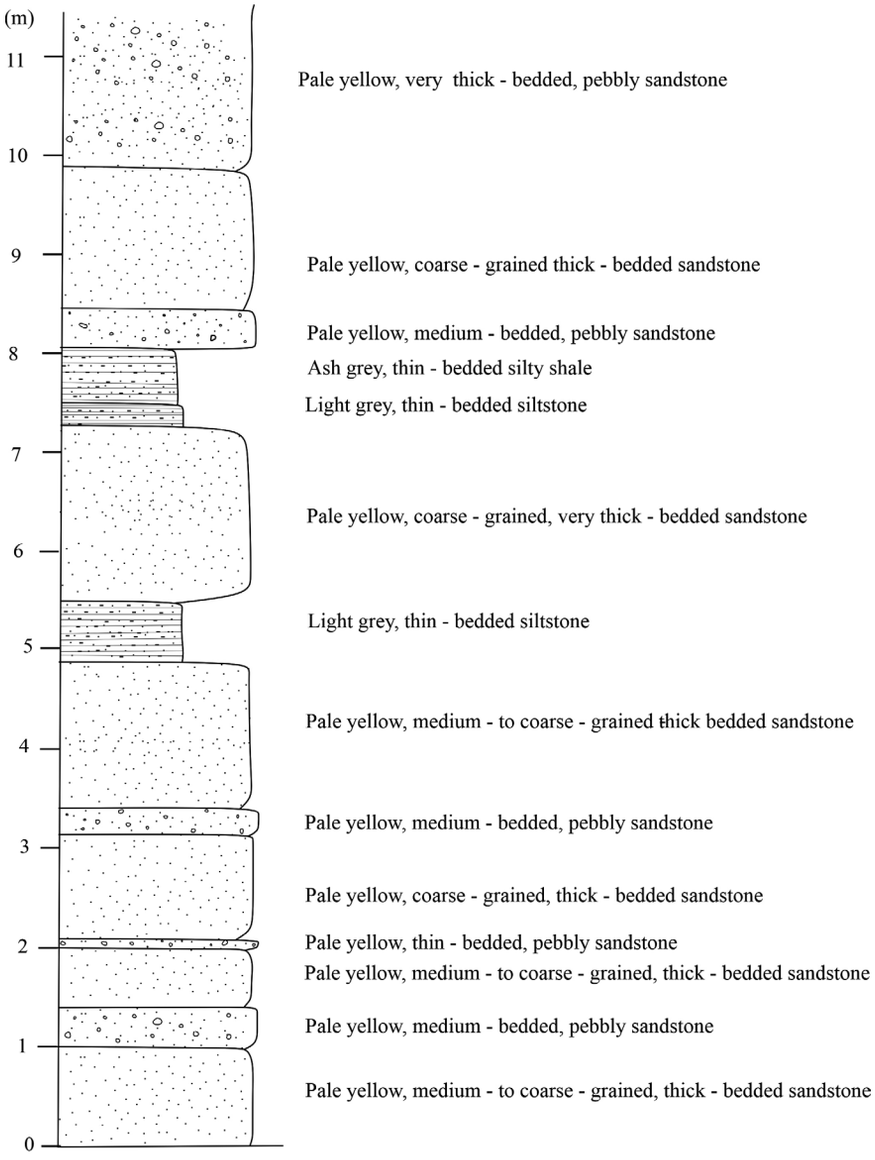

Fig. 8: A detailed columnar section of part of the Middle Siwalik 2 unit, near the Mathillo Mahajani [GPS 444831 E, 2971323 N].

Fig. 9: Field photograph showing pebbly sandstone interbedded with coarse-grained sandstone in the Middle Siwalik 2 unit, at the right bank of the Khutti Khola [attitude: 51°/ 19° NW; GPS 444050 E, 2972838 N].

Fig. 10: Clast supported conglomerate bed of the Upper Siwalik unit at the right bank of the Khutti Khola, ≈ 1 km upstream from the confluence of the Khutti Khola and the Dalame Khola [attitude: 134°/ 29 NE; GPS 444452 E, 2973794 N].

Terai plain

The Terai plain is subdivided into the Bhabar Zone and the Middle Terai. The Terai plain consists of boulders, gravel, silt, and clay of quaternary alluvium deposits. The Bhabar Zone (129 m to 200 m) lies immediately south of the Main Frontal Thrust on the foothill of the Chure range (Fig. 11). The Bhabar Zone comprises rounded to sub-rounded gravel, cobble, pebble, coarse-grained sand, and clay is well exposed in the Khapanitol, Kushmaha, Ranaha, and Bishnupur areas. The Middle Terai ranges from 113 m to 129 m mainly comprised of rounded to sub-rounded gravel, coarse to fine-grained sand, silt, and clay. The velocity of the stream decreases, the size of the sediments diminishes, and the appearance of water on the stream towards the southern section is noted near the confluence of the Balan Nadi and the Khutti Khola. The sediments of the Middle Terai are observed in the Bastipur, Bhadaiya, Lahan, Lahangoth, and Biharpur areas (Fig. 12).

Recent Riverbed Deposits

The Recent Riverbed Deposits are developed along the river course which includes boulders, cobbles, pebbles, sand, silt, and clay. During the monsoon, the river's discharge is at its highest, leading to the sweeping away of less compacted sediments due to heavy floods. These sediments are deposited in areas where the river's velocity decreases. Recent sediments are predominantly found in the channel of the Khutti Khola and its tributaries as observed in both the Chure Hills and the Terai Plain.

Geological structures

The study area exhibits several regional, local as well as small-scale primary as well as secondary geological structures. Primary structures like parallel lamination, cross lamination, convolute structure, mud drapes, and sand balls are observed in various parts of the study area. Parallel lamination is observed in the sandstone and siltstone bed of the Middle Siwalik near the Mahajani village and on the left bank of the Sarre Khola near the Ambas village (Fig. 13). Cross-lamination is observed in the salt and pepper texture sandstone bed of the Middle Siwalik 2 at the Dalame village indicating the beds are in normal stratigraphic order. Convolute lamination in the lower part of the Middle Siwalik sandstone bed at Ambas village in the Sarre Khola section is attributed to vibrations during the depositional period (Fig. 14). Mudball concretions are observed in the Middle Siwalik upstream from the confluence of the Khutti Khola and the Madhyan Khola (Fig. 15 and Fig. 16). The most important regionally present secondary geological structure is the Main Frontal Thrust. Along the Main Frontal Thrust (MFT), the Siwalik rocks have been thrusted over the Terai sediments. The Bhabar Zone is observed immediately south of the Main Frontal Thrust. Evidence of the MFT in the Khutti Khola watershed includes crushed sandstones with slickensides, several landslides at and around the vicinity, fault gouges, fault breccias, some quartz veins and sudden topographic breakages. Small-scale folds are evident in both the Lower and Middle Siwalik sections in the Sarre Khola and the Khutti Khola at Aahale (Fig. 17). The attitude of the left limb and right limb of folds plotted in the Dips 6.0 software shows a trend of 322° with a plunge of less than 1° i.e., a non-plunging fold (Fig. 18). Rock strata exhibit a strike of 297° and dip of 20°, predominantly dipping towards the northeast (Fig. 19).

Petrography

The claystone of the Lower Siwalik unit exhibits very fine-grained, microscopic fine laminations with predominant cementing materials that are calcareous and siliceous. The mineralogical composition constitutes clay mineral ≈ 70%, quartz ≈ 10%, calcite ≈ 10%, rock clast, and ferruginous clast ≈ 10% (Fig. 20). The siltstone of the Lower Siwalik unit is fairly weathered with some microcracks constituting clay minerals ≈ 55%, quartz ≈ 15%, plagioclase feldspar ≈15%, muscovite ≈ 7%, and unidentified minerals ≈ 8% (Fig. 21). The sandstone

Fig. 11: Photograph showing the Lower Siwalik and Bhabar Zone separated by the MFT (looking right bank of the Khutti Khola from Dadatol area, GPS 445775 E, 2955257 N).

Fig. 12: Photograph showing the Middle Terai in the Khutti Khola at the Lahangoth area [GPS 450321 E, 2955257 N].

Fig. 13: Parallel lamination in the sandstone bed seen on the left bank of Sarre Khola about 100 m upstream from the Ambas village [GPS 441744 E, 2971274 N].

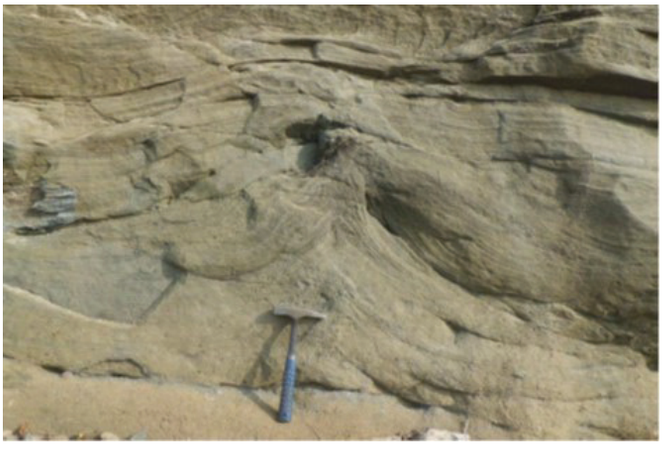

Fig. 14: Convolute bedding observed in sandstone rock succession of the Middle Siwalik 1 at Ambas [GPS 441744E, 2971274 N].

Fig. 15: Mud concretion in sandstone rock succession of the Middle Siwalik 1 which is at the left bank of the Khutti Khola [GPS 444586 E, 2966308N].

Fig. 16: Sand ball concretion of the Middle Siwalik at the left bank of the Khutti Khola section [GPS 444203 E, 2967159 N].

Fig. 17: Outcrop of small-scale anticlinal fold observed in the Lower Siwalik near Aahale [GPS 444277 E, 2966308 N].

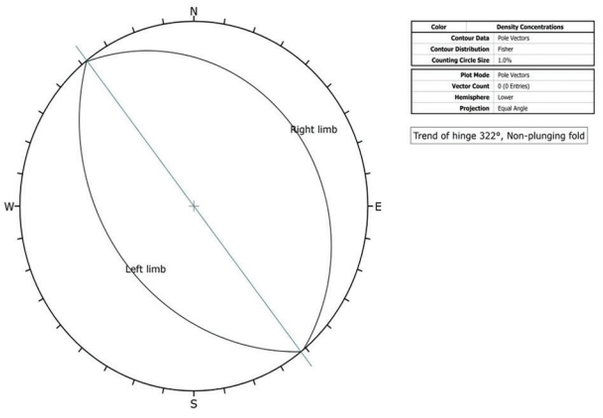

Fig. 18: Stereographic plot of the small antiformal fold in equal angle, lower hemispherical projection [GPS 444277 E, 2966308 N].

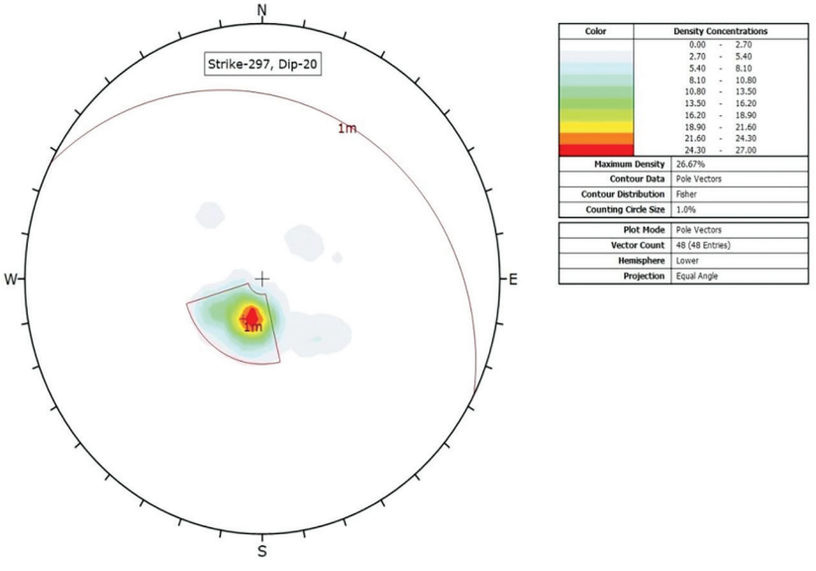

Fig. 19: Stereographic plot of all measured attitudes of beds in equal angle, lower hemispherical projection of the study area.

of the Middle Siwalik-1 unit is moderately sorted, coarse-grained, salt-and-pepper type, fairly weathered mineral with siliceous cementing material. The bimodal distribution of grains within the matrix is observed with an anhedral to subhedral and angular to subrounded shape. The sandstone constitutes quartz ≈ 24%, plagioclase feldspar ≈ 20%, orthoclase ≈ 10%, biotite ≈ 10%, muscovite ≈ 3%, rock fragments ≈ 5%, clay minerals ≈5%, ferruginous/opaque ≈ 13%, and unidentified ≈ 10% (Fig. 22). The sandstone of the Middle Siwalik-2 unit exhibits medium- to coarse-grained, salt (quartz and plagioclase)-pepper (biotite and tourmaline)-type sandstone with sub-rounded to rounded quartz and feldspar and flaky mica (0.2 mm - 0.5 mm) detrital minerals. Abundant microfractures are sub-parallel to across the bedding and a bleaching effect is seen on orthoclase and plagioclase feldspar while quartz is unaltered. The sandstone constitutes quartz ≈ 35%, plagioclase feldspar ≈ 30%, orthoclase ≈ 10%, biotite ≈ 10%, muscovite ≈ 10%, opaque and unidentified ≈ 5% mineral (Fig. 23). The sandstone of the upper part of the Middle Siwalik-2 unit comprises medium-grained salt-pepper type calcareous sandstone with clay lamina. The mineral grains have floating, tangential, and straight contact. The calcite-cemented sandstone constitutes quartz ≈ 35%, plagioclase feldspar ≈ 25%, orthoclase ≈ 10%, biotite ≈ 10%, muscovite ≈ 10%, opaque ≈ 8%, clay minerals ≈ 4%, and calcite ≈ 8% (Fig. 24). The sandstone of the Upper Siwalik unit is coarse- to very coarse-grained, moderate to highly weathered, matrix-supported, and poorly cemented in nature. Abundant microcracks bearing sandstone constitutes quartz ≈ 20%, plagioclase feldspar ≈ 20%, orthoclase ≈ 20%, biotite ≈ 5 %, muscovite ≈ 5%, heavy minerals/opaques ≈ 15%, calcite ≈ 4%, rock clast ≈ 5%, clay minerals ≈ 5%, and unidentified mineral ≈ 1% (Fig. 25). The Lower Siwalik and Middle Siwalik units consist of quartz, feldspar, and lithic fragments, along with more than 15% matrix is categorized as Feldspathic Wacke and the Upper Siwalik unit with unstable rock fragments with less than 15% matrix is classified as Lithic Arenite based on the revised Dott's classification by Pettijohn et al. (1987).

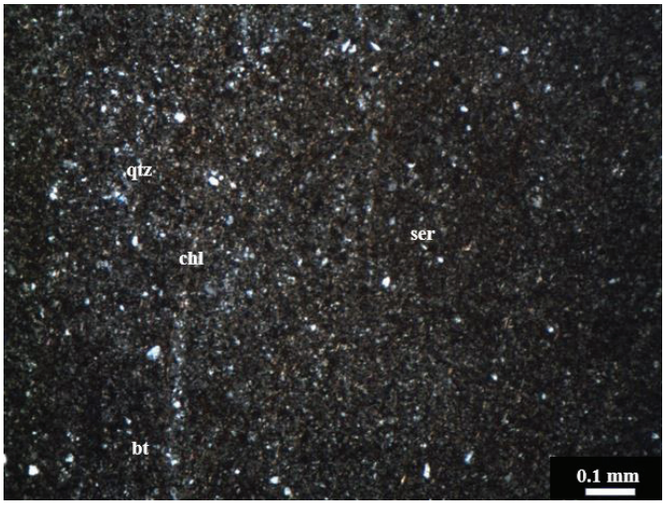

Fig. 20: Photomicrograph of the claystone of the Lower Siwalik unit with some silt-sized particles of the Gadame area at 10 x 4 magnification under cross-Nicol's.

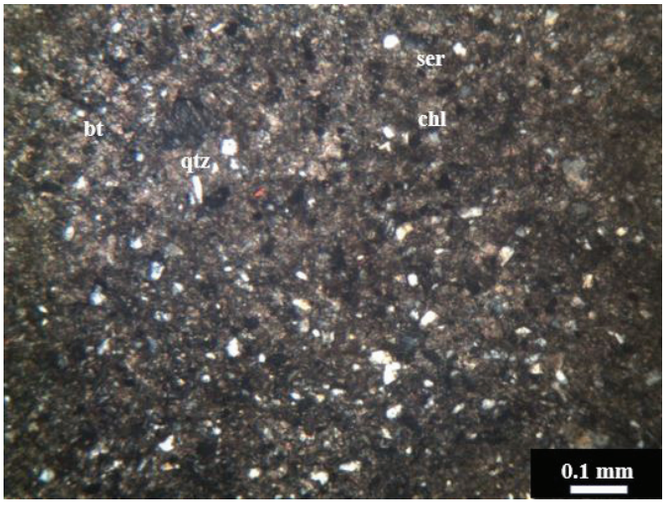

Fig. 21: Photomicrograph of the siltstone of the Lower Siwalik unit of the Ambas area at 10 x 4 magnification under cross-Nicols.

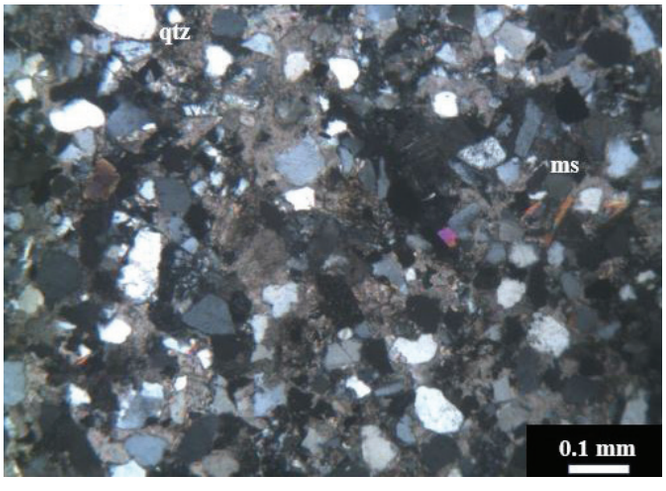

Fig. 22: Photomicrograph of the Coarse-grained salt-pepper type sandstone of the Middle Siwalik-1 unit of the Madhyan Khola area at 10 x 4 magnification under cross-Nicol's.

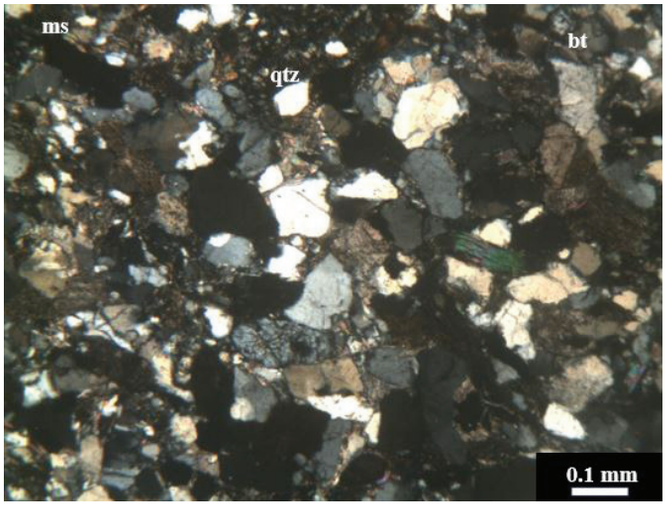

Fig. 23: Photomicrograph of the medium- to coarse-grained salt-pepper type sandstone of the Middle Siwalik-2 unit of the Dalame area at 10 x 4 magnification under cross-Nicol's.

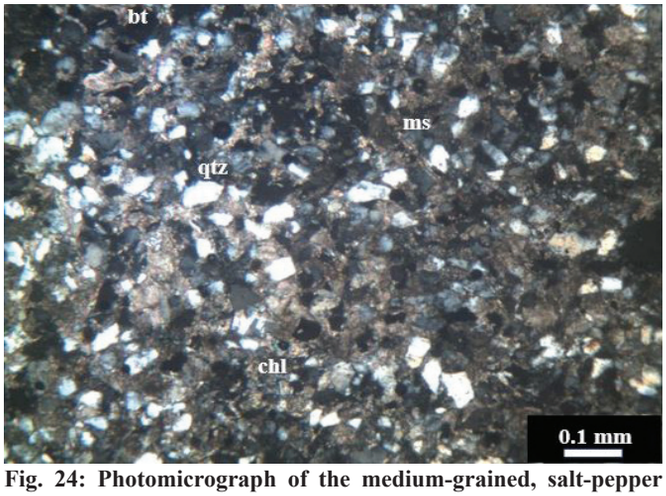

Fig. 24: Photomicrograph of the medium-grained, salt-pepper type calcareous sandstone of the upper part of the Middle Siwalik-2 unit of the Madhyangaun area at 10 x 4 magnification under cross-Nicol's.

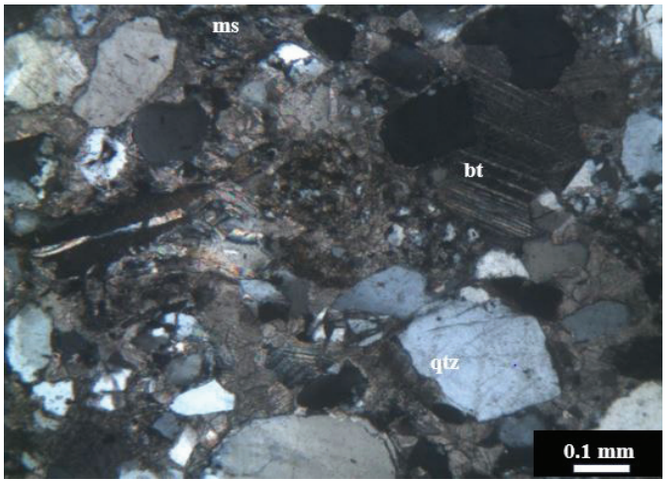

Fig. 25: Photomicrograph of the coarse-to-very-coarse-grained sandstone of the upper part of the Upper Siwalik unit of the Sirangaun area at 10 x 4 magnification under cross-Nicol's.

Lithofacies and depositional environment

The Siwalik deposits consist of eroded materials from the Lesser and Higher Himalayas, which have been transported and deposited over time by rivers and streams. The lithofacies in the study area are categorized into three distinct types from the bottom to the top of the section: Mudstone Facies, Sandstone Facies, and Conglomeratic Sandstone Facies. The Mudstone Facies consisting of laminated mudstone, silty claystone, fine-grained sandstone, and shales, are deposited in floodplains by rivers carrying suspended loads in calm environments and are typically found in deeper basins with low hydrodynamic forces. The Sandstone Facies consisting of medium to coarse-grained sandstone are formed through sediment transport processes such as traction currents acting as bed load, intermittent suspension or saltation, and sediment gravity flows, particularly within braided channels of fan deltas and subaqueous environments influenced by high-density turbidity currents. The Conglomeratic Sandstone Facies consisting of poorly sorted pebbly sandstone supporting conglomerates are formed at the base of high-density turbidites.

DISCUSSIONS

The nomenclature of the stratigraphic units of the Khutti Khola watershed was adopted from PEPP, (2006), Pradhan et al. (2004), and Dhital (2015). Pradhan et al. (2004) have prepared a detailed geological map of the Khutti Khola watershed area in the 1:250000 scale. In the present study, the map is prepared in 1:25000 and the lithological units proposed by Pradhan et al. (2004) were revised (Fig. 26). They classified the Terai Plain into the Quaternary deposits. While, in the present study, the Terai plain is divided into the Bhabar Zone and Middle Terai and sediments developed along the river course are classified as the Recent Riverbed Deposits. The Main Frontal Thrust is traced with evidence of various geological features such as topographic breakage, spring line development, landslides, slickensides on sandstone, shear zones, fault gouges, fault breccias, and some quartz veins. The Bhabar Zone lies immediately south of the Main Frontal Thrust.

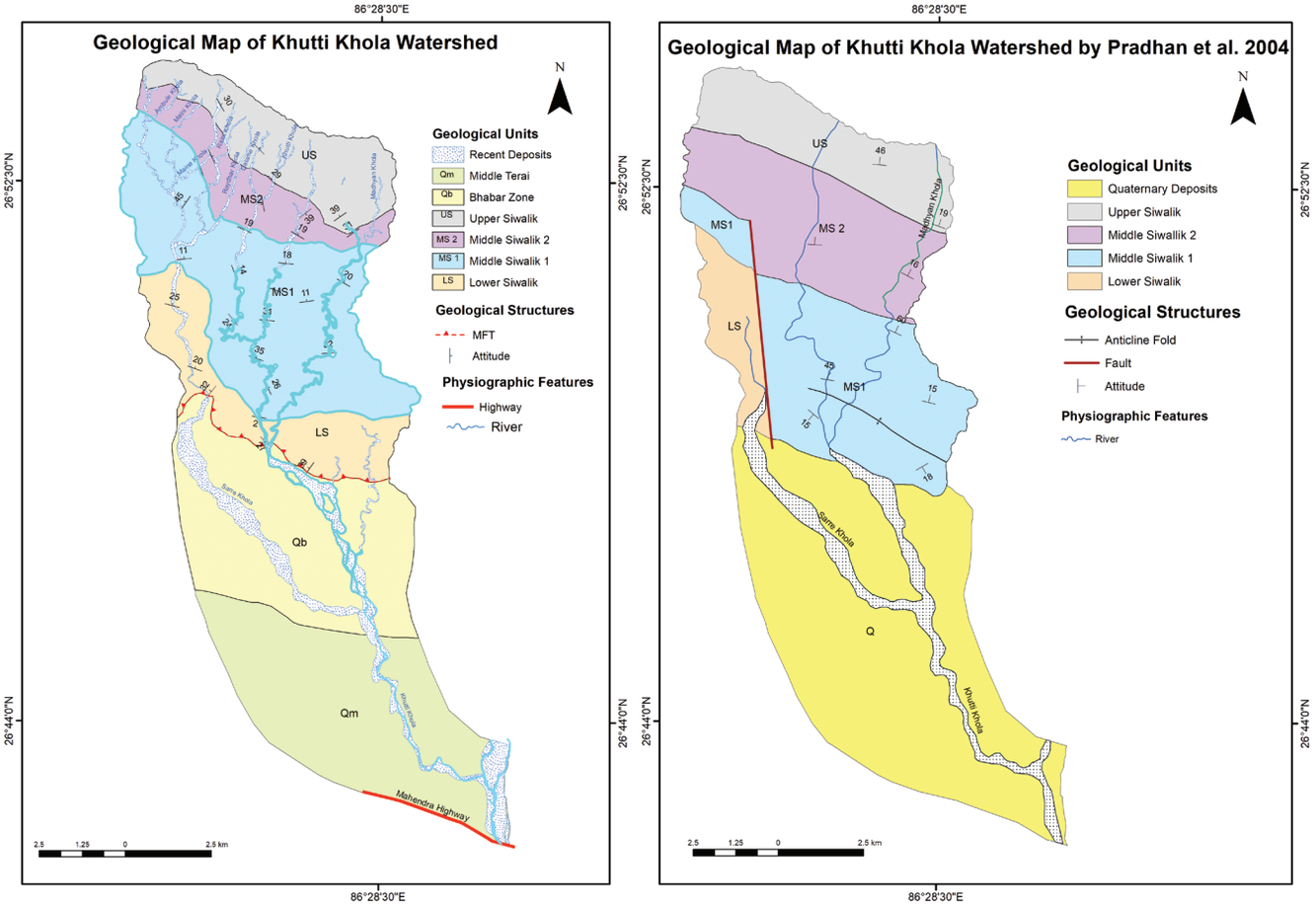

Fig. 26: Comparison of present geological map and geological map of the Khutti Khola by Pradhan et al. (2004).

CONCLUSIONS

The following conclusions are drawn from the present study:

Geological mapping of the Khutti Khola watershed area at a scale of 1:25000 encompasses the Terai plain to the south and the Siwalik Group succession to the north, separated by the Main Frontal Thrust (MFT). The Terai Plain which is subdivided into the Lower Terai, Middle Terai, and the Bhabar Zone lies to the south, while the Siwalik Group is classified into the Lower Siwalik, Middle Siwalik, and Upper Siwalik units. The Recent Riverbed Deposits present along the river course provide valuable insights into ongoing geomorphological processes and environmental changes within the region. The lithological composition is mainly characterized by sedimentary rocks including siltstone, variegated mudstone, and fine to coarse-grained sandstone along with pebbly sandstone and conglomerate, often exhibiting coarsening upward patterns. Moreover, within specific beds of the Siwalik rocks, fining upward sequences where grain size decreased towards the top is observed.

The sedimentary basin and paleo-environment of the area are characterized by a variety of primary structures, including parallel lamination, cross lamination, convolute bedding, mud drapes, and sandball concretions. Additionally, the Main Frontal Thrust (MFT) is the major regional secondary geological structure, evidenced by the presence of crushed sandstone and mudstone near the shear zone, slickensides, landslides, fault breccia, quartz veins, and abrupt changes in topography.

The Lower Siwalik and the Middle Siwalik units with quartz, feldspar, and lithic fragments, along with more than 15% matrix are categorized as Feldspathic Wacke, and the Upper Siwalik unit with loose rock fragments along with less than15% matrix are classified as Lithic Arenite.

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