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Assessment of Neotectonic Influence on Intermountain Terraces Developed in Tista River, Sikkim Darjeeling Himalaya

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Abstract

Tista River is flowing through the major lithotectonic units and thrust system of the Himalayas. In this aspect, river terraces preserve valuable geological records and are exposed at different locations along the river course. Therefore, it is needed to investigate these river terraces for understanding the response of rivers to intermountain deposits as influenced by tectonic processes. The present study area focused on intermountain deposits from Dikchu to Melli. The methodology consisted of calculation of Vf ratio as a geomorphic parameter, facies analysis by field sedimentology, grain size and heavy mineral analysis of selected terrace sediments, and correlation of terraces. The Vf ratio as an indicator to differentiate between tectonic activity or tectonic quiescence in the area, which showed considerable variation in the proximity of valley areas of thrust within the intermountain area. The results of field sedimentological studies showed that terraces of the upper part of Tista valley preserved alluvial records of channel and bar deposits, while lower parts in addition comprised floodplain deposits indicating differential aggradation process operating in the valley fill. Grain size analysis showed that Tista River sediments are characterized by higher clastic fractions than a fluid phase. The heavy mineral analysis revealed the provenance of sediments from lesser and Higher Himalayan regions while ZTR index values indicated mineralogical immaturity of sediments. Therefore, Tista River terraces were alluvial in origin and have varied developmental stages in intermountain front depositional zones in Sikkim-Darjeeling Himalaya.

Keywords: Tista River, Neotectonic, Terraces, Sedimentology, Geomorphology, Sikkim

Introduction

The fluvial system in the Himalayan region is evolved through geological time as a result of interactions with tectonic and climatic forces. This interaction was continuously modifying the geomorphology of the region and associated landforms. Therefore signatures of these interactions are well preserved in the form of fluvial landforms of the region. These records are preserving both erosional and depositional processes in these landforms. This gains the importance to study these landforms for understanding processes (Burbank and Anderson, 2001; Bull, 2007). The Himalayan foreland basin preserves the older records of fluvial sequences along strike of the orogen as well studied sections from Pakistan, Indian, Nepal, and Tibet. In NW Himalaya the Subathu sub-basin studies show Dagshai and Kasauli mark the continental deposits followed by the Siwalik group represent thickest fluvial deposits in the foreland. This marine regression and fluvial facies dominance is the result of forced regression along with progressive orogenic uplift (Raiverman, 1979; Sangode *et al.,* 2010; Badekar *et al.,* 2010). The Siwalik group of sediments study also reveals a link between monsoon intensity and pulses of Himalaya uplift. The tectonic impact on the fluvial deposits of Plio-Pleistocene was also reported from the Himalayan foreland basin (Kumar *et al.*, 2003).

The major river systems developed in the Himalayan region are Ganga, Bramhaputra, Indus, and Tistaare characterized by their alluvial sediments. These rivers are carrying high sediment loads and deposit at foothills. They are forming large alluvial mega fans after reaching foothills which are observed on a regional scale. These mega fans preserve the record of tectonic activity and climatic imprints of the associated orogenic belts (Chakraborty and Ghosh, 2010). The intermontane fans are well developed in the frontal region of WesternHimalaya. These landform and landscape evolution preserve the record of tectonic processes associated with deforming orogenic fronts (Singh and Tandon, 2010; Verma and Bhattarcharya, 2016). The studies on river deposits from other part of India are also reported in reference to facies aspects (Gurav *et al.,* 2021)

In the eastern Himalaya Tista river is one of the major river systems developed in the region. The fluvial record of river aggradations and incisions are preserved along the river stretch in its deposits. These valley-fill deposits in Sikkim-Darjeeling Himalaya are providing opportunity to study landform development and landscape evolution. Sinha-Roy (1980) studied Tista River deposits from Mankha to Sevoke and inferred a three-tier terrace system developed in this stretch. Mukul *et al.*(2007) reported terraces formed between the Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) as a result of deformation processes in the region. Meetei *et al.* (2007) studied these valley-fill deposits near Mangalbare village and summarized as climate change plays a dominant role in aggradation and incision cycles. Then, Singh *et al.* (2017) studied deposits near the confluence of Tum Thang Khola and Tista river and inferred the influence of climate and tectonic on river deposits. The geomorphic indices are computed for the Relli river basin which is a part of the Tista river basin to study the evolution of topography, landscape, and neotectonics of the region that result in the identification of reactivation of Munsiari thrust (Mukul *et al.,* 2017). Abrahami *et al.* (2018) studied hinterland and megafan deposits and inferred synchronous incision between terraces in the hinterland and megafan surfaces. A number of geomorphic studies from Himalaya reported the evidence of active tectonics from parts of Main Boundary Thrust (MBT) and Main Frontal Thrust MFT, which also include parts of Darjeeling Himalaya (Mukul and Singh, 2016). The Himalayan river response to neotectonic and climate are studied in a number of parts of Himalaya (Srivastava *et al.,* 2016). The Tista River is flowing through all the major lithotectonic units and thrust systems of the Himalayas. Therefore the river response to the tectonic system is needed to investigate through well-preserved deposits throughout its stretch. The present study mainly focuses on intermountain deposits which are exposed between MCT and MBT.

Regional-Study Area Geology and Geomorphology

The Sikkim Darjeeling Himalayan comprises major litho units of Himalayan orogeny. These units from north to the south separated by thrust system evolved in the region as the South Tibet Detachment (STD), Main Central Thrust System (MCT-1 and MCT-2), the Ramgarh Thrust (RT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT) are marked in Figure.1. In the north, STD separates Tethyan sedimentary sequence from Greater Himalayan Sequence (GHS) comprising Para-gneisses (Darjeeling/ Kanchenjunga Gneiss). The MCT consist of a zone comprising MCT-1 and MCT-2 which exposes granulite facies, and amphibolites facies of the GHS.This MCT zone separates GHS from the Lesser Himalayan sequence. In lesser Himalayan sequences, the Upper Lesser Himalayan sequence is separated from Lower Lesser Himalaya by RT. the lesser Himalayan sequences and Sub-Himalayan sequences are separated by MBT. In the southern part, MFT separates the Foreland sedimentation of Siwalik Group from the recent alluvium of the Indo-Gangetic plains (Bhattacharyya and Mitra, 2009).

The Tista River flowing is through all major litho units and structural elements of Himalaya from north to south. The regional and study area maps show the major structural elements of a region in which the Tista River is flowing (Fig. 1). This river originates from Pauhunri (or Tista Kangse) glacier at 7127m above mean sea level (MSL), which also shows glacial processes are also influencing the geomorphology of these parts. Then river action dominates and interaction with lithology result in erosional landforms developed in areas mainly of GHS. The decreased gradient in LHS and Sub-Himalayan part is characterized by depositional landforms in the intermontane area. The foothill part of the Himalaya alluvial fan system is well developed(Chakraborty and Ghosh, 2010).

Methodology

The methodology adopted for present work in i) Geomorphic parameter as Vf ratio, ii) Field Sedimentology iii) Grain Size and Heavy Mineral Analysis iv) River Incision, Migration, and Correlation of terraces. In the present work

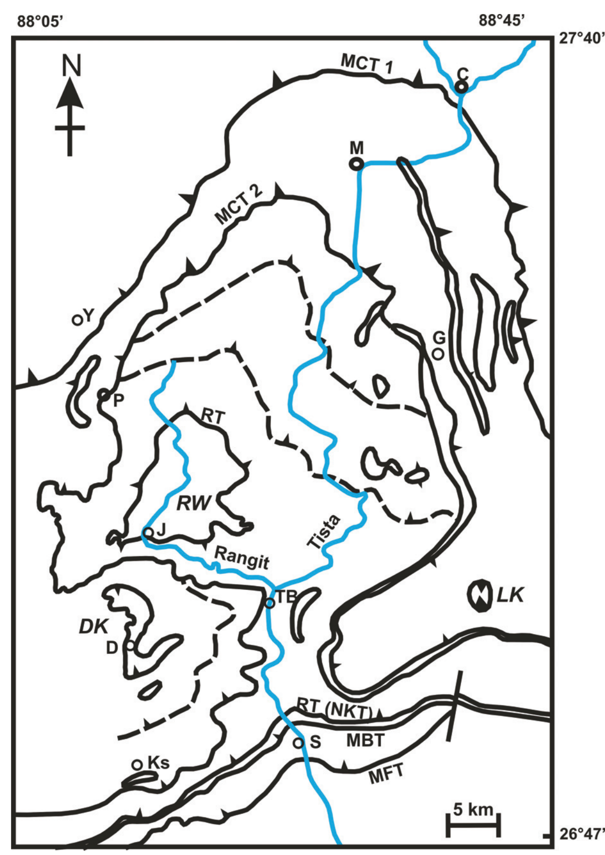

Fig.1. Major structural units of Darjeeling and Sikkim Himalaya Geology (Mitra *et al.,* 2010)

valley floor width to valley floor height ratio (Vf) ratio was used to understand neotectonic activities along the Tista River. The Google Earth is used to generate river profiles as longitudinal and cross-sections. Then the required parameters for the Vf ratio are measured along with these profiles. The V_f ratios calculation formula given by Bull and Mc Fadden, 1977 *i.e.* $V_f = 2V_{fw}/ [(E_{ld}-E_{sc}) + (E_{rd}-E_{sc})]$ are used and the V_f ratio is interpreted as active, moderate, and stable tectonic activity. Vf is defined as an index to assess an area for its tectonic activity. The Vf index is given by: $V_f= 2V_{fw} / [(E_{ld}-E_{sc})+(E_{rd}-E_{sc})]$.Where V_{fw} is the width of the valley floor, E_{sc} is the elevation of the valley floor or stream channel, E_{ld} and E_{rd} are the elevations of the left and right valley divides respectively. This index reflects the difference between the V-shaped valleys in which downcutting is prominent in response to active uplift indicating a relatively high tectonic activity, and the U- shaped broad floored valleys with dominant lateral erosion into the adjacent hill slopes in response to relative base-level stability of tectonic quiescence. ii) Field Sedimentological studies: The Field sedimentology and facies variation study include an extensive reconnaissance survey has been conducted from Dikchu to Melli, in the Sikkim Himalaya area. The sections are selected and the sedimentological observations in each section have been carried out as, documentation of grain size and color variation, upper/lower contact relationships, the geometry of the sand bodies, lateral changes, and primary sedimentary structures that are useful to describe the facies and depositional environments. iii) Grain size and Heavy Mineral Analysis: is carried out for samples collected from these terraces. The standard procedure for grain size analysis is adopted for samples using a sieve shaker, and obtained data is processed in Gradistat software to get statistical parameters (Blott and Pye, 2001). The Heavy Mineral Analysis is conducted using the standard procedure of gravity separation mentioned (Mange and Maurer, 1992). The Bromoform ($CHBr_3$) is a heavy liquid used for the separation of heavy minerals from sediments and then they are mounted on petrographic glass slides for study. iv) River Incision, Migration, and Correlation of terraces: This is based on data collected from terraces as Elevation of terraces, Elevation of River channel base, Incision (vertical) in meters, Incision (Lateral) and Migration in meters, Migration towards Right/Left, and Vertical / Lateral variation. Then these terraces are correlated and compared with each other in reference to elevation and facies. This will provide information about river course and help for identification of anomalies, which are also used to relate with tectonics.

Results

Geomorphic Parameter as Vf Ratio

The river responses are very characteristic and the best indicators of tectonic activity. Their pattern, behavior, and variation in thickness of sediments are evidence of tectonic activity. In these studies, valley floor profiles are very important and sensitive indicators of tectonic activity. The 240 km intermountain stretch of the Tista River from its source to downstream is selected for the present study Vf ratio calculation (Fig. 2; Table 1). Total 54 locations are selected for valley cross profiles along these river paths. The different ratio parameters are measured along with these profiles and the Vf index is calculated (Table 1). The studies related to the Vf ratio index inferred V shape valleys with low Vf values <1.0 developed in response to active uplift, while U shape valleys with higher than >1.0 developed in response to lateral erosion as a stable base or tectonic quiescence (Wells *et al.,* 1988; Silva *et al.,* 2003; Bull and McFadden, 1977; Malik and Mohanty, 2007). The present study of the Tista River Vf ratio is ranging from 0.15 to 7.56. the Vf index <1.0 are observed v shape valley and indicating most tectonic uplift, while Vf indices in the range between 1-1.5 indicate moderate tectonic uplift whereas the Vf indices >1.5 are characterized by broad U shape valleys, whereas the stable base level of tectonic quiescence.

The Vf ratio indicates separate this studied location into three different zones as upper, middle, and lower zones from north to south (Fig. 2). The upper zone occupies a position near the source of the Tista River, and it is characterized by higher Vf indices inferring U shape valleys which are developed in response to glacial processes dominating the tectonic processes. The middle zone extends over the large studied area and is dominated by lower Vf indices. This area is characterized by V shape valleys and incised river terraces. This area is traversed by a number of thrusts MCT1, MCT2, MT, PT, and RAT. The area between distances of 120m to 170m reflecting the mixed response of the Vf ratio indicating fluvial processes also in action with tectonic processes. This area is characterized by broad valleys and raised terraces. The lower zone covers the area south of MFT. They are characterized by higher values of the Vf ratio. These comprise mainly foothills part of Himalaya with alluvial plain deposits. Therefore the valleys are U shape wider and show mainly migratory nature of the channel. This indicates fluvial processes are more dominating over this zone.

The U shapes valleys are developed near-source as the influence of glacial processes are dominating these parts. The U shape valleys are also very well developed near foothill parts of the Himalayas as a result of fluvial processes are constantly acting in the area. V shape valleys are dominating in the intermediate area, while the area around Rangpo shows the development of both types of valleys within the stretch. These areas reflect the influence of tectonic on fluvial processes as the presence of thrusts as MCT1, MCT2, 1st, 2nd, NRT, MBT, and MFT. These thrusts are marked intermountain fronts as they preserve records of older mountain fronts. Therefore, Intermountain fronts provide important information about the evolution of the fluvial system with the tectonic development of the area.

Table 1: The Vf ratio calculated at different locations on Tista River and their result

Sr. No.	Lithological Units	Distance (in m)	Eld (in m)	Erd (in m)	Esc (in m)	Vfw (in m)	Vf ratio (in m)	Valley shape	Result
1	Lachi Formation	4.75	5332	5181	5076	786	4.35	U shape	Stable base level/ Tectonic quiesence
2		10	5223	5243	5047	1031	5.54	U shape	Stable base level/ Tectonic quiesence
3	Darjeeling/ Kanchenjunga Gneiss	14.5	5077	5161	4991	873	6.82	U shape	Stable base level/ Tectonic quiesence
4		19.2	4946	4999	4846	764	6.04	U shape	Stable base level/ Tectonic quiesence
5		23.6	5149	5129	4707	572	1.32	Intermediate shape	Moderately Active
6		28	5011	5130	4476	672	1.13	Intermediate shape	Moderately Active
7		34	4943	5041	4228	414	0.54	V shape	Most Active Tectonic Uplift
8		39	4531	4244	3853	469	0.88	V shape	Most Active Tectonic Uplift
9		44	3989	4394	3600	408	0.69	V shape	Most Active Tectonic Uplift
10		49	4181	4285	3205	186	0.18	V shape	Most Active Tectonic Uplift
11		53	3935	3962	2943	191	0.19	V shape	Most Active Tectonic Uplift
12		57	3825	4053	2549	231	0.17	V shape	Most Active Tectonic Uplift
13		64	3425	4157	2134	362	0.22	V shape	Most Active Tectonic Uplift
14		70	3795	2921	1885	452	0.31	V shape	Most Active Tectonic Uplift
15	Paro Gneiss	75	2754	2369	1627	253	0.27	V shape	Most Active Tectonic Uplift
16		79	3128	3123	1488	279	0.17	V shape	Most Active Tectonic Uplift
17		83	2037	2286	1342	230	0.28	V shape	Most Active Tectonic Uplift
18		88	2507	2262	1071	193	0.15	V shape	Most Active Tectonic Uplift
19		94	2703	1782	901	278	0.21	V shape	Most Active Tectonic Uplift
20		98	2135	1568	716	252	0.22	V shape	Most Active Tectonic Uplift
21		103	1496	1750	664	270	0.28	V shape	Most Active Tectonic Uplift
22	Daling Group	110	1998	2521	587	407	0.24	V shape	Most Active Tectonic Uplift
23		113	1683	1736	551	203	0.18	V shape	Most Active Tectonic Uplift
24		118	2115	2271	497	413	0.24	V shape	Most Active Tectonic Uplift
25		125	1571	1909	458	748	0.58	V shape	Most Active Tectonic Uplift
26		129	1117	1345	396	814	0.97	V shape	Most Active Tectonic Uplift
27		133	1531	804	374	1000	1.26	Intermediate shape	Moderately Active
28		138	947	923	342	454	0.77	V shape	Most Active Tectonic Uplift
29		140	1196	1369	323	479	0.50	V shape	Most Active Tectonic Uplift
30		142	679	823	312	820	1.87	U shape	Stable base level/ Tectonic quiesence
31		145	947	1304	303	1020	1.24	V shape	Most Active Tectonic Uplift
32		146	504	878	298	972	2.47	U shape	Stable base level/ Tectonic quiesence
33		147	509	915	287	1027	2.42	U shape	Stable base level/ Tectonic quiesence
34		149	542	483	278	191	0.81	V shape	Most Active Tectonic Uplift
35		151	824	756	271	1050	2.02	U shape	Stable base level/ Tectonic quiesence
36		152	693	674	266	836	2.00	U shape	Stable base level/ Tectonic quiesence
37		155	856	684	258	507	0.99	V shape	Most Active Tectonic Uplift
38		156	432	646	248	634	2.18	U shape	Stable base level/ Tectonic quiesence
39		157	1181	598	250	278	0.43	V shape	Most Active Tectonic Uplift
40		160	852	829	231	448	0.74	V shape	Most Active Tectonic Uplift
41		162	961	770	241	248	0.40	V shape	Most Active Tectonic Uplift
42		164	1011	727	224	331	0.51	V shape	Most Active Tectonic Uplift
43		166	784	801	226	276	0.49	V shape	Most Active Tectonic Uplift
44		171	1073	1152	211	308	0.34	V shape	Most Active Tectonic Uplift
45		174	799	791	197	419	0.70	V shape	Most Active Tectonic Uplift
46		179	730	392	188	228	0.61	V shape	Most Active Tectonic Uplift
47		184	813	839	165	409	0.62	V shape	Most Active Tectonic Uplift
48	Gondwana / Bauxa Formation	188	1063	420	160	609	1.05	Intermediate shape	Moderately Active
49	Siwalik Group	192	615	666	169	222	0.47	V shape	Most Active Tectonic Uplift
50		193	423	392	175	289	1.24	Intermediate shape	Moderately Active
51	Quaternary Alluvium	194	304	287	146	400	2.68	U shape	Stable base level/ Tectonic quiesence
52		194.2	256	258	146	614	5.53	U shape	Stable base level/ Tectonic quiesence
53		194.8	243	227	144	688	7.56	U shape	Stable base level/ Tectonic quiesence
54		214	138	136	103	118	3.47	U shape	Stable base level/ Tectonic quiesence

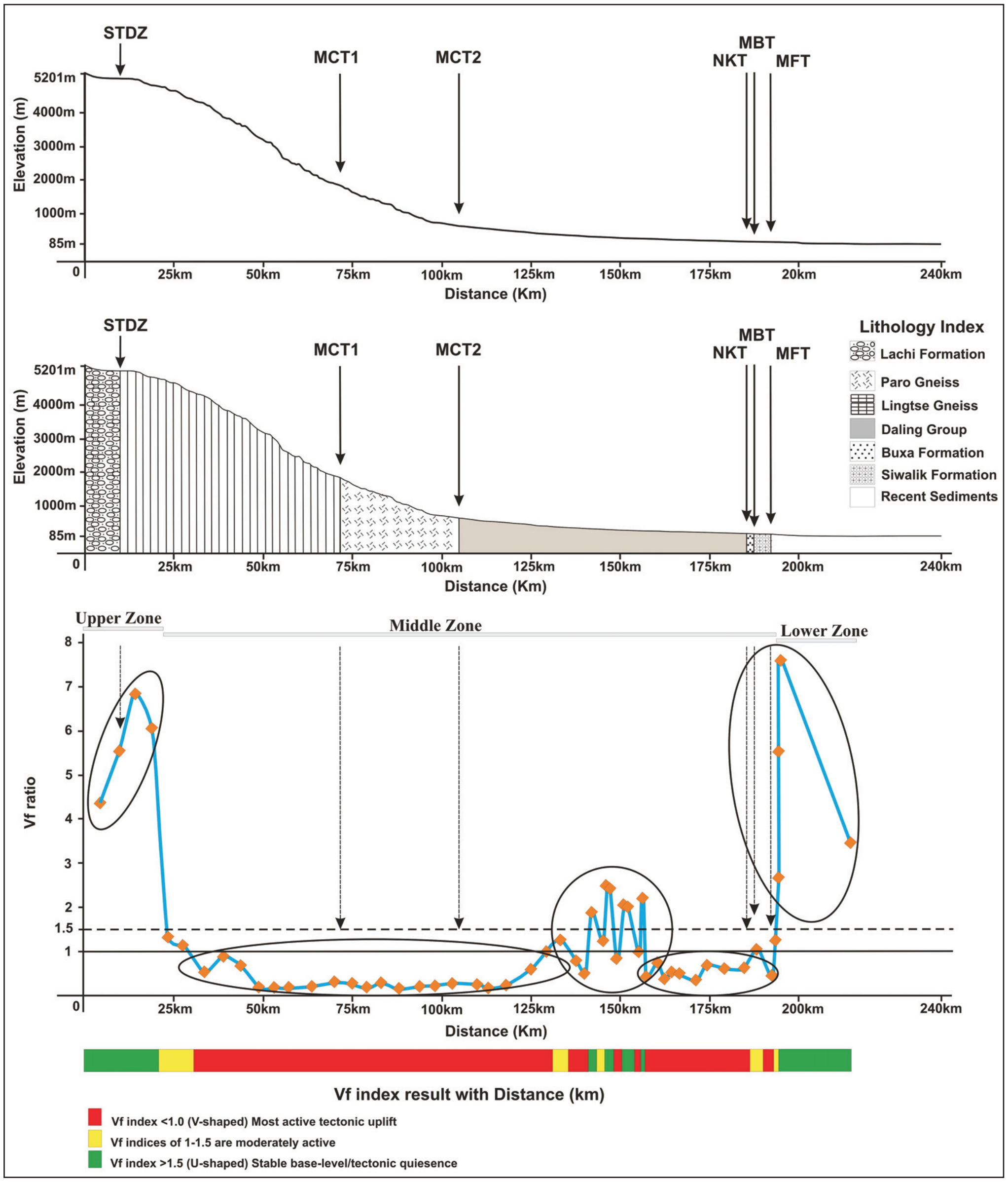

Fig.2. Tista river profile, Lithotectonic units, Vf ratio variation and Vf index with distance

Field Sedimentology

The geomorphic index (Vf index) shows the middle zone of the Tista River is characterized by higher tectonic activity but in the southern part shows an anomalous variation (Fig. 2). This middle zone on a river profile marks a transitional zone between higher and lower altitudes, which also represents a zone of gradient change. This topographic gradient change provides a low relief area to develop the depositional geomorphologic landforms. These landforms are needed to investigate in detail with a sedimentological approach. Therefore the well-exposed terraces in Tista River downstream from Dikchu to Malli are selected for the present study.

There are 18 terraces that were studied from a distance of 110km to 167km of the Tista River (Fig. 3). These all terraces were developed in the elevation range of 700m to 200m. This show within 57km of downstream distance about ~500m of elevation difference indicates rapid elevation change in a shorter distance. They indicate the development of terraces in different steps like appearances. The six steps were observed with variable degrees of slope pattern within these deposits. The morphology of these terrace deposits indicates intermontane alluvial fan deposits. This infers Tista River evolves through high topographic gradient change with the number of intermediate breaks in the deposition.

The sedimentological studies of selected terraces include detailed field sedimentological documentation and facies analysis (Table 2). All terraces studied in the present study are mainly of unpaired nature. From a total of 18 terraces, 13 were developed on the left bank of the river while the remaining 5 were on the right bank of Tista. These terraces

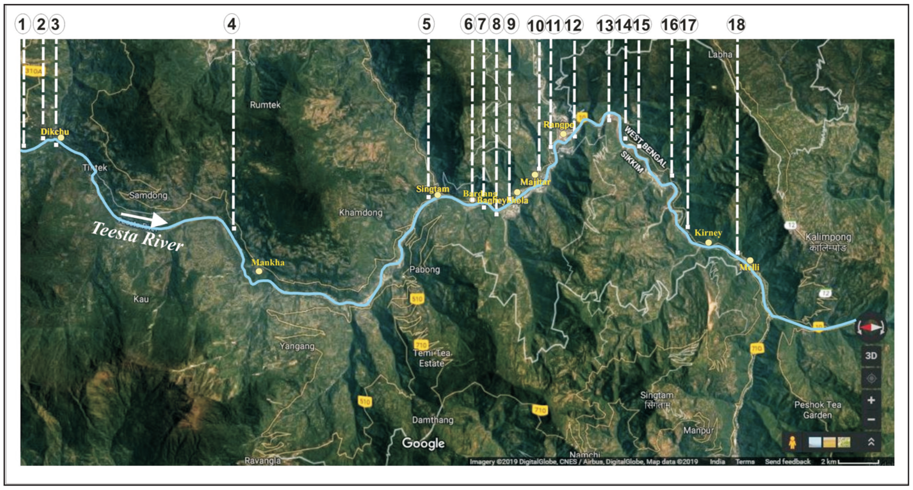

Fig. 3. Tista River terrace locations selected for sedimentological studies on Google Earth image

are exposed in variable thickness along the stretch of the Tista River. The sedimentological studies of these terraces include the identification of facies based on the color of lithology, grain size, sedimentary structures, and shape of the deposit. These parameters of facies identification were used for depositional environment interpretation.

The detailed sedimentological observation terrace wise as follows: These locations are grouped as nearby places towards downstream in 10 well-known localities as near Dikchu it includes locations 1, 2 and 3; near Mankha location 4; near Singtam location 5; near Bardang locations 6, 7, 8 and 9V) Near Majitar 10 VI) Near Rangpo locations are 11 and 12VII) Near Tumthang locations 13, 14, 15; near Tar 16; Kirney 17 and near Melli location is 18. The field sedimentological studies are used to identify sedimentary facies assigned by various workers (Miall, 1985, 1996; Einsele, 2000).

Near Dikchu

The 3 locations near Dikchu are selected for study, which are well-exposed terrace deposits (Fig. 4). North of Dikchu (1): (Gcd) In this area T1 terrace deposit of 6.5m thick is observed, which comprise a thick unit of the boulder, gravel, and very coarse sand. They represent disorganized, clast supported; polymictic conglomerate, Boulder, and pebbles are subangular to rounded. This rapid deposition by stream flood with clast concentration indicates debris flow deposit. Near Dikchu bridge (2): In this outcrop, T1 and T2 terraces are exposed T1 is characterized by (Gcd) thick large deposit of unsorted boulders and sand, the boulder, and cobbles are sub angular to sub rounded in nature. Dominated by large debris flow deposits indicate the proximal part of the alluvial deposit. T2 show (Gco) clasts are in an organized manner, clast-supported and polymictic in nature. The cobble and pebbles are in normal grading, with weak imbrication. This represents traction bedload and transported by persistent fluvial stream. Opposite Dikchu Bazaar (3): this outcrop show T1 (Gt) with clasts supported framework with cross-stratification. The cobble and granules are in normal grading, with imbrication. This represents the channel fill deposit of the fluvial stream.

Near Mankha

Mankha (4): The coarsening up sequence identified. The basal part (St) comprises medium to coarse sand, reddish in color, and trough cross-stratification (Fig. 5). This part indicates dune migration. This is followed by a debris flow (Gci) deposit base dominated by comparatively finer material with pebble cobles and sand, while the upper part is dominated by boulder and cobbles-dominated sequence. These deposits indicate proximal to the intermediate part of the alluvial river.

Near Singtam

Singtam Bazar (5): This outcrop exposing lateral as well as vertical variation in facies (Fig. 5). The lateral variation consists of Gcd, Gco, Gt, and St sedimentary facies. This facies variation in the bottom part of the outcrop comprises unsorted boulders, cobbles and pebbles, and sand.The vertical succession of that developed above St sedimentary facies comprises mainly fining upward sequences. These individual sequences consist of St, Sh, Sl, and Fl sedimentary facies and comprise mainly sand, silt, and mud. The lateral facies variation of basal part indicates rapid deposition as stream flood, traction bedload, transverse bar, channel fill, and dune migration depositional condition. The vertical succession infers planer bed flow, antidunes formation as in the upper flow regime while suspension load accumulation indicates overbank or flood deposits.

Near Bardang

Baradang (6): The T1 outcrop shows basal part consists of Gt facies while the upper part is Sh facies (Fig. 6-7).

Table 2: Tista River terraces field sedimentological documentation

Sr. No.	Location of Terraces	River bank on Terraces present	Sediment types	Facies	Elevation of terraces	Elevation of River channel base	Incision (vertical) in meters	Incision (Lateral) and Migration in meters	Migration towards Right/ Left	Vertical or / lateral variation
1	Towards Mangan	Left River Bank	Pebble, Cobble and Sand	Channel+Bar	632	587	45	191	Towards Right	Verical Sequence
2	Dikchu bridge	Left River Bank	Pebble, Cobble and Sand	Channel+Bar	615	577	38	169	Towards Right	Verical Sequence
3	Dikchu bazar	Right River Bank	Pebble, Cobble and Sand	Channel+Bar	602	567	35	92.5	Towards Left	Verical Sequence
4	Mankha	Left River Bank	Pebble, Cobble and Sand	Channel+Bar	496	465	31	257	Towards Right	Lateral Sequence
5	Near Singtam	Left River Bank	Pebble, Cobble, Sand, Silt and Clay	Channel+ Thick Bar+ F. Plain	386	345	41	117	Towards Right	Verical Sequence
6	Near Bardang	Left River Bank	Pebble, Cobble and Sand	Channel+ Bar	355	329	26	75	Towards Right	Verical Sequence
7	Near Bardangoppo tunnel	Right River Bank	Pebble, Cobble and Sand	Thick Channel +Bar	347	326	21	86	Towards Left	Verical Sequence
8	oppo of bridge	Right River Bank	Pebble, Cobble and Sand	Channel +Bar	358	320	38	…… (96)	Tributary Fan lobe	Verical Sequence
9	Bhagyakhola Petrol	Left River Bank	Pebble, Cobble and Sand	Channel +Bar	346	308	38	337	Towards Right	Lateral Sequence
10	Majitar	Left River Bank	Pebble, Cobble and Sand	Channel +Bar	369	304	65	---- (714)	Tributary Fan lobe	Lateral Sequence
11	WiWI Factory	Left River Bank	Pebble, Cobble, Sand, Silt and Clay	Channel+ Bar+ F.plain	354	293	61	330	Towards Right	Verical Sequence
12	Near Rangpo	Right River Bank	Pebble, Cobble, Sand, Silt and Clay	Channel+ Bar+ F.plain	352	285	67	167	Towards Left	Lateral Sequence
13	Near Tarkhola	Right River Bank	Pebble, Cobble, Sand, Silt and Clay	Channel+ Thick bar+ F.plain	334	270	64	418	Towards Left	Lateral Sequence
14	Near Tumthang	Left River Bank	Pebble, Cobble, Sand, Silt and Clay	Channel+ Bar+ F.plain	314	262	52	295	Towards Right	Lateral Sequence
15	After Tumthang	Left River Bank	Pebble, Cobble and Sand	Channel+ Bar	307	260	47	201	Towards Right	Verical Sequence
16	Tar Khola and Sand	Left Bank	Pebble, Cobble	Channel+ Bar	312	255	57	---- (729)	Tributary Fan lobe	Lateral Sequence
17	Near Kirney	Left Bank	Pebble, Cobble and Sand	Channel	276	232	44	225	Towards Right	Verical Sequence
18	Near Melli	Left River Bank	Pebble, Cobble and Sand	Channel+ Bar	283	231	52	---- (175)	Tributary Fan lobe	Verical Sequence

These basal sequences are characterized by pebble and granules at the base that fining upward in the sand. These are clast-supported trough cross-stratified conglomerates. The upper part is dominated by horizontally stratified sand representing the upper flow regime. This deposit reflects the channel fill sequence followed by planer bed flow sediments. Opposite to Barding tunnel (7): This T1 terrace deposit comprises facies from base to top as Gcd, Gco, and. The Gcd facies are characterized by disorganized, clast supported, polymictic, no grading, boulders, and pebbles of angular and rounded nature. This facies infers rapid deposition of clast concentrated debris flow. This is followed by Gco facies which comprises organized clast, clast supported framework, normal grading and infer traction bedload. Then

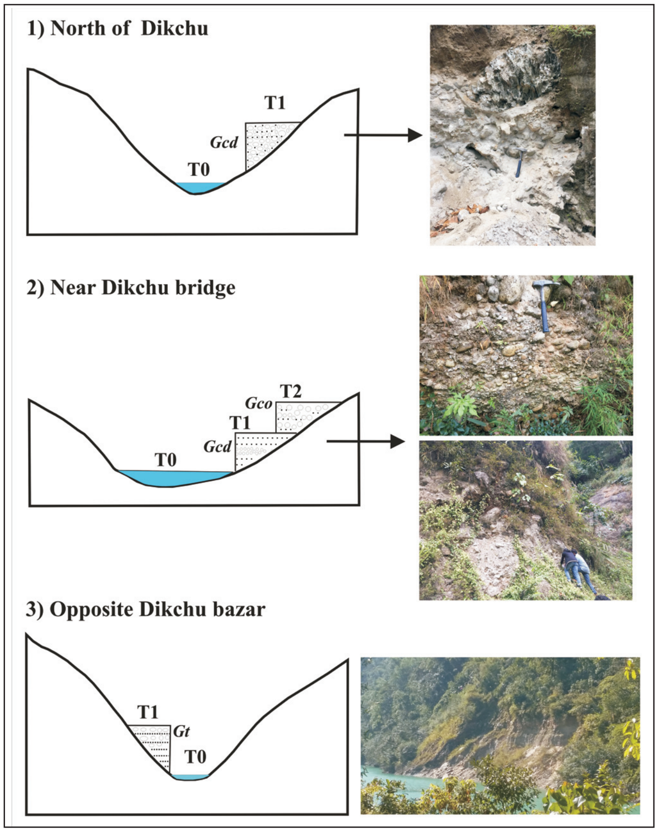

Fig. 4. Tista valley profiles with field photographs of river terraces at localities near Dikchu are: 1) North of Dikchu, 2) Near Dikchu Bridge, 3) Opposite Dikchu Bazar

Gt consists of a cross-stratified clast supported framework inferring transverse bar deposit. Bardang near the bridge (8): This T1 terrace expose 4m thick alluvial fan deposits which show Gcd facies and are characterized by disorganized, clast supported framework, subangular to rounded clast, and infer rapid deposition from clast concentrated stream flow. Bhagyakhola (9): T1 shows Gco facies exposed and characterized by are in organized clasts, clast-supported and polymictic in nature, cobble and pebbles are in normal grading, subangular to rounded clast with weak imbrications. This represents traction bedload and transported by persistent fluvial stream.

Near Majitar

Majitar (10): The T1 exposes Sh facies comprises medium to coarse sand, grey in color, and horizontal stratification (Fig.7). This infers the planer bed flow deposit. Then T2 terrace comprises basal Sh facies followed by Gco facies which are characterized by horizontal stratification and medium to coarse sand in Sh facies while clasts are in an organized manner, clast-supported and polymictic in nature, normal grading, with weak imbrications in Gco facies. Then T3 is also consisting of Gco facies inferring traction bedload deposit.

Near Rangpo

Wiwi Factory (11): This outcrop exposes three terraces as T1, T2, and T3. The T1 consists of Sl facies that show very fine to medium sand, well-sorted laminated sand, and inferring antidune deposits (Fig.7). Then T2 exposes Gco facies with organized clasts, clast-supported framework, polymictic composition, normal grading, with weak imbrications. The T3 terraces comprise Gmd facies show disorganized clast, matrix-supported, polymictic in composition, subangular to rounded clast, and 5m thick unit. These three terraces infer T1 as bar sediments, T2 as channel traction bedload, while T3 as debris flow deposit. Near Rangpo on the right bank of Tista River (12): This area's river deposits are exposed in T1, T2, T3, and T4 terraces. The T1 terrace is characterized by channel, bar, and flood plain deposits which comprise Gcd, Sm, and Fl facies respectively. These Gcd and Sm facies infer rapid deposition while Fl represents suspended load deposit. Then T2 terrace is characterized by large boulder, and cobble with 2 m thick unit of Gcd facies. The T3 terrace comprises basal Gco and top Sh facies. These facies represents traction load channel deposit and followed by planer bed flow bar deposits. Then T4 terrace is consist of mainlySmw and Fl facies consisting of mainly very fine sand, silt, and mud with characteristic wavy and laminated nature. These deposits infer suspended load deposits of a low flow regime (Fig.7).

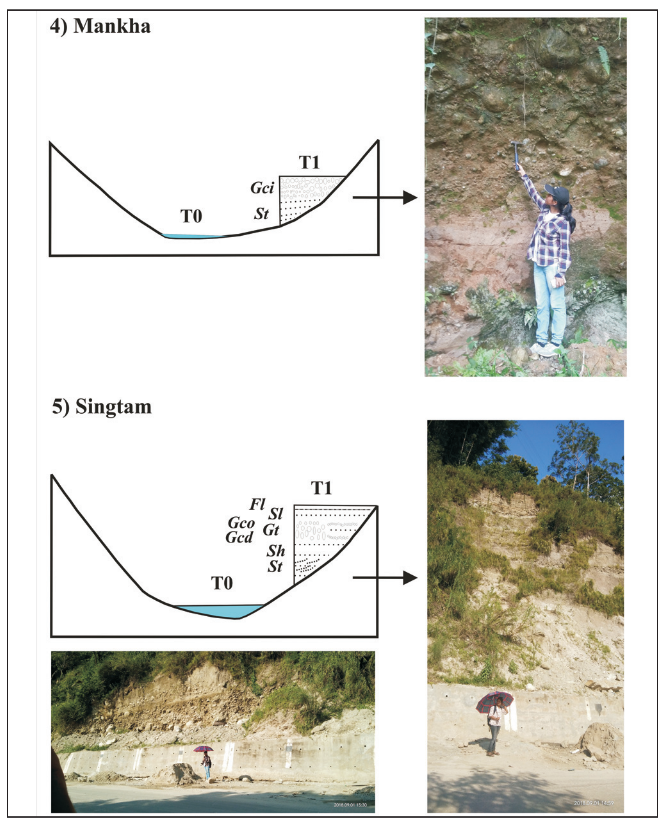

Fig. 5. The valley profiles with field photographs of river terraces at localities 4) near Mankha and 5) near Singtam

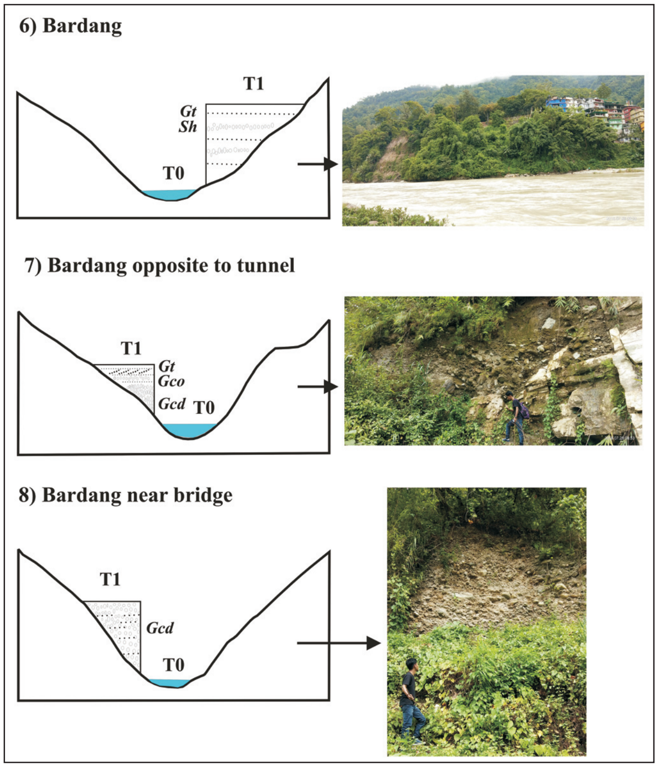

Fig.6. The valley profiles with field photographs of river terraces at localities near Bardang locations, 6) Bardang, 7) Bardang opposite to tunnel, 8) Bardang near bridge

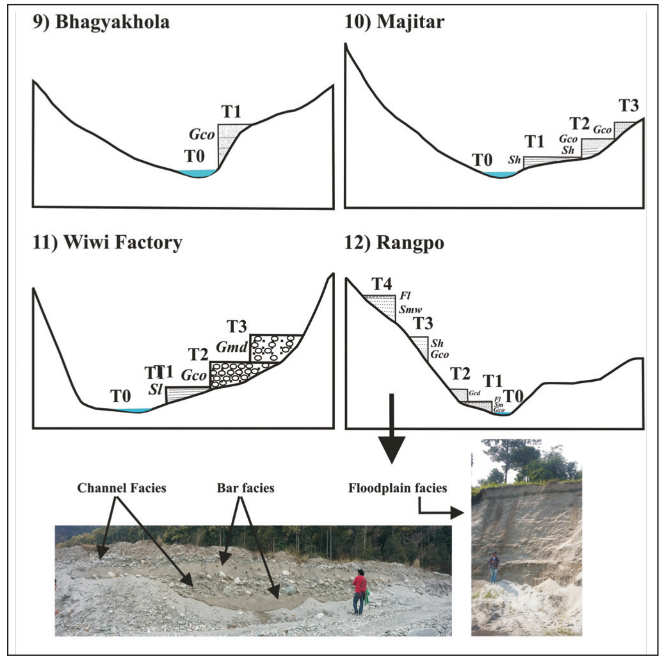

Fig.7. The valley profiles with field photographs of river terraces at localities Near Bardang location: 9) Bhagyakhola; Near Majitar: 10) Majitar and Near Rangpo: 11) Wiwi Factory, 12) Rangpo

Near Mamring

Mamring (13): This area consists of three terraces as T1, T2, and T3. T1 and T2terraces are characterized by Gco facies comprise of organized clast, clast-supported framework, polymictic composition, weak imbrications, boulder, and cobble dominance (Fig. 8). T3 terrace is consists of Sh and Fl facies which horizontal stratification, moderately to well-sorted nature of sediments, and mainly grain size of very coarse sand to fine sand in Sl facies while fine laminated mud and silt in Fl facies. The Sh represent planer bed flow deposits of bar and Fl as suspended sediments of flood plain deposit. Tumthang Khola (14): T1 terraces show vertical as well as lateral variation in facies as they consist of Gco, Gh, Sm, Sh, Sr, and Fl facies. They represent Channel, bar, and flood plain deposits (Fig. 8). The T2 terrace is characterized by Gco facies indicates channel deposit. Next to Tumthang Khola (15): This T1 terrace consists of Gco and Gh facies which infers channel and granular bar deposits (Fig. 8).

Near Tar Khola

Tar Khola (16): The T1 terrace deposit is characterized by Gcd facies which consist of alluvial fan deposits (Fig. 9). This deposit comprises a 4m thick unit of clast supported framework, subangular to rounded pebble, cobble, and granules.

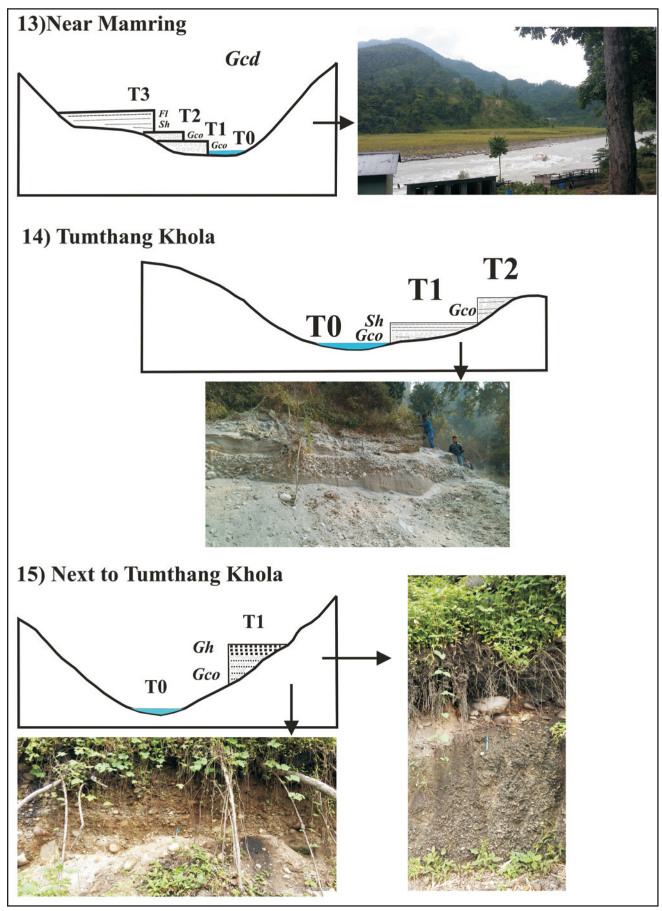

Fig.8. Valley profiles with field photographs of river terraces at localities near Mamring; 13) near Mamring 14) Tumthang Khola 15) next to Tumthang Khola

Near Kirney

Kirney (17): This terrace T1 consists of Gcd and Gco facies in which Gcd shows disorganized, clast supported framework, subangular to rounded clast, and infer rapid deposition from clast concentrated stream flow (Fig.9). The Gco facies comprises organized clast, clast supported framework, normal grading, and infer traction bedload.

Near Melli

Melli (18): This T1 terrace is exposing an alluvial fan deposit of tributary stream and consists of Gmd and Gcd facies (Fig. 9). The Gmd facies show disorganized clast, matrix-supported, polymictic in composition, subangular to rounded clast, and 4m thick unit and infer mass flow deposit. Gcd shows disorganized, clast supported framework, subangular to rounded clast, and infer rapid deposition from clast concentrated stream flow.

The sedimentological observation shows these terraces are not only exposing Tista river deposits but also Tista tributary deposits at the confluence. These tributary deposits are characterized by the development of an alluvial fan system at the confluence. These thick deposits of alluvial fans are incised by TistaRiver. This indicates depositional and erosional processes are acting near the confluence of tributaries. The sedimentological studies of facies variation show channel and bar facies were dominant in the northern part while the southern part (downstream) is dominated by channel, bar, and flood plain deposits. This reflects northern part deposits are restricted within V shape valleys while southern part deposits were widely spaced U shape valleys.The elevation profile of the study area shows the area between Dikchu and Makha is located in higher elevations and higher slope areas, they also become a part of higher to the lower gradient of river profile. This area also provides less accommodation space that reflects in the development of the main channel and bar facies. The downstream area consists of gentler gradients that provide space for the development of flood plain facies along with channel and bar facies.

Grain Size and Heavy Mineral Analysis

Grain Size Analysis

The sediment samples are collected from Dikchu, Mankha, Rangpo, and Tumthang Khola of Tista river terrace downstream deposits. The Dikchu and Mankha represent the proximal parts of alluvial river deposits while Rangpo and Tumthang Khola as the distal parts. These samples are collected is the focus with reference to represent Channel, Bar, and Flood plain facies. A total of 60 sand-size sediment samples are analyzed for grain size analysis. The grain size data of individual samples is used for statistical calculations. The GRADISTAT v8 software is used for calculations of the statistical parameters as MEAN, SORTING, SKEWNESS, and KURTOSIS. These parameters are presented (Fig. 10; Table 3) and used for the assessment of the textural maturity of sediments.

The grain size analysis is carried out for a total of 60 sediment samples collected from studied river terraces. These samples are representative of sedimentary facies of channel, bar, and floodplain as 20 samples from each facies. The mean values of sediments show clearly demarcating separation in facies as the channel is dominated by coarse sand, while bar facies are ranging from coarse to fine sand, and the flood plain facies are mainly comprised of very fine sand to coarse silt. The sorting in sediment samples of channel mainly of poorly to moderately sorted in nature. The bar samples are mainly of poorly to moderately sorted. The samples of flood plain show variations as poorly, moderately to the moderately well-sorted range. These samples from the Rangpo area floodplain show poorly to moderately sorted while Tumthang Khola is moderately well sorted. The skewness in ranging from very coarse skewed to very fine skewed nature. The very fine skewed sediments dominating in channel facies but the location of Dikchu and Mankha are exceptionally showing coarse skewed nature. The skewness of bar samples ranging through very coarse skewed, coarse skewed, symmetrical, fine skewed, and very fine skewed. The samples of the Rangpo area dominate in coarse skewed nature while that of Tumthang Khola samples are fine skewed. The kurtosis in all sediment samples is mainly very platykurtic, platykurtic, and mesokurtic while fewer samples are in the range of leptokurtic. This indicates the majority of samples' contribution from all sizes is a higher side, while single size dominant is less.

The grain size analyses of sediments show differentiable and characteristic grain sizes of individual facies in channel, bar, and flood plain. The channel and bar facies are showing distinct separation from flood plain in sorting, skewness, and kurtosis. These parameters show channel and bar are

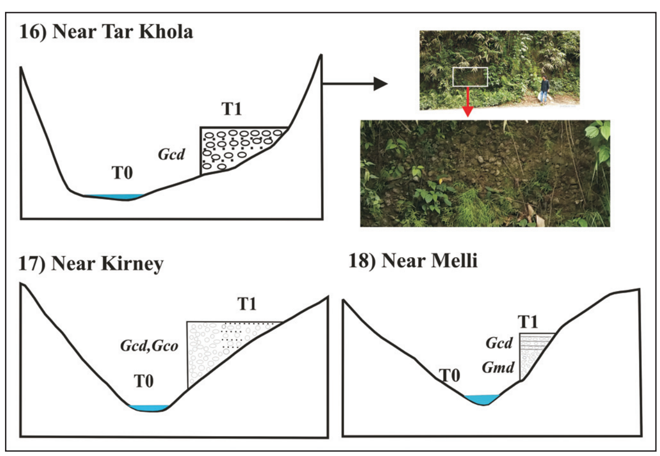

Fig.9. Valley profiles with field photographs of river terraces at localities near Tar Khola: 16) Tar Khola and near Kirney: 17) Kirney X) near Melli: 18) Melli

Table 3: Tista River terrace sediments statistical parameters and description

Sample Type	Sample Name	Textural Group	Folk And Ward Method (Phi)				Folk And Ward Method (Description)			
			Mean	Sorting	Skewness	Kurtosis	Mean	Sorting	Skewness	Kurtosis
Channel Samples	D1Ch	Sand	1.29	1.62	-0.05	0.65	Medium Sand	Poorly Sorted	Symmetrical	Very Platykurtic
	D2Ch	Sand	0.97	1.28	-0.24	1.31	Coarse Sand	Poorly Sorted	Coarse Skewed	Leptokurtic
	D3Ch	Sand	0.94	1.51	0.69	0.52	Coarse Sand	Poorly Sorted	Very Fine Skewed	Very Platykurtic
	M1Ch	Sand	0.84	1.11	-0.36	0.97	Coarse Sand	Poorly Sorted	Very Coarse Skewed	Mesokurtic
	M2Ch	Sand	0.83	1.09	-0.34	0.93	Coarse Sand	Poorly Sorted	Very Coarse Skewed	Mesokurtic
	M3Ch	Sand	0.92	1.24	-0.18	0.85	Coarse Sand	Poorly Sorted	Coarse Skewed	Platykurtic
	R1Ch	Sand	0.07	0.91	1.64	1.44	Coarse Sand	Moderately Sorted	Very Fine Skewed	Leptokurtic
	R2Ch	Sand	0.38	1.07	0.88	0.65	Coarse Sand	Poorly Sorted	Very Fine Skewed	Very Platykurtic
	R3Ch	Sand	0.64	1.26	0.76	0.64	Coarse Sand	Poorly Sorted	Very Fine Skewed	Very Platykurtic
	R4Ch	Sand	0.25	1.06	0.73	0.58	Coarse Sand	Poorly Sorted	Very Fine Skewed	Very Platykurtic
	R5Ch	Sand	0.25	0.97	1.14	0.65	Coarse Sand	Moderately Sorted	Very Fine Skewed	Very Platykurtic
	R6Ch	Sand	0.15	0.97	1.55	0.82	Coarse Sand	Moderately Sorted	Very Fine Skewed	Platykurtic
	T1Ch	Sand	0.38	1.04	0.76	0.58	Coarse Sand	Poorly Sorted	Very Fine Skewed	Very Platykurtic
	T2Ch	Sand	0.24	0.94	1.27	0.62	Coarse Sand	Moderately Sorted	Very Fine Skewed	Very Platykurtic
	T3Ch	Sand	0.59	1.24	0.89	0.63	Coarse Sand	Poorly Sorted	Very Fine Skewed	Very Platykurtic
	T4Ch	Sand	-0.07	0.55	1.41	0.75	Very Coarse Sand	Moderately Well Sorted	Very Fine Skewed	Platykurtic
	T5Ch	Sand	0.49	1.27	1.39	0.89	Coarse Sand	Poorly Sorted	Very Fine Skewed	Platykurtic
	T6Ch	Sand	0.15	0.78	1.14	0.60	Coarse Sand	Moderately Sorted	Very Fine Skewed	Very Platykurtic
	T7Ch	Sand	0.99	1.41	-0.16	0.80	Coarse Sand	Poorly Sorted	Coarse Skewed	Platykurtic
	T8Ch	Sand	0.44	1.03	0.84	0.60	Coarse Sand	Poorly Sorted	Very Fine Skewed	Very Platykurtic
Bar Samples	M1Br	Sand	0.95	1.20	-0.23	0.96	Coarse Sand	Poorly Sorted	Coarse Skewed	Mesokurtic
	R1Br	Sand	1.57	0.96	0.07	2.05	Medium Sand	Moderately Sorted	Symmetrical	Very Leptokurtic
	R2Br	Sand	0.98	1.26	-0.20	1.06	Coarse Sand	Poorly Sorted	Coarse Skewed	Mesokurtic
	R3Br	Sand	0.97	0.96	-0.46	1.18	Coarse Sand	Moderately Sorted	Very Coarse Skewed	Leptokurtic
	R4Br	Sand	2.70	0.98	-0.03	0.72	Fine Sand	Moderately Sorted	Symmetrical	Platykurtic
	R5Br	Sand	1.27	1.16	-0.13	1.67	Medium Sand	Poorly Sorted	Coarse Skewed	Very Leptokurtic
	R6Br	Sand	1.44	0.89	0.07	2.48	Medium Sand	Moderately Sorted	Symmetrical	Very Leptokurtic
	R7Br	Muddy Sand	2.77	1.49	-0.27	1.30	Fine Sand	Poorly Sorted	Coarse Skewed	Leptokurtic
	R8Br	Sand	0.25	0.97	1.14	0.65	Coarse Sand	Moderately Sorted	Very Fine Skewed	Very Platykurtic
	R9Br	Sand	0.91	1.05	-0.19	1.26	Coarse Sand	Poorly Sorted	Coarse Skewed	Leptokurtic
	T1Br	Sand	2.37	0.94	0.30	0.76	Fine Sand	Moderately Sorted	Very Fine Skewed	Platykurtic
	T2Br	Sand	0.31	1.04	1.07	0.69	Coarse Sand	Poorly Sorted	Very Fine Skewed	Platykurtic
	T3Br	Sand	1.47	1.66	0.01	0.45	Medium Sand	Poorly Sorted	Symmetrical	Very Platykurtic
	T4Br	Sand	1.29	1.55	-0.02	0.80	Medium Sand	Poorly Sorted	Symmetrical	Platykurtic
	T5Br	Sand	2.27	0.87	0.39	0.90	Fine Sand	Moderately Sorted	Very Fine Skewed	Mesokurtic
	T6Br	Sand	1.26	1.50	-0.15	0.88	Medium Sand	Poorly Sorted	Coarse Skewed	Platykurtic
	T7Br	Sand	0.50	1.16	0.14	0.54	Coarse Sand	Poorly Sorted	Fine Skewed	Very Platykurtic
	T8Br	Sand	2.28	0.87	0.36	0.91	Fine Sand	Moderately Sorted	Very Fine Skewed	Mesokurtic
	T9Br	Sand	2.61	0.90	0.20	0.77	Fine Sand	Moderately Sorted	Fine Skewed	Platykurtic
	T10Br	Sand	1.01	1.42	-0.14	0.76	Medium Sand	Poorly Sorted	Coarse Skewed	Platykurtic
Flood Plain Samples	R1Fp	Muddy Sand	3.10	1.40	-0.30	1.80	Very Fine Sand	Poorly Sorted	Coarse Skewed	Very Leptokurtic
	R2Fp	Muddy Sand	3.40	0.90	0.10	1.20	Very Fine Sand	Moderately Sorted	Symmetrical	Leptokurtic
	R3Fp	Muddy Sand	3.50	0.90	0.20	1.20	Very Fine Sand	Moderately Sorted	Fine Skewed	Leptokurtic
	R4Fp	Muddy Sand	3.00	1.00	-0.20	1.00	Very Fine Sand	Moderately Sorted	Coarse Skewed	Mesokurtic
	R5Fp	Muddy Sand	4.00	1.20	0.30	1.00	Very Fine Sand	Poorly Sorted	Very Fine Skewed	Mesokurtic
	R6Fp	Muddy Sand	3.40	0.70	0.00	0.80	Very Fine Sand	Moderately Well Sorted	Symmetrical	Platykurtic
	R7Fp	Muddy Sand	3.50	1.00	0.10	1.40	Very Fine Sand	Poorly Sorted	Symmetrical	Leptokurtic
	R8Fp	Muddy Sand	3.00	1.30	0.00	1.00	Fine Sand	Poorly Sorted	Symmetrical	Mesokurtic
	R9Fp	Muddy Sand	3.50	0.90	0.10	1.30	Very Fine Sand	Moderately Sorted	Fine Skewed	Leptokurtic
	R10Fp	Muddy Sand	2.80	1.10	-0.10	0.80	Fine Sand	Poorly Sorted	Coarse Skewed	Platykurtic
	T1Fp	Muddy Sand	3.21	0.70	-0.10	0.91	Very Fine Sand	Moderately Well Sorted	Symmetrical	Mesokurtic
	T2Fp	Muddy Sand	3.28	0.66	-0.11	0.95	Very Fine Sand	Moderately Well Sorted	Coarse Skewed	Mesokurtic
	T3Fp	Muddy Sand	3.21	0.70	-0.10	0.91	Very Fine Sand	Moderately Well Sorted	Symmetrical	Mesokurtic
	T4Fp	Muddy Sand	3.33	0.55	0.00	0.74	Very Fine Sand	Moderately Well Sorted	Symmetrical	Platykurtic
	T5Fp	Muddy Sand	3.32	0.56	0.00	0.74	Very Fine Sand	Moderately Well Sorted	Symmetrical	Platykurtic
	T6Fp	Muddy Sand	3.29	0.66	-0.12	0.97	Very Fine Sand	Moderately Well Sorted	Coarse Skewed	Mesokurtic
	T7Fp	Muddy Sand	3.27	0.66	-0.10	0.91	Very Fine Sand	Moderately Well Sorted	Symmetrical	Mesokurtic
	T8Fp	Muddy Sand	3.05	0.77	-0.09	0.83	Very Fine Sand	Moderately Sorted	Symmetrical	Platykurtic
	T9Fp	Muddy Sand	3.04	0.80	-0.11	0.86	Very Fine Sand	Moderately Sorted	Coarse Skewed	Platykurtic
	T10Fp	Muddy Sand	3.23	0.68	-0.09	0.91	Very Fine Sand	Moderately Well Sorted	Symmetrical	Mesokurtic

indicating the proximity of source while flood plain at distal part. This indicates flows are highly concentrated with clast contribution as a result of less fluidal phase during deposition. This also indicates the Himalayan flux in the form of Tista river sediment is characterized by higher clastic fractions than a fluid phase.

Heavy Mineral Analysis

A total of 12 samples of Tista river terrace sediments are used for heavy mineral analysis mainly collected from Ditch, Manchu and Rangoon. The Ditch and Manchu samples represent the proximal part of the alluvial fan part while Rangoon is a distal part. The heavy minerals are identified based on optical properties and more than 300 grains are identified and counted for each slide. The heavy mineral count is normalized to 100% and presented in Table 4. The heavy mineral assemblage consists of opaque and non-opaque minerals. The non-opaque minerals are zircon, tourmaline, rutile, chlorite, biotitic, garnet, Kyanite, sillimanite, and staurolite (Fig.11).

Heavy mineral analysis result gives information about provenance as well as the maturity of sediments. The heavy mineral assemblage infers provenance of low to higher grade metamorphic sources for sediment as the presence of chlorite, biotite, garnet, kyanite, sillimanite, and staurolite. This metamorphic source of sediment indicating provenance is Lesser Himalaya and Higher Himalaya. The presence of heavy minerals as zircon, tourmaline, and rutile infer source from igneous and sedimentary rock lithology. These lithologies occupied a position in a stratigraphic succession of Greater Himalayan Sequence (GHS) and Tethyan sedimentary sequence. The ZTR index suggested by Hubert (1962) is calculated to estimate mineralogical maturity in heavy mineral suites. The formula used for calculation is ZTR% INDEX = Zircon + Tourmaline + Rutile / $\sum$ non-opaque×100. The ZTR index values are range between 5 to 31% indicates mineralogical immaturity of sediments. This also suggests that less dissolution of unstable minerals and geological younger succession. The ZTR index average of proximal part areas as Dikchu and Mankha is 19.55% while that of the distal part as Rangpo area is 9.23% comparatively lower. This reflects the higher contribution of unstable heavy minerals in the distal part.

River Incision, Migration and Correlation of Terraces

The Tista River is characterized as an alluvial river, which is indicated by a thick sedimentary record along the stretch of the river. These depositional landforms are spread entire stretch of the study area. These thick deposits are transacted by vertical and lateral incisions resulting in the formation of present-day topography dominated by a number of terraces in the area. These depositional landforms are

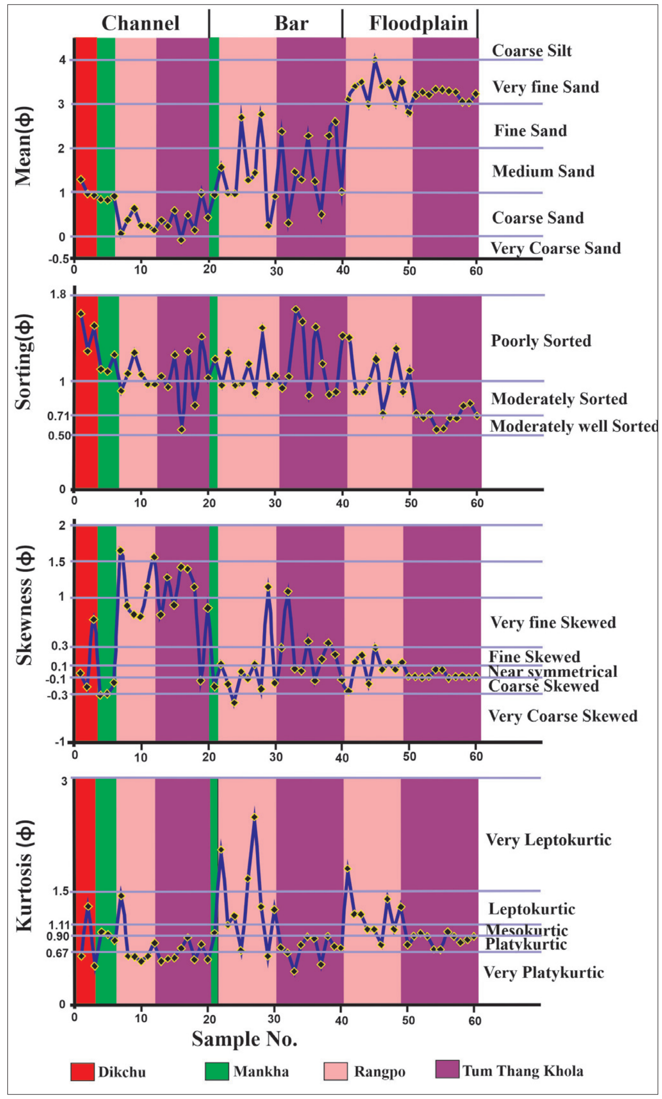

Fig.10. Tista River terrace locations with sediments statistical parameters and description represented in chart

mainly valley-fill deposits, which are incised by erosional processes. These terraces are developed at a different elevation from present-day river channel elevation indicate differential incision at different places. The chart of location versus incision shows variable degrees of incision at different locations (Fig.12a). The incision is comparatively higher in southern locations than downstream. This indicates comparatively higher upliftment in the southern part.

The incision process continues laterally indicates a shift in the river channel resulting in migration. This migration is measured at studied terraces shows the maximum shifting of channels observed in southern locations (Fig. 12b). The shift of channel is mainly controlled by the valley floor, as V shape valleys provide less space to shift channel while U shape valleys provide maximum space to migrate. Tista River provides more U shape valleys to shift the channel.

The incision and migration chart shows at some locations vertical incision is maximum with less shift inferring

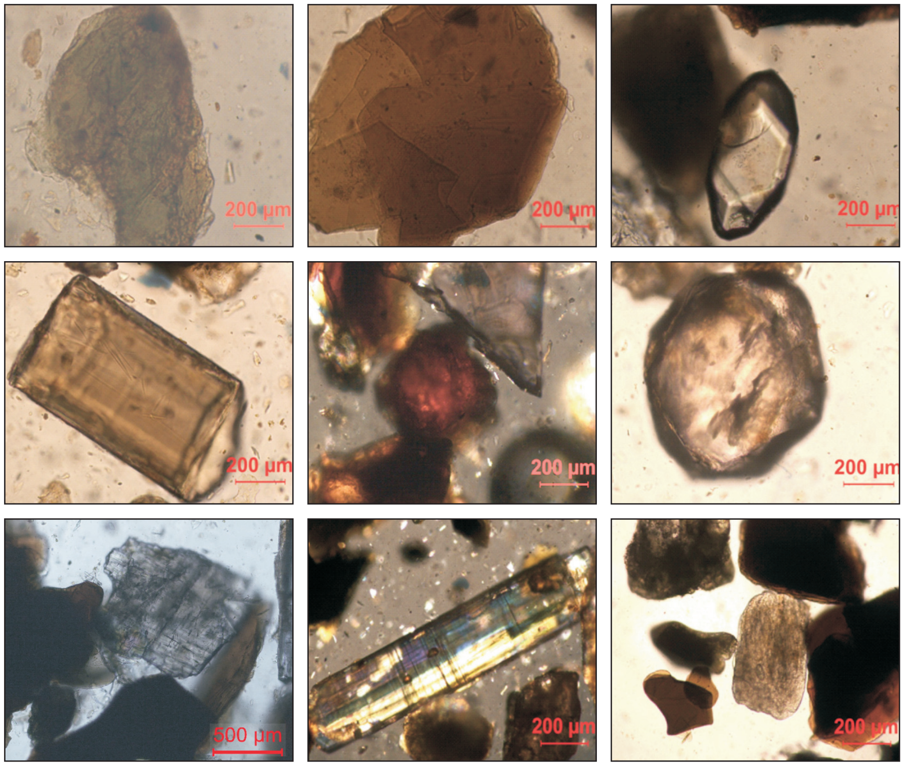

Fig. 11. Heavy mineral assemblage in Tista River terrace sediments a) Chlorite b) Biotitie c) Zircon d) Tourmaline e) Rutile f) Garnet g) Kyanite h) and i) Sillimanite

restricted narrow channel valley (Fig.12a-b). This indicates tectonic processes are dominating over the erosional process. While at some locations the vertical incision is less but covers maximum lateral shift indicating a wider channel valley. These areas indicate erosional processes are dominating over tectonic processes.

The migration *vs* downstream distance chart shows Left bank records maximum migrations in studied locations (Fig.12c). This infers the left bank areas are experiencing maximum upliftment comparative to the right bank. The southern locations studied show a maximum degree of shift in river channel than in southern locations. This indicates in the northern part channels are restricted in narrow valleys while southern part channels are shift along the wider valley floor.

The correlation of terraces from Dikchu to Melli implies differential development as paired as well as unpaired terraces in this stretch indicating variable responses of the river to tectonic processes. These unpaired terraces show differential development on both river banks indicating the influence of the thrust system developed in these mountainous areas. The left bank migration is maximum as compared to right bank migration indicate upliftment in the majority of the left bank

Table 4: Tista River terrace sediments heavy mineral assemblage normalized to 100%

Sr. No.	Sample Name	Opaque %	Zircon %	Tourmaline %	Rutile %	Chlorite %	Biotite %	Garnet %	Staurolite %	Epidote %	Kyanite %	Sillimanite %	ZTR Index
1	D1	5.33	8.67	6.00	0.67	16.67	24.00	32.00	0.00	0.67	0.67	5.33	16.20
2	D2	8.82	4.90	2.94	0.49	17.16	29.90	14.71	0.49	1.96	3.92	14.71	9.14
3	D3	14.15	8.36	3.86	0.96	13.50	30.87	16.08	0.00	0.64	0.64	10.93	15.36
4	M1	6.81	7.85	3.14	4.19	5.76	27.75	24.08	0.00	1.05	2.62	16.75	16.29
5	M2	4.79	7.78	2.40	8.98	7.19	17.96	29.94	0.00	1.20	4.19	15.57	20.13
6	M3	7.74	14.88	5.36	4.76	7.14	19.05	18.45	0.00	2.38	4.17	16.07	27.10
7	M4	11.79	18.97	4.62	4.10	3.08	14.36	28.72	0.00	3.08	4.62	6.67	31.40
8	M5	4.85	11.45	2.64	5.73	8.81	30.84	15.42	0.44	1.76	4.85	13.22	20.83
9	R1	15.66	2.02	1.52	1.01	17.68	38.89	11.62	0.00	1.01	0.51	10.10	5.39
10	R2	7.32	4.88	1.83	0.61	13.41	32.93	21.34	0.00	0.00	6.71	10.98	7.89
11	R3	7.27	3.03	4.24	2.42	24.85	43.03	1.21	0.61	1.21	1.21	10.91	10.46
12	R4	11.11	9.26	2.47	0.00	8.64	37.04	14.20	0.00	1.85	2.47	12.96	13.19

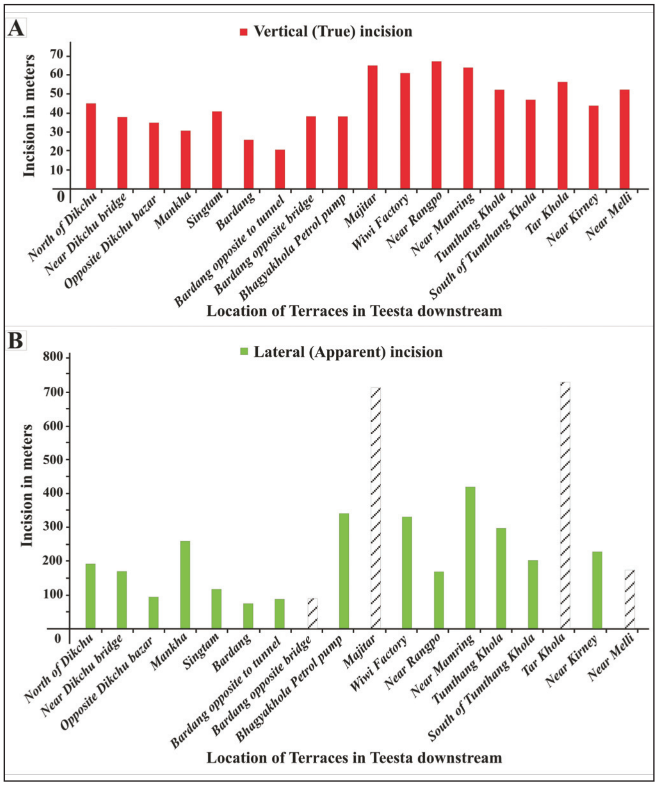

Fig. 12a-b. The Tista river incision (vertical) and (lateral) record at different locations in downstream

part (Fig. 12c). This indicates the differential regional uplift influences migration of river channels. The left bank terraces are the result of upliftment which provides space for the accommodation of sediments, so their form is small and shaped lenticular, while right side terraces are comparatively large and have thicker accumulation as a result of depression fill deposits. The Sedimentological study shows these terraces represent intermountain alluvial fan deposits. In which channel facies were dominated in northern part that forms proximal part of the fan while, southern part dominated by flood plain deposits as they mark the distal part of the fan.

Discussion

In NW Himalayan intermountain deposits are characterized by a well-developed alluvial fan system in the proximity of major thrusts (Sukumar *et al.,* 2017), while in comparison these Tista River deposits are developed in less accommodation space, in response to uplift associated with thrust system in the shorter area. In NW Himalayan these alluvial fans are well developed with proximal and distal fan deposits, but here in Tista River the debris (channel) facies are dominating throughout depositional areas therefore distal fan deposits are not well developed. These indicate regional tectonic elements as thrust influence and provide less accommodation space for the Tista river intermontane deposit. Abrahami *et al.* (2018) inferred synchronous incision between terraces of hinterland and megafan, which is reflecting in the present study that formation of a number of terraces in the hinterland. The present study also suggests a major shift but the majority of migration in the hinterland is indicated towards the west side. This indicates differential processes were operating in hinterland and megafan areas. These valley fill deposits are preserving best interaction record of regional and local tectonic processes with river response. The river carrying large sediments flux from Higher and Lesser Himalaya, depositing the in the areas provided by tectonic geomorphology of a region. There is also a further need to study in detail about these deposits that can provide the information about river and tectonic process interaction.

Conclusions

The regional structural elements of Sikkim-Darjeeling Himalaya influence the fluvial landform of the Tista River as the Higher Himalayan part is dominated by V shape valleys while; lesser Himalayan part shows mixed nature with the development of V and U shape valleys. These V shape valleys in the Lesser Himalayan part are the result of the proximity of thrust while U shape valleys are developed in response to tectonic quiescence or bedrock interaction. The field sedimentological infers V shape valleys are characterized by channel and bar dominated facies while U shape valleys provide space for the development of the channel, bar, and flood plain facies. The grain size analysis of terrace deposits indicates the Himalayan fluxes in the TistaRiver sediments are characterized by higher clastic fractions than the fluid phase.The heavy mineral analysis shows provenance for sediment from lesser and Higher Himalayan region while the ZTR index values indicate mineralogical immaturity of sediments. The sedimentological studies from Tista River terraces reveal deposition of sediments took place in higher topographic gradient, while the present-day raised terraces are the result of the reduced gradient with a maximum incision in the southern part. This part also suggests maximum deposition and maximum incision as resulting from climatic influence and tectonic uplift in the area.

The maximum terraces are developed on the left bank of the river and the comparatively considerable elevations of left bank terraces are higher than that of the right bank. These terraces developed through the differential process as the meandering and migratory nature of the river, while high incision of deposits. This indicates climate as well as tectonic process influence on Tista river deposits.These terrace deposits are developed south of Main central thrust (MCT) in response to fill the accommodation space. Therefore the MCT represent the intermontane front characterized by alluvial fan deposits. The minor thrusts present in the south of MCT as 1st and 2nd also influence river landforms and modify accommodation space in the area. Their result of uplift develops narrow valleys in the area, which influence present-

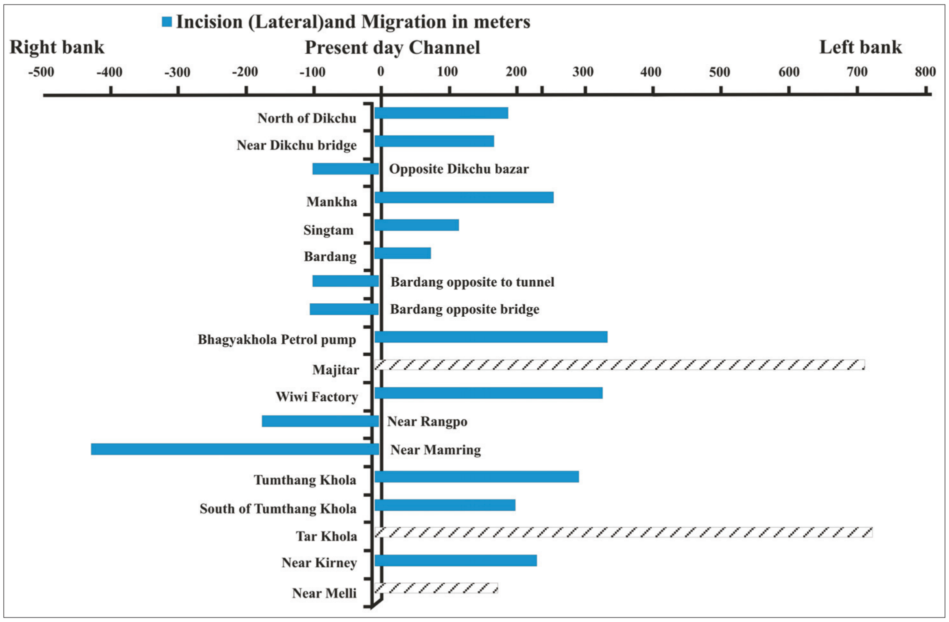

Fig. 12c. The Tista River terrace Incision (Lateral) and Migration record

day geomorphology as mixed nature of U and V shape valley in the area. Therefore the Tista River terraces study infer alluvial river system developed in response to intermountain front deposits which are influenced by thrust system developed and resulting deformation in Sikkim-Darjeeling Himalaya.

Authors' Contributions

Ananda Badekar: Investigation, Conceptualization, Methodology, Writing-Original Draft, Supervision, Reviewing and Editing. **Dipika Dutta:** Investigation, Formal Analysis and Editing.

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