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RESEARCH ARTICLE

River terraces mapping and assessment of their characteristics along the middle section of the Madi River, Western Nepal, Lesser Himalaya

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ABSTRACT

The Madi River, a major tributary of the Sapta Gandaki River in west-central Nepal, exhibits well-developed fluvial terraces that provide insights into Late Quaternary landscape evolution in the Lesser Himalaya. This study focuses on the middle section of the Madi River, from Duipiple to Rudi Dhoban, where three distinct terrace levels higher, middle, and lower were identified along both banks. Six representative sites (Mohoriyatar, Dihi, Dargau, Syastri, Bhatbesi, and Tallobesi) were examined from south to north. The higher terrace, measuring approximately 80 m in height and 46 m in width relative to the modern channel, is composed predominantly of large boulders of gneiss, quartzite, garnet schist, and metasandstone, and is interpreted as the product of glaciofluvial deposition. The middle terrace is widely distributed at around 40 m above the active channel and extends up to 90 m in width, consisting of unsorted, consolidated boulders, cobbles, pebbles, and granules derived from gneiss, quartzite, schist, phyllite, and metasandstone. The lower terrace is the youngest unit, lies ~20 m above the modern river and extends ~120 m in width, containing rounded to sub-rounded sediments sourced from the Higher and Lesser Himalaya. Tributary inputs contribute angular clasts of phyllite and metasandstone to the middle and lower terraces. Sediment provenance analysis indicates transport from both the Higher Himalaya and Lesser Himalaya zones. The terrace stratigraphy and sedimentology suggest that the higher terrace formed under glaciofluvial conditions, while the middle and lower terraces are products of purely fluvial processes.

Keywords: ***River terraces mapping, Higher terrace, Sediment provenance, Glaciofluvial deposition***

INTRODUCTION

Most major rivers in Nepal originate within the Higher Himalaya and Tethys Himalaya zones, exhibiting a range of geomorphological and geological features such as valleys, terraces, and gorges. The evolution of river channels, controlled by flow direction and sediment transport dynamics, has varied significantly from ancient to modern times. River terraces are key geomorphic markers, serving not only as sources of construction aggregates but also as archives of hydrogeological conditions, flood regimes, and sediment supply histories.

The Madi River, a glaciofluvial tributary of the Sapta Gandaki River, originates from Kapuche Lake (Fig. 1) and joins the Seti River near Damauli. It traverses the Higher Himalaya and Lesser Himalaya, with its headwaters in the Tethys Himalaya (Fig. 1). The Tethys Himalaya sequence comprises Paleozoic (Cambrian–Permian) sedimentary rocks, including limestone, sandstone, and shale. The Higher Himalayan Crystalline consists predominantly of Precambrian high-grade metamorphic rocks such as gneiss, quartzite, and marble, with migmatite, granite, and gneiss dominating the upper structural levels (DMG, 2020). The Main Central Thrust (MCT) demarcates the contact between the Higher Himalayan Crystalline and the Lesser Himalaya.

Within the Lesser Himalaya, three lithostratigraphic units are recognized in the study area, arranged from oldest to youngest: the Ranimatta Formation, Naudanda Formation, and Ghan Pokhara Formation (DMG, 2020). The Ranimatta Formation comprises grey to greenish shale, phyllite, slate, garnetiferous phyllite, greyish-white quartzite with carbonate interbeds, and amphibolite. The Naudanda Formation is characterized by fine- to medium-grained white quartzite with ripple marks and thin intercalations of green chlorite phyllite. The Ghan Pokhara Formation, the youngest unit, consists primarily of black to grey carbonaceous slate and green shale.

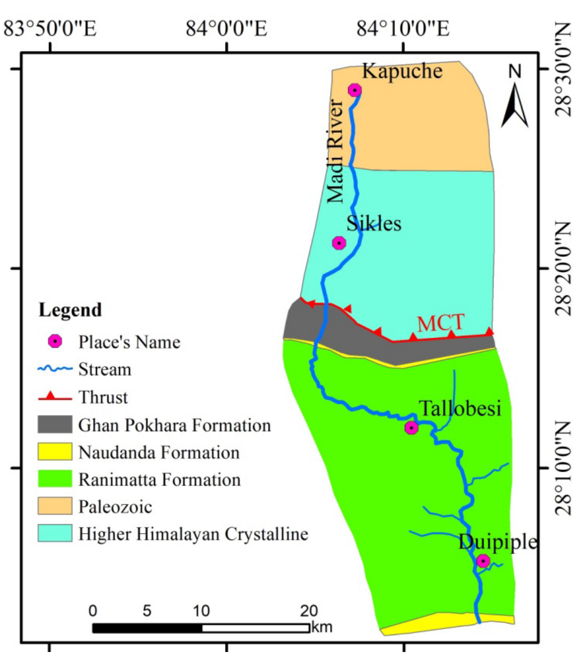

Fig. 1: Geological map of Madi River section from the Duipiple to Kapuche Lake, Modified after (DMG, 2020)

Hiroshima (1972) divided the river terraces into higher, middle, and lower terraces of the Marsyangdi River. According to him, the middle and lower terraces are distributed along the middle terraces. The middle terraces rise 70 to 80 meters above the riverbed and the lower 15 to 20 meters, and both terraces are accumulation ones. Sharma et al. (1980) gave the names of the terraces as T_1, T2, and T_3, which were studied along the middle Kali Gandaki between Kusma and Behadi. According to them, the T_1 terrace is 400 to 300 meters above the riverbed, and the T_2 is 25 to 60 meters lower than the $T_{1.}$ A poorly sorted, non-stratified consolidated conglomerate is present in T_1 and T_2. The T_3 terrace rises 10 to 15 meters above the riverbed, and it is made up of younger, unconsolidated deposits.

Iwata et al. (1982) studied the glacial landform and river terraces in the Thakkhola region, central Nepal. The study clarifies the relationship between the river terrace and glacial landform with the deformation of the Kaligandaki river terraces. A series of field surveys were carried out in the upper course of the Kaligandaki. In the Thakkhola region, the two stages of glacial morines, which fall possibly into the late glacial age. They divided the river terrace into higher, middle, and lower terraces. The higher terrace is denoted by H, the middle terraces (M_1–MM_4) and the lower terrace is L. The higher terraces consist of conglomerates and are about 360–400 meters above the flood plain. The Middle Terrace (M_1, M_2, M3, and M_4) is above the riverbed at about 260 m, 200 m, 150 m, and 110 m, respectively. The Lower Terrace is composed of non-consolidated fluvial gravels.

River terraces along the Middle Kali Gandaki and the Marsyandi River are all valleys filled with deposits formed by glacial fluvial sediments (Yamanaka and Iwata, 1982). The formation of terraces along both rivers was controlled by local and accidental geomorphic events. The tectonic movements along the Kaligandaki resulted in the northern and southern regions being comparatively uplifted during the late quaternary. (Yamanaka and Iwata, 1982) classified the Kaligandaki river terraces into 3 groups, i.e., higher, middle (M_1–M_5) and lower terraces.

Yamanaka and Iwata (1982) also discussed the geomorphological development in the Kaligandaki River. They conclude that the Kaligandaki is deepening and has reached the present level. The Kaligandaki started downcutting and eroded the deposit. They studied the river terraces along the Marsyandi, from Nayagaon to Dumre. The terraces are divided into six groups: Highest (HH), Higher (H), and Middle Terrace (M), Intermediate-Level Terrace (m), between the middle and lower terraces, and Lower (L) and Lowest Terrace (L') terraces are too limited. The Higher Terrace is about 150 meters thick and composed of pebble- and cobble-sized gravels and silty materials. Middle Terrace is about 70 m and consists of angular to sub-angular gneiss gravels and gray silty materials. It is unsorted and not stratified. Lower Terrace has a maximum width of 500 meters and consists of sub-angular to sub-rounded gneiss gravel and sandy deposits in general. Mapping the river terrace level within the Upper Pindar River determines the current and historic hydrogeology, along with the present terrain characteristics of the area (Nandy et al., 2021). The whole region has gone through polycyclic landform development to form steps like river terraces. The wide altitudinal spacing of the river terrace levels indicates the relative change of base level due to the combined effect of tectonic instability. Meikle et al. (2010) mentioned the importance of river terraces. River terraces are important landform as they can provide i) sources of aggregate for construction (Smith and Collis, 2001), ii) information about hydrology for flood management and planning purposes (Carney and Napier, 2004) and iii) archives of longer – term environmental changes that are driven by combinations of climate or anthropogenic related changes in flood regime and sediment supply (Bridgland, 2000) or by tectonic and eustatic changes in base- level (Cunha et al., 2008).

Madi River creates a straight, meandering, and braided channel from beginning to end. The middle section of the Madi River consists of terrace deposits, which are dominantly present in the meandering pattern of the river flow channel. The main aim of the study is to figure out the fundamental characteristics of terraces. This study demonstrates the sequence as well as the development of river terraces in response to the terrace genesis process.

Study Area

The study area lies within Gandaki Province, Nepal, encompassing parts of Kaski, Lamjung, and Tanahun districts, and is accessible via the Prithvi Highway. It is situated approximately 15 km north of Damauli. The middle section of the Madi River, investigated in this study, extends for ~20 km between the Duipiple, Lamjung, in the south and Rudi Doban in the north. The southern and northern boundaries are demarcated by the confluences of the Risti Khola and Rudi Khola, respectively (Fig. 2). The Madi River channel forms the district boundary between Kaski and Lamjung. River terraces are distributed along the Rupa Rural Municipality (Kaski District) and the Madhya Nepal Municipality (Lamjung District). Geographically, the study area extends from 28°04'43" N, 84°13'57" E in the south to 28°12'17" N, 84°20'18" E in the north. Channel elevations range from approximately 378 m at the southern end to 550 m at the northern end.

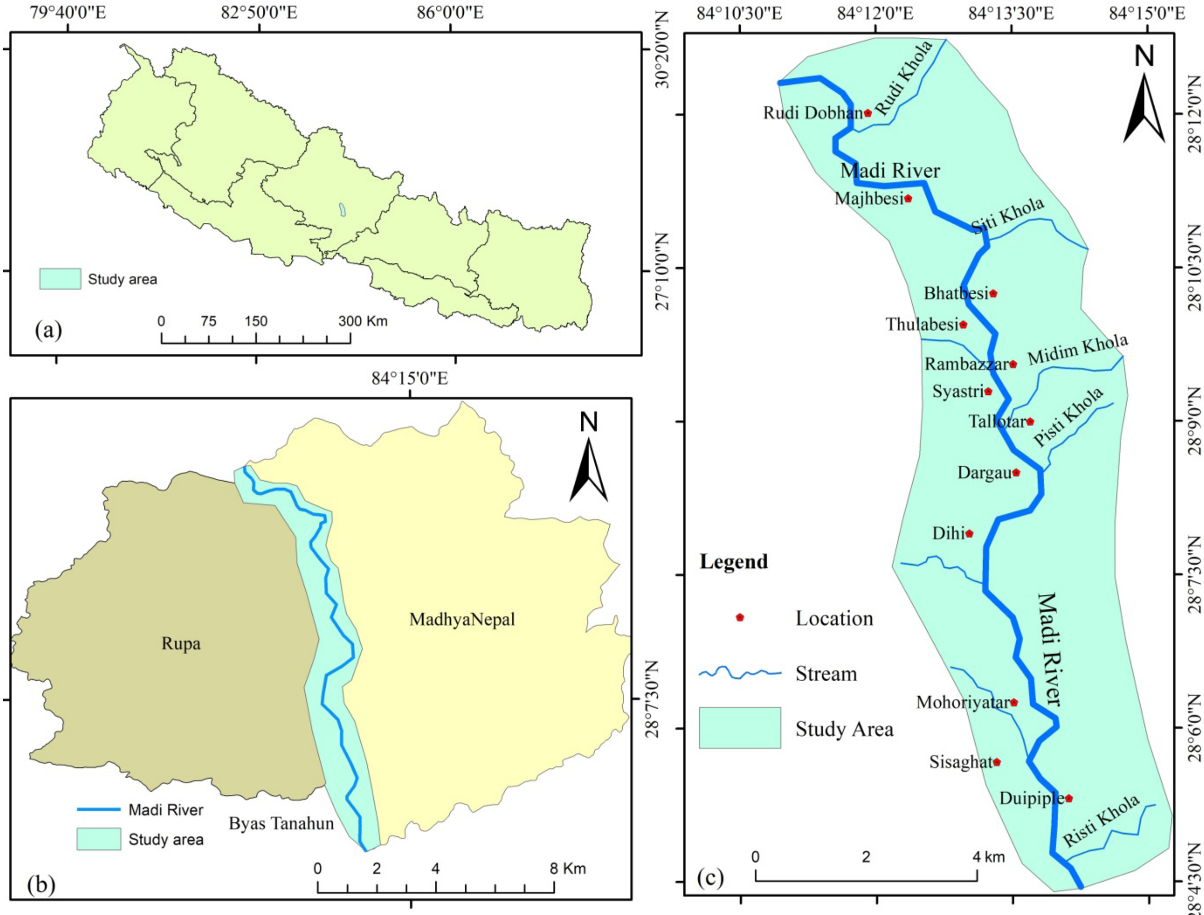

Fig. 2: Location map of the study area (a) Location in map of Nepal, belongs to Gandaki province, (b) Study area showing the Madi River, flows in between Rupa and Madhya Nepal Municipality and (c) Details information about the location of the researched area

METHODOLOGY

The study employed a combination of field investigations, desk-based analysis, and detailed observations of terrace deposits within the basin. Bedrock lithology and composition were also documented during fieldwork. Secondary data were obtained from published journal articles, reports, and relevant geological maps. River terrace analysis involved systematic field observations, detailed geomorphic mapping, and outcrop description (Fig. 3). Columnar sections were prepared for representative terrace exposures, accompanied by systematic photographic documentation. Terrace height and width were measured in the field using measuring tapes and altimeters; for inaccessible sites, Google Earth Pro was used to estimate dimensions. Geographic Information System (GIS) software was employed to prepare geomorphic maps, and CorelDRAW was used for drafting cross-sections and final illustrations. For classification, terraces were designated sequentially as T0, T1, T2, T3, and so forth, where T0 represents the present-day active river channel, T1 is the first terrace above T0, T2 is the second terrace above T1, and T3 lies above T2.

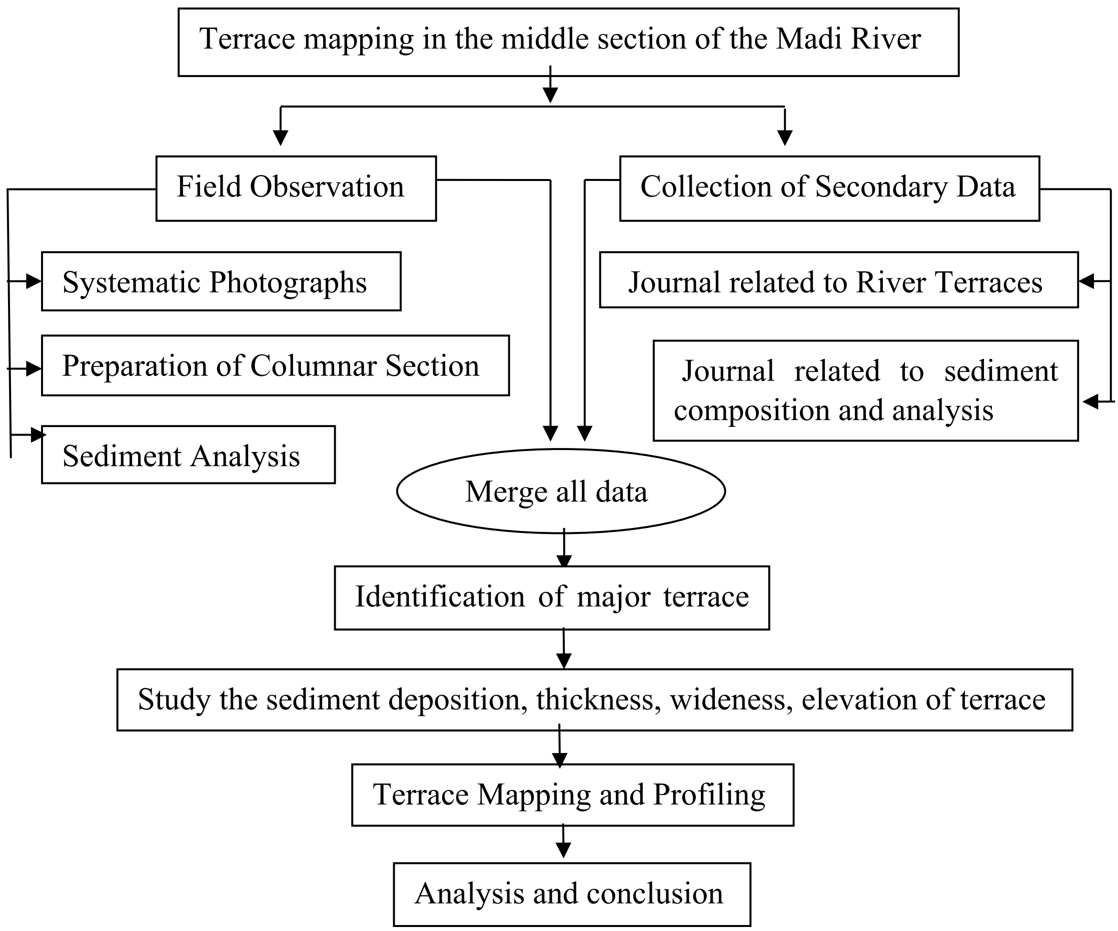

Fig. 3: Methodology flowchart showing the study and analysis of Madi river terrace and their characteristics

RESULTS AND DISCUSSIONS

Detailed geological investigation combined with terrace mapping provided a comprehensive understanding of the study area. River sedimentary deposits are sharply bounded against the underlying bedrock, indicating a distinct depositional gap and the presence of an unconformity. The bedrock in the study area is predominantly assigned to the Ranimatta Formation of the Lesser Himalaya. Based on relative elevation, morphology, and sedimentological characteristics, the river terraces are classified into three distinct levels: higher terrace, middle terrace, and lower terrace.

Ranimatta Formation

The middle reach of the Madi River flows across bedrock exposures belonging to the Ranimatta Formation (Fig. 4). This formation comprises grey, thin- to medium-bedded, fine- to medium-grained metasandstone interlayered with light grey, thinly foliated muscovite–biotite phyllite. River terrace deposits overlie these bedrock exposures, a relationship clearly visible at the Dargau Terrace site (Fig. 8). The bedrock strata in this section generally dips southward.

Higher Terrace

The higher terrace (T3) is distributed across the Dihi (Fig. 5 b), Dargau, Syastri and Bhatbeshi areas (Fig. 4) and rises approximately 130 m above the present Madi River channel (Table 1). At Dargau, T3 forms a well-preserved flat surface with a width of ~80 m. The terrace deposits consist of unsorted and unstratified, sub-rounded to sub-angular large boulders, cobbles, pebbles, and granules composed of augen gneiss, banded gneiss, garnetiferous schist, metasandstone, granite, quartzite, and phyllite. Boulder dimensions reach up to ~5 m × 2 m × 1.5 m. In many areas, the original terrace surface has been modified by colluvial accumulation and agricultural activities, producing a gentle slope. On the opposite bank near the confluence of the Madi River and Pisti Khola, a conglomerate exposure is interpreted as a remnant of the higher terrace (T3).

Middle Terrace

Middle Terrace (T_2) is distributed all over the study area from Duipiple to Rudi Doban (Fig. 4). It is well deposited on the right bank of Madi River. It rises about 40 meters above the riverbed of the Madi River (Table 1). The Middle Terrace is flat terrace of about 70 – 110 meters width with diverse composition (Fig. 6). It is further classified into type a) and type b) according to the sediment type and association. Type a) consists of unconsolidated, unsorted deposit of sub – angular to sub - rounded large boulder, cobble, and pebble with granules association of granite, gneiss, garnet schist, quartzite and metasandstone. In Dihi (Fig. 9), Dargau and Syastri, type a) composition is observed (Fig. 5b, 5c and 5d). This terrace turns into gentle slope and is used for agriculture and settlement. Type b) is composed of firmly consolidated, unsorted, sub – rounded boulder, cobble, pebble, granules and coarse brown sand matrix supported sediment. The Mohoriyatar and Duipiple terraces are type b) of Middle Terraces (Fig. 5a).

Lower Terrace

Lower Terrace (T_1) is distributed all over the study area from Duipiple to Rudi Doban (Fig. 4). It is well deposited on the bank of Madi River. It rises about 20 meters above the riverbed of the Madi River. The Middle Terrace is flat terrace of about 110 – 190 meters width with diverse composition (Table 1). Lower Terrace consists of relatively fine sediments than the Middle and Higher Terraces. Duipiple, Mohoriyatar, Dihi, Dargau, Syastri, Bhatbesi, Majhbesi and Tallobesi area dominantly occupied by the Lower Terrace (Fig.4 and 5). It consists of unconsolidated and moderately sorted boulder, cobble, pebble, granules with coarse to fine sand, silt and clay matrix (Fig. 6). Sub- rounded to round sediment of granite, gneiss, quartzite, garnet schist, pegmatite, metasandstone and phyllite are deposited which is observable throughout the study area (Fig.7, 8 and 10). Sand, silt and clay materials are deposited with alternation of pebble, cobble deposition.

Recent Deposition

Recent Deposition (T_0) is the latest deposition by Madi River which lies in the current flow channels and its bars (Fig. 4). The height of T0 is about 2-7 meters from the current riverbeds. The widening of rivers makes more width of the T0 which is around 60-130 meters at now (Table 1). The Recent Deposition consists of poorly sorted, consolidated, rounded – sub – rounded boulders, cobble, pebble, granules with sandy matrix (Fig. 6). The compositions of these sediments are granite, gneiss, quartzite, pegmatite, and metasandstone (Fig. 5).

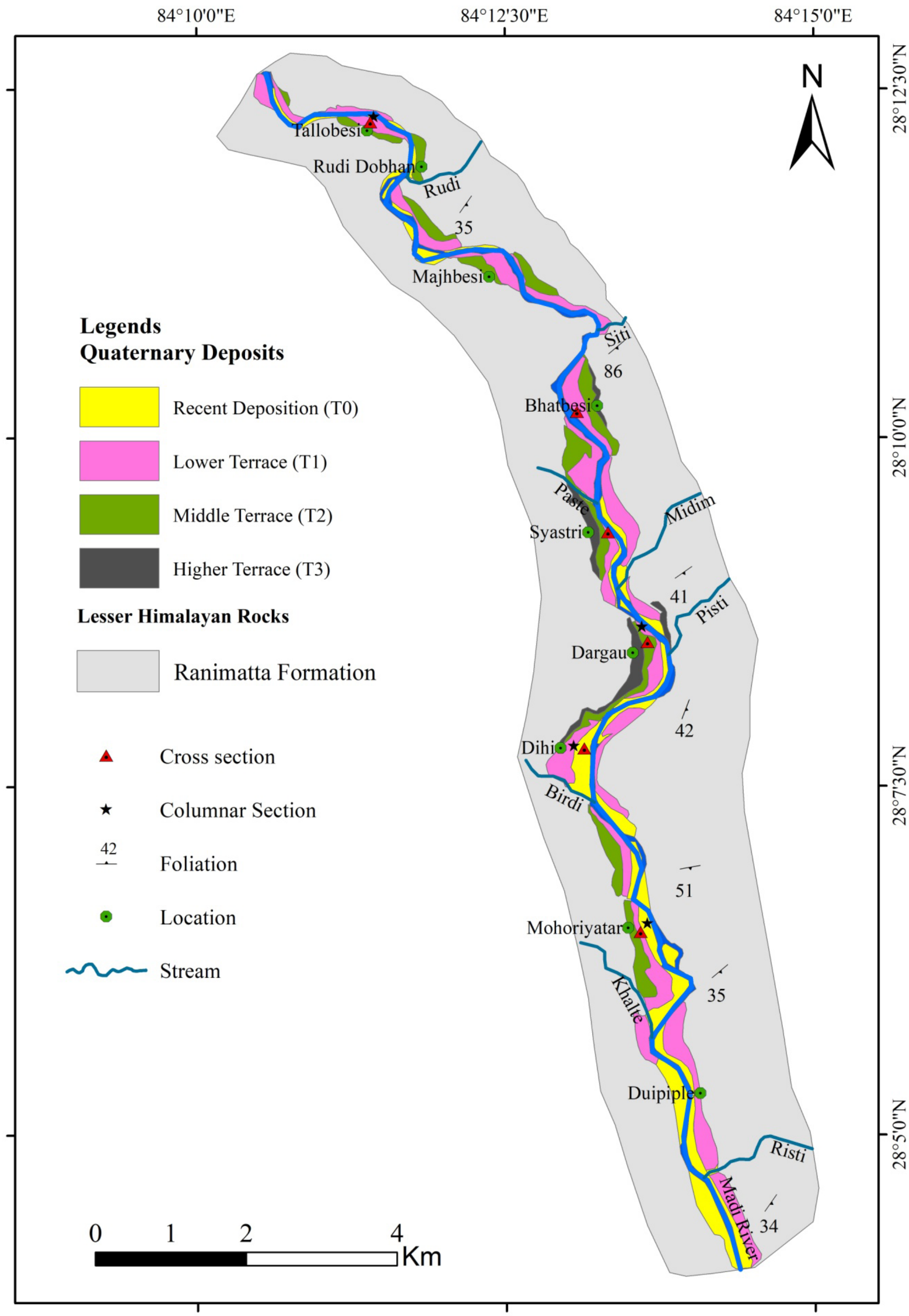

Fig. 4: Geological and terrace deposit map of the Middle Madi River section from the Duipiple to Rudi Doban

Table 1: Terrace of middle Madi River section and their characteristics

S. N.	Name of Terrace	GPS/ Elevation (Based on T_0)	T0	T1		T2		T3		Composition
				Height is measured from T0 in meter scale						
			W(m)	H	W	H	W	H	W	
1	Mohoriyatar	28° 06' 15" N/ 84° 13' 37" E (398m)	285	12	143	35	160			Middle Terrace consists of a matrix of weakly consolidated sub- angular boulder, cobble and pebble of gneiss, quartzite, schist and metasandstone. Lower Terrace consists of the matrix of unsorted, weakly consolidated, sub –rounded to rounded boulder, cobble and pebble, granules with sand, silt association of gneiss, quartzite, and granite.
2	Dihi	28° 07' 55" N/ 84° 13' 06" E (417m)	264	20	80	40	65	80	46	Large boulder of granite and gneiss in Higher Terrace, unsorted sediments in Middle Terrace and weakly consolidated, sub – rounded sediment in the Lower Terraces.
3	Dargau	28° 08' 40" N/ 84° 13' 30" E (434m)	106	12	72	40	81			Unconsolidated sediment in the Middle Terrace. Lower Terrace consists of alternation of sand and granules just above the Bed rocks.
4	Syastri	28° 09' 30" N/ 84° 13' 06" E (454m)	110	11	93	39	67			Poorly sorted, association of sub angular to sub – rounded sediment of granite, gneiss, quartzite, garnet schist, metasandstone and phyllite in both Lower and Middle Terrace.
5	Bhatbesi	28° 10' 16" N/ 84° 12' 50" E (470m)	88	18	104	39	98			Gentle slope consisting of boulder of gneiss, quartzite, and meta sandstone in T3, sub angular – rounded sediment of quartzite, schist and phyllite in T2 with sandy matrix sediment in T1.
6	Tallobesi	28° 12' 13" N/ 84° 11' 28" E (547m)	72	10	38	32	54			The lower part consists of a large boulder, middle part has matrix supported cobble, pebble and upper part has sandy soil of the Lower Terrace.

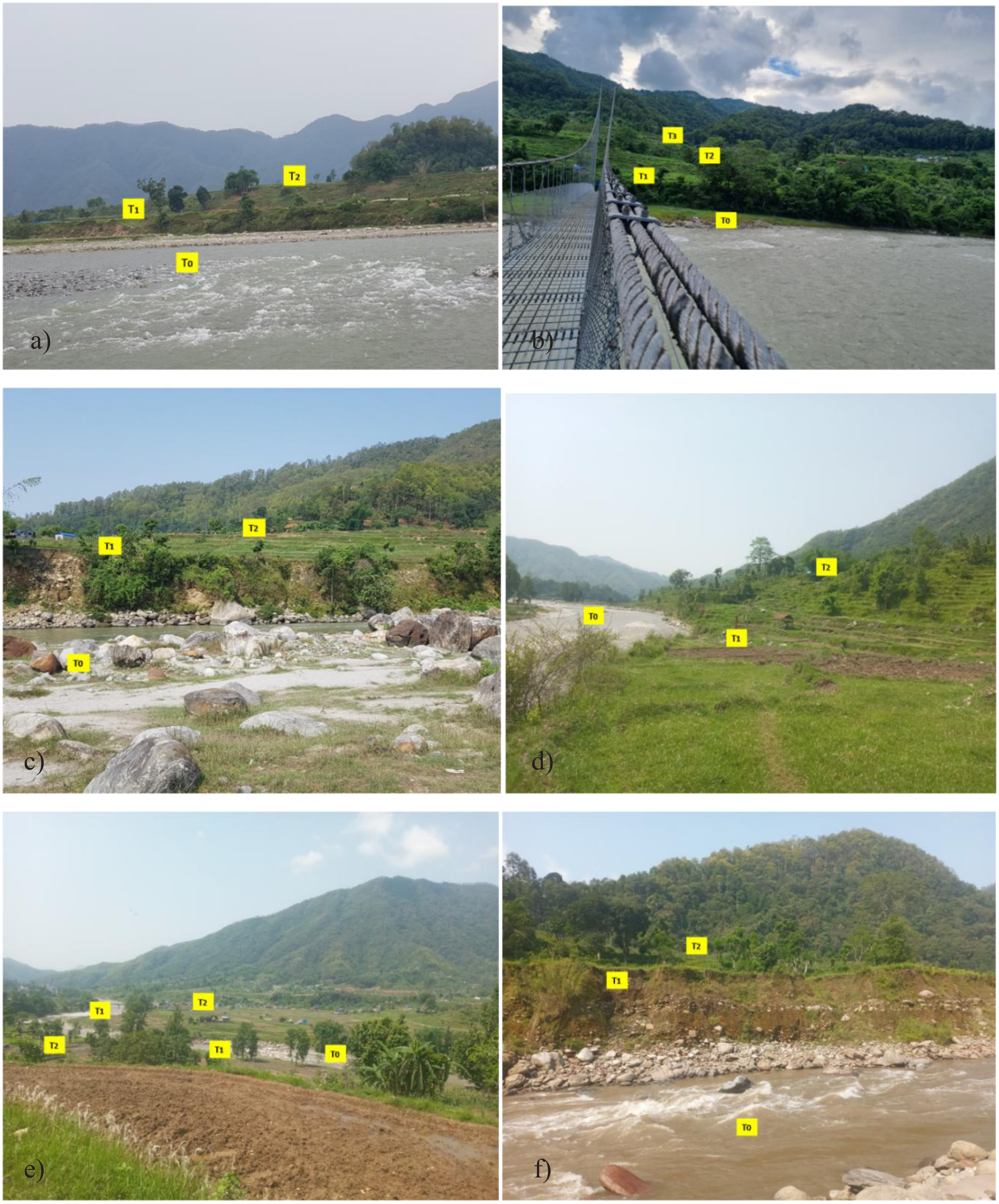

Fig. 5: Images of river Terraces in different part of the middle Madi River, (a) two level terrace with floodplain at Mohoriyatar, (b) three level terrace at Dihi, (c) two level terrace at Dargau, (d) lower and middle terrace at Syastri, (e) two level terrace in Bhatbesi – Thulabesi, (f) lower and middle terrace with flood plain at the right bank of Madi River at Tallobesi

Terrace Cross section

The illustrated cross-sections represent the stratigraphic and geomorphic arrangement of river terraces (T_0, T_1, T_2, and in one case T_3) along the middle section of the Madi River in the Lesser Himalaya (Fig. 6). Each profile demonstrates a distinct separation between the bedrock, composed of the Ranimatta Formation, and the overlying unconsolidated fluvial sediments. The bedrock is shown dipping predominantly towards the south or southeast and is overlain by terrace deposits of varying thicknesses. The lowest terrace (T_0) occurs adjacent to the modern river channel, composed primarily of coarse-grained fluvial sediments resting directly on the bedrock surface. Successively higher terraces (T_1, T_2, and T_3) are inset into the valley slopes, representing older depositional episodes, with the highest terraces occurring at elevations exceeding 500 m in some profiles. The stepped nature of these terraces reflects episodic river incision events, likely driven by tectonic uplift and climatic fluctuations.

A consistent pattern is observed in all cross-sections: the terrace sediments are sharply bound at their base by the bedrock surface, marking a pronounced erosional unconformity. The thickness of sedimentary cover varies laterally, with the highest terraces (T_2–T_3) containing thicker, well-preserved deposits compared to the more eroded lower terraces. The horizontal scale indicates that the valley width varies between 80 m and over 100 m in different sections, influencing terrace preservation. The stratigraphic architecture suggests multiple phases of river aggradation followed by incision, controlled by regional uplift of the Lesser Himalaya and episodic high-energy sediment supply from upstream catchments. This geomorphic and stratigraphic framework provides key evidence for reconstructing the Quaternary landscape evolution of the Madi River valley.

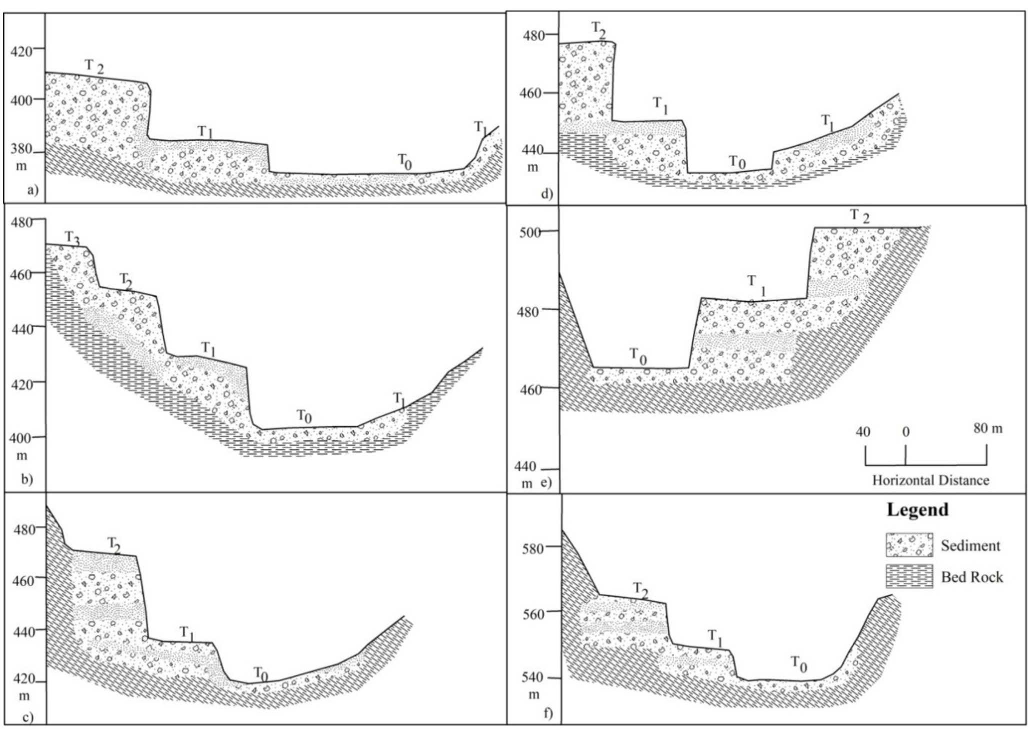

Fig. 6: Terrace cross sections of the middle Madi River, (a) two level terrace with floodplain at Mohoriyatar; (b) three level terrace at Dihi; (c) two level terrace at Dargau; (d) lower and middle terrace at Syastri; (e) two level terrace in Bhatbesi – Thulabesi; (f) lower and middle terrace with flood plain at the right bank of Madi River at Tallobesi

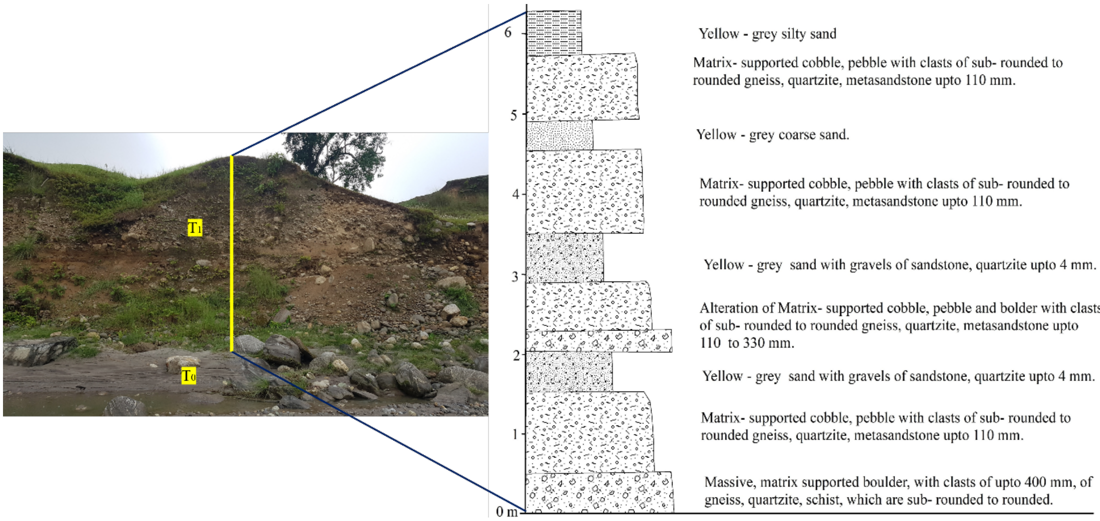

Fig. 7: Columnar section of Lower (T_1) of Mohoriyatar Terrace (Fig. 5a)

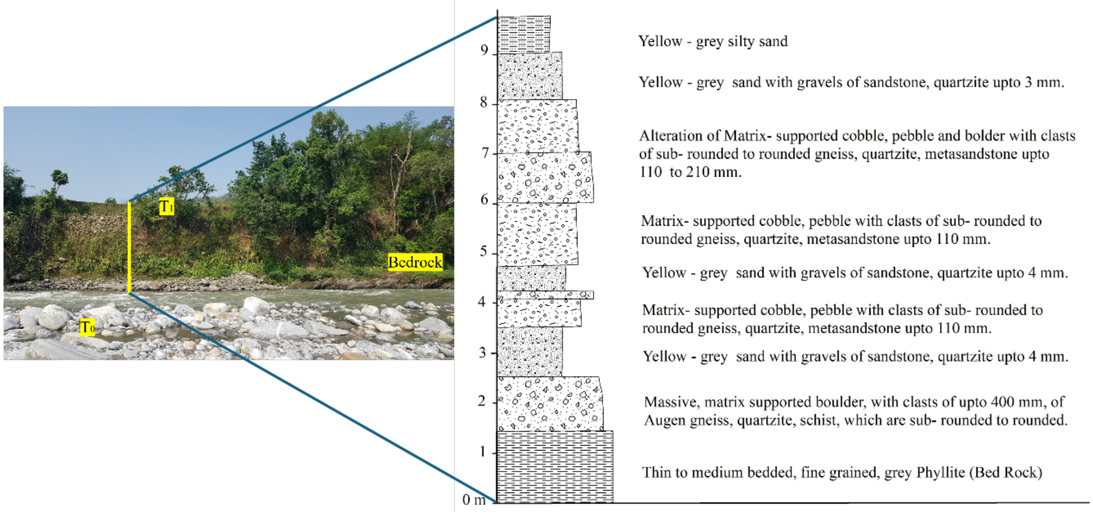

Fig. 8: Columnar section of Lower (T_1) of Dargau Terrace (Fig. 5c)

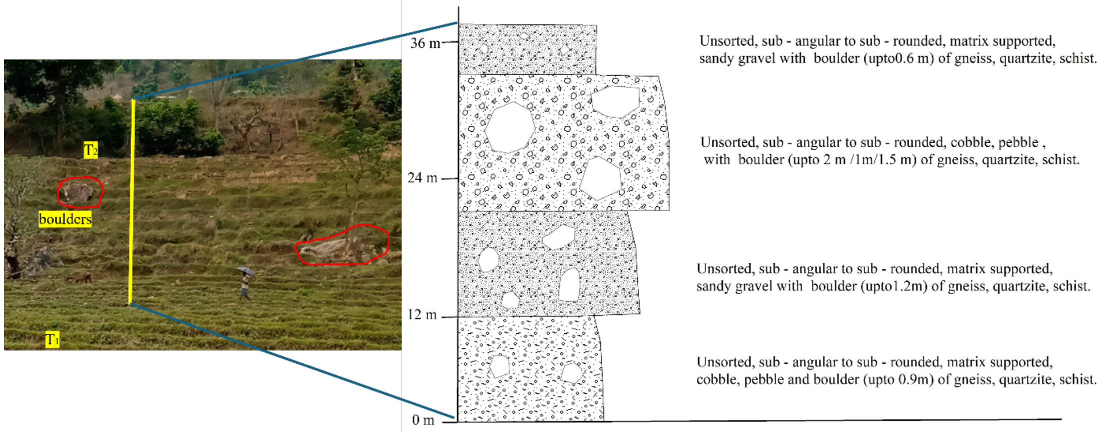

Fig. 9: Columnar section of Middle (T_2) of Dihi Terrace (Fig 5b)

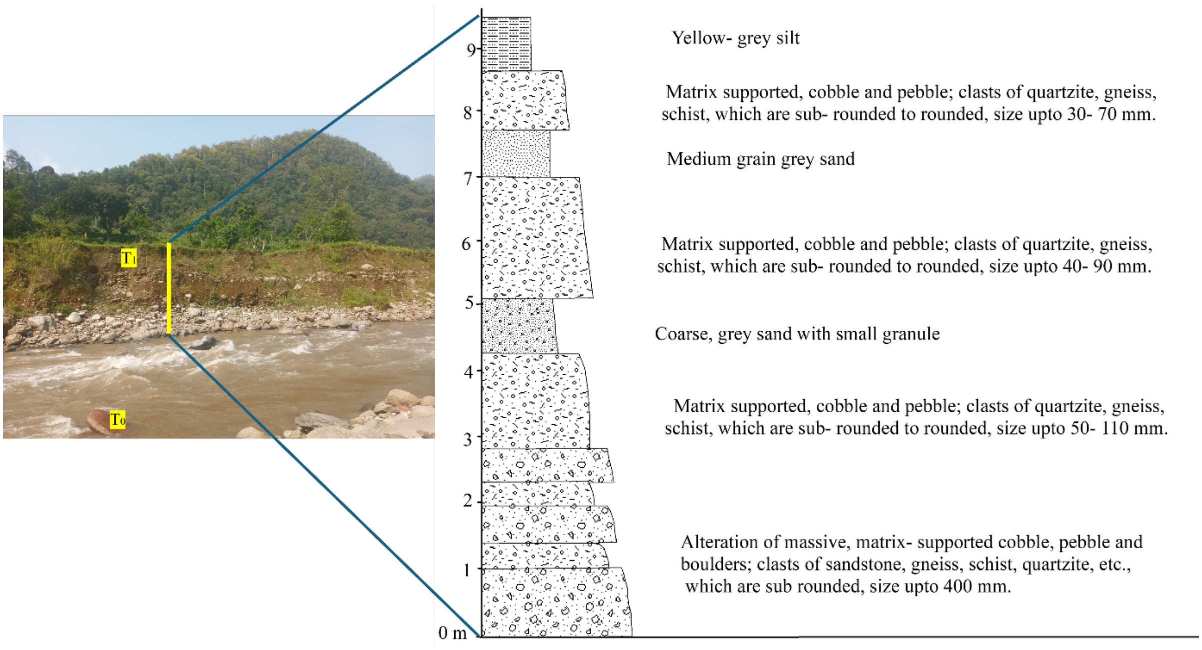

Fig. 10: Columnar section of Lower (T_1) of Tallobesi Terrace (Fig. 5f)

Sequences of Valley Development

Analysis of the river terrace cross-sections along the middle reach of the Madi River reveals three prominent regional terraces, which are interpreted to record three major phases of Himalayan uplift since the river's inception. During the initial phase, the Madi River occupied a broad floodplain, depositing extensive alluvial sediments under relatively stable tectonic conditions. Subsequent episodes of tectonic uplift and associated river incision produced the higher, middle, and lower terraces observed in the present landscape.

Well-developed terraces occur in the Dihi, Dargau, and Mohoriyatar sectors, representing distinct geomorphic levels formed during these incision phases. In addition, tributaries of the Madi River have contributed to the development of wide, laterally extensive terraces within the basin, suggesting a combination of regional uplift, climatic fluctuations, and local base-level adjustments as primary controls on valley evolution.

Terrace Genesis

Different factors are responsible for the genesis of terraces in different environments. The composition of sediment, their deposition pattern and geometry give the sediment origin and maturity. The Higher Terrace consist unsorted, sub – angular to sub – rounded large boulders in gentle slope; Middle Terrace consists consolidated, unsorted, sub- angular to sub – rounded, boulders, cobble, pebble with granules and the Lower Terrace is composed of fairly sorted, consolidated, sub – rounded to rounded small boulders, cobble and pebble, granules with sand and silt matrix. The sediment composition belongs to high grade metamorphic rock like granite, gneiss, schist, garnet schist, quartzite, metasandstone and phyllite. Lesser Himalaya and Higher Himalayan zone is the source of the sediment, which is composed of high-grade metamorphic rock. Recent flood channel consists of fine and coarse sediments which arrived from no of kilometers along with Madi River.

The deposition pattern is diverse in all terraces. The fine sediments (sand, silt) are deposited in alteration with coarser sediment (boulders, cobble, pebble, granules). Low current velocity river is favorable for the deposition of fine sediments. The coarse sediments are deposited by the high velocity current of Madi River. River channel's current velocity is low in winter season and high in summer season. So, finer sediments are deposited in winter season and coarser sediments are deposited in summer season.

Order of Terrace Development

The stratigraphic and geomorphic evidence indicates that the terraces along the middle Madi River were formed in three distinct phases of river incision and aggradation, corresponding to episodic tectonic uplift and changes in fluvial regime.

Higher Terrace (T3) – The Higher Terrace represents the earliest phase of terrace formation and is interpreted as a product of glaciofluvial deposition (Yamanaka and Iwata, 1982). This phase is associated with the initial regional uplift, during which the river established its first extensive floodplain. The T3 surface of the Dihi Terrace contains thick channel-fill deposits, dominated by large, poorly sorted sediments, indicative of high-energy flow conditions within a braided channel system.

Middle Terrace (T2) – The second uplift phase led to the incision of the Higher Terrace and the development of the Middle Terrace, both along the main Madi River and its tributaries. This terrace level is preserved throughout much of the study area and consists predominantly of fluvial deposits. These surfaces are more susceptible to erosion than the higher terraces, reflecting partial reworking of earlier deposits.

Lower Terrace (T1) – The Lower Terrace formed during the third uplift phase, marking the most recent major incision event. Compared with the older terraces, the T1 deposits are finer-grained, indicating reduced stream power and a transition toward more stable, meandering channel conditions.

Influence of Tributaries on Terrace Formation

The terrace morphology and sedimentology of the middle Madi River are significantly influenced by its major tributaries, including the Rudi Khola, Paste Khola, Midim Khola, Birdi Khola, and several smaller streams. Tributary junctions contribute additional sediment loads and influence local hydrodynamics, promoting terrace development. This influence is evidenced by the occurrence of angular to sub-angular phyllite and metasandstone clasts within the Middle and Lower Terraces, particularly well documented in the Dihi and Syastri terrace exposures. The confluence zones between the Madi River and its tributaries commonly host relatively wide terraces, reflecting enhanced sediment storage. These depositional surfaces result from alternating phases of aggradation and degradation, driven by tributary-supplied sediments and subsequent reworking during river incision.

CONCLUSION

River terrace mapping along the middle section of the Madi River reveals a well-preserved sequence of Higher (T3), Middle (T2), Lower (T1), and recent (T0) depositional surfaces, reflecting distinct phases of Himalayan uplift and fluvial response. The Higher Terraces, averaging 80 m in height and 46 m in width, are dominated by large boulder deposits formed under glacio-fluvial conditions during the earliest uplift phase. The Middle Terraces, with an average height of 40 m and width of 90 m, comprise a mixture of coarse and fine sediments, indicating fluvial deposition with significant tributary influence and partial reworking of earlier deposits. The Lower Terraces, averaging 20 m in height and 120 m in width, are composed predominantly of rounded, poorly sorted sediments deposited under lower-energy river conditions.

The spatial distribution, sediment composition, and geometry of these terraces demonstrate that terrace formation in the Madi River valley is the product of combined tectonic uplift, climatic fluctuations, and tributary sediment inputs. Wide terrace surfaces near tributary junctions reflect localized aggradation, while alternating phases of sediment accumulation and incision indicate a dynamic balance between uplift and river down-cutting. The multi-terrace system preserved in this region therefore serves as a geomorphic archive of Quaternary landscape evolution in the Lesser Himalaya, recording both the tectonic history and the changing hydrological regime of the Madi River and its tributaries.

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Author Contributions

All the authors have made significant contributions to preparing these research articles. First Mr. Ashok Dhakal did the study of concept and design. Mr. Sunil Lamsal guided him in field study. Dr. Kabi Raj Paudyal analyzed the field data and provided the framework for the article. The first draft of the manuscript was written by Ashok Dhakal and all authors contributed to making the draft form of the manuscript into the final version. Finally, all the authors contributed to making corrections as per the suggestion of reviewers.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that supports the findings of this study are available from the corresponding author, upon reasonable request.

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