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Late Quaternary evolution of Tista River terraces in Darjeeling-Sikkim-Tibet wedge: Implications to climate and tectonics

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ABSTRACT

Terraces in the Himalayas are important geomorphic archives which preserve the signature of tectonics and past environment. Terraces in eastern part of the Himalayan fold and thrust belt have not received much attention of the geologists. A geochemical approach using luminescence dating has been applied to understand the evolution of paired and deformed terraces between major thrust boundaries of the eastern Himalayas, on the either banks of the Tista River in Darjeeling-Sikkim-Tibet wedge. These terraces are located at the confluence of Tum Thang khola and the Tista River. Three levels of terraces are present in general and also in the study area. The terrace T3 was formed during last interglacial period and the T2 terrace during last glacial maximum (LGM) and in the humid phases after LGM. The top section of T2 terrace (~2.5 m thick) was formed in the transition phase (arid to humid) after Younger Dryas event. The region has experienced several deformational events, (i) one after 45 ka which raised the T3 terrace to its present level, (ii) another one after 11.9 ka which raised the T2 to its present level and this event is also associated with the shifting of the Tum Thang khola, and (iii) the region is still tectonically active as shown by the warping of the T1 and T0 surfaces, which are of recent origin. These terraces have complex input of sediments from Higher Himalayan Crystalline (HHC) rocks and from locally present Lingtse granites.

1. Introduction

Fluvial systems respond promptly to change in gradient, discharge and sediment supply induced either by change in climate or tectonics or both (Sahu et al., 2010; Peeters et al., 2015). The river systems in active fold and thrust belts of Himalayas are governed by the Indian Monsoon (Kale, 2003; Bookhagen et al., 2005, 2006; Juyal et al., 2010; Agrawal et al., 2012; Singh et al., 2016) and also by structures and tectonics (Howard et al., 1994; Shukla et al., 2009). These river systems may provide an opportunity to understand the influence of the climate (Bookhagen et al., 2005, 2006) and tectonics (Nakata, 1972; Mukul et al., 2007; Suresh et al., 2007; Goswami et al., 2013; Singh et al., 2016) on the Himalayas. River terraces are important geomorphic archives (Hancock and Anderson, 2002; Starkel, 2003; Pazzaglia, 2013) present almost along all the rivers in the Himalayas and have been studied to understand the influence of climate change (Bookhagen et al., 2005, 2006; Meetei et al., 2007; Srivastava et al., 2008) and tectonics (Lavé and Avouac, 2000; Mukul et al., 2007) on fluvial systems. River terraces are complex geomorphic entities which are the result of several cycles of aggradation and incision in a river valley. These are the result of transient perturbations in environment (Pazzaglia, 2013) resulting from unsteady active tectonics (Nakata, 1972; Lavé and Avouac, 2000; Mukul et al., 2007; Goswami et al., 2013) or climatic fluctuations (Pratt et al., 2002; Bookhagen et al., 2006; Bridgland and Westaway, 2008; Srivastava et al., 2008; Juyal et al., 2010; Ray and Srivastava, 2010; Kar et al., 2014) or both (Singh et al., 2016). In Himalayas, both tectonics and climatic perturbations are the dominant factors responsible for terrace formation.

The aggradation and incision in a valley depends on many geomorphic parameters including climate, tectonics and sediment load. Due to enhanced monsoon, destabilization of hill slopes (Hoek and Bray, 1977) leads to huge influx of sediments which overtakes the carrying capacity of the stream and leads to valley aggradation (Pratt et al., 2002). Once the sediment supply is restricted by stabilization of the hill slopes, the discharge will overwhelm the

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sediment flux and would lead to incision (Pratt et al., 2002). Thus high discharge may lead to aggradation or incision depending on the sediment supply to the valley. The formation of mega fans in Himalayan foreland took place in the transient glaciation to deglaciation phase (Singh, 1996). During glacial periods weathered material remained in situ due to lack of transporting media and in the initial phases of deglaciation, these were transported downstream forming megafans (Singh, 1996). Another school of thought proposes that high precipitation during enhanced monsoon phases leads to aggradation and weak monsoon leads to incision (Bookhagen et al., 2006; Juyal et al., 2010; Dey et al., 2016). Thus one may conclude that higher discharge may either lead to aggradation or incision. Similarly, lower discharge may also lead to aggradation or incision. The important point to be noted here is that all these studies are specific to certain tectonic-climatic settings and cannot be generalized to each and every environment. The sedimentation pattern should be closely monitored as it is in direct correlation with discharge, aggradation and incision (Schumm, 2007; Reineck and Singh, 2012).

Tista, a turbulent river, is one of the important tributaries of the mighty Brahmaputra River, had been a tributary of the Ganga River till 1787 (Fergusson, 1863; Mukul, 2000) darts through the Darjeeling-Sikkim Himalayas. It originates from Pauhunri (or Tista Kangse) glacier (Meetei et al., 2007) at 7127 m above mean sea level (amsl) (Wiejaczka et al., 2014). Tista River flows through major structural units of Himalayan thrust belt from north to south. The quaternary deposits along the Tista River provide an opportunity to explore the climate and tectonic imprints on them.

Sinha Roy (1980) studied terraces on a 65 km long stretch along the Tista River from Mankha (in mountains) to Sevoke (in plains) summarizing that three tier terrace system occurs intermittently on this stretch (Fig. 1). At places like Mankha and south Rangpo, middle terrace is not present. At Singtam middle and lower terraces are absent and at Deorali upper terrace is absent. Mukul et al. (2007) reported six tier terraces system in a region between the Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) bounded by the South Kalijhora Thrust (SKT) in the north and Andherijhora khola, a tributary of the Tista River. In this, four strath terraces (T3 to T6) and two (T1 − T2) terraces are part of modern flood plain. This study shows that the tectonics played a major role in formation of these terraces. Terraces developed along the Tista River near Mangalbare locality between Main Central Thrust (MCT) and MBT were studied by Meetei et al. (2007) and they suggested that the formation of these terraces were controlled by the paleoclimatic perturbations.

A numbers of studies have been done in the frontal part of Himalayas to understand the neotectonic activity along the Main Frontal Thrust (MFT) (Wesnousky et al., 1999; Thakur, 2004; Kumahara and Jayangondaperumal, 2013) with an assumption of decreased tectonic perturbations in the middle and higher Himalayas. However, reactivations of older thrusts such as MBT and MCT in recent geological past have also been reported due to out of sequence thrusting and reactivation of existing major boundary faults (Valdiya, 2001; Mukul et al., 2007; Kothyari et al., 2010; Joshi and Kotlia, 2015). A lot of work has been done in the western and central Himalayas to understand the paleoclimate and tectonics (e.g. Bookhagen et al., 2005, 2006; Kotlia et al., 2010, 2015; Ray and Srivastava, 2010; Nag and Phartiyal, 2014; Kothyari et al., 2016) while such work is less common in the eastern Himalayas. In this work terraces at the confluence of the Tum Thang Khola (read as Tum Laang, a tributary of Tista) and the Tista River (Fig. 2) have been studied. This area lies between MCT and MBT near Barah Mile locality in the Darjeeling District of West Bengal and will help to understand that if there is any out of sequence deformation (e.g. Wobus et al., 2005; Mukul et al., 2007). Here, 3 tier Quaternary fluvial terrace system is well developed on the banks of Tista River. A sedimentological and geochronological approach will highlight the role of climate and tectonics in shaping the morphology of the area (eg. Kumar et al., 2003; Sinha and Sarkar, 2009). The geochemical data is a powerful tool to determine the provenance and to understand the tectonics and chemical weathering (Srivastava et al., 2008; Singh, 2009; Lupker et al., 2013). In order to understand the complexity involved in the sedimentary inputs of the river Tista and its tributary Tum Thang khola, geochemical studies have been done. Very few absolute dates of terraces in the Tista valley have been reported (Mukul et al., 2007). Luminescence dating of these terraces will provide an opportunity to understand the timing of tectonic activities and climatic perturbations.

2. Geology and geomorphology of region

The under thrusting of the Indian plate below the Eurasian plate around 50 Ma (Besse and Courtillot, 1991; Kind et al., 2002) resulted in the north-south contraction of the lithosphere and foreland ward propagating fold and thrust belt (FTB) (Molnar and Tapponnier, 1975; Molnar, 1984; Guha et al., 2007). This collision resulted in the formation of one of the youngest mountain range, i.e. the Himalayas and southward migration of FTB has formed several north dipping thrust belts. The major tectonic elements are the Main Central Thrust (MCT), thrusting high grade gneiss and schist of Higher Himalayas over Lesser Himalayas; the Main Boundary Thrust (MBT) thrusting meta sedimentary and meta volcanic rocks of Lesser Himalayas over the Siwaliks; the Main Frontal Thrust (MFT) thrusting the sedimentary rocks of the Siwaliks over the Quaternary sediments (Heim and Gansser, 1939; Gansser, 1964).

The Tista in the study area has three tier terrace system, following the conventional method of nomenclature, named as T3, T2 and T1; based on its decreasing elevation from present day channel (T3 being the highest, T0 being the modern flood plain). T3 occur as a paired terrace on both the banks of the river Tista at a height of 325−330 m amsl (27−30 m above river channel) (Fig. 2). Bedrocks are exposed at some places confirming this as a strath terrace. T2 is present only on the left bank of the Tista River and has thickness of 9−10 m. T1 is present only on the right bank and has a thickness of 2−3 m. T3 is primarily made up of thick sand beds with intermittent layers of matrix supported angular to sub-angular pebbles and cobbles (Fig. 3). The top section (~1 m thick) is matrix supported rounded cobbles and pebbles. T2 terrace is primarily composed of clast supported pebbles and cobbles beds with intermittent sand beds. Some boulder beds are also present. The cobbles and boulders at the bottom are well rounded and show imbrications. The top layer has randomly arranged matrix supported sub angular cobbles (Fig. 3). T1 could not be studied due to inaccessibility to the exposure but seems to be primarily made up of sandy facies, based on distant observation.

Tum Thang khola also shows three tier terrace system. The conventional method of nomenclature is followed (for the terraces present on left bank of Tum Thang khola), terraces are named as TT3, TT2 and TT1 based on their relative altitude from the river bed (Fig. 2). TT0 represents the present day channel deposit. TT3 is 310−312 m amsl (seems to be a paired terrace of T3). TT2 is ~3 m above TT1 and is present on both the banks of Tum Thang khola. TT2 near the confluence of Tum Thang khola with the Tista River has a slope of 10° towards North by East-South by West (NbE-SbW). TT1 is ~1−1.5 m above TT0 and is present only on the left bank of

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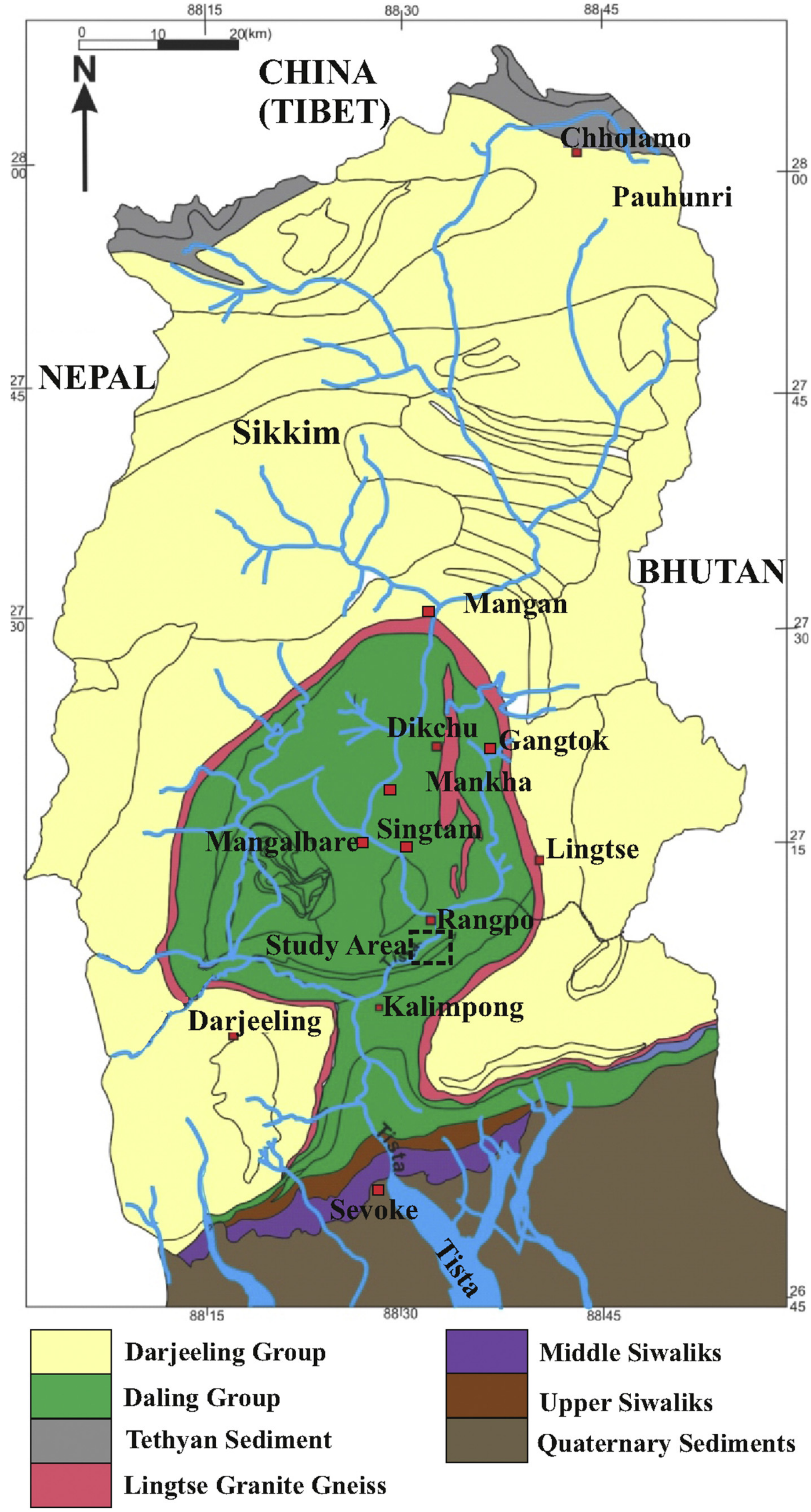

Fig. 1. The drainage basin map of the Tista River with major lithologies found in the basin. The study area is marked by black dashed rectangle (simplified after Basu, 2013).

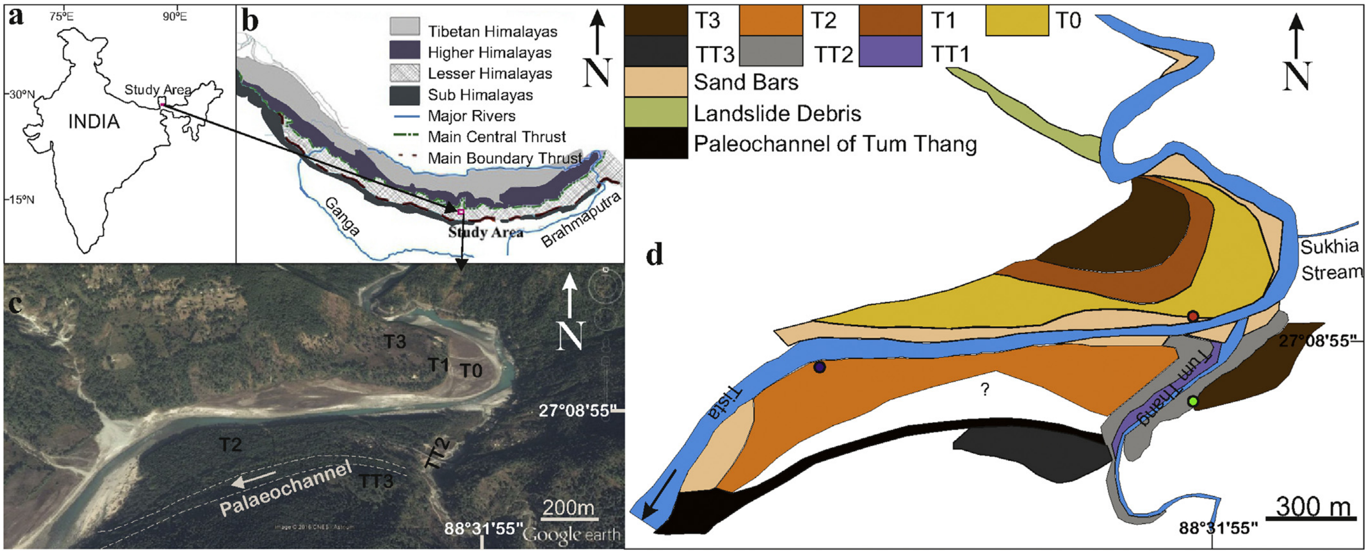

Fig. 2. (a) Map of India showing the study are, (b) Map showing the major tectonic elements of the Himalaya with the study area, (c) Google Earth image of the study area with the geomorphic features observed in the study area, (d) Location and geomorphological map of the studied area showing extent of the various terraces formed by the Tista River and its tributary Tum Thang khola. The sampling site for T3 terrace is shown by the light green circle. The red circle is the place where warping in the T1 and T0 surfaces were observed. The purple circle marks the place where deformation in the T2 surface was observed. The sampling site of the T2 terrace was few meters upstream from this point. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Tum Thang khola. All these terraces are made of cobbles and pebbles with intermittent sand beds and lenses, except the top layer of TT2 which is made up of small boulders with average size of 30 cm. The well imbricated sub-angular clasts show the flow direction and suggest short transportation history. A palaeochannel of Tum Thang khola was identified in the field (Fig. 4, highlighted by dashed line) and as well as in the satellite imagery (Fig. 2, highlighted by black filled thick line).

TT3 has a similar height i.e. 10–12 m, above TT2 on both the banks of the Tum Thang khola but the terrace material on both the banks is very different. On the left bank it is primarily made up of massive boulders, few even greater than 8 m in length and on the left bank it is made up of medium to fine grained sand (Fig. 2). Thus, we infer that the terrace on the right bank is primarily the work of the Tista River and that on the left bank is the remnant of alluvial deposits of Tum Thang khola.

3. Sampling and methodology

The different geomorphic features were identified in the field and the geomorphic map was prepared using the satellite images (source: Google Earth) along with geochemical analysis and supported by Luminescence dating.

3.1. Geochemical and textural analysis

Total 14 sediment samples were collected from different strata of river terrace deposits of the Tista River and Tum Thang khola for geochemical and textural analysis (Fig. 3). Bedload sample (TR/14-BL1) was collected from the study area and TR/14-BL2 was collected downstream near Sevoke. About 1–2 Kg of each sample was dried at 60 °C and then cone and quartered to make sub samples to ensure homogeneity. About 500 g of sub samples were taken for the textural analysis and 100 g for powdering. Sub samples for powdering were sieved to remove grains of size greater than 2 mm. Samples were powdered in an agate mortar using Retsch Vibratory Disc Mill RS 200 with average time of 30 min at 700 RPM to achieve a non-gritty homogenous powdered sample. Approximately 60 mg of powdered sample were taken in Teflon vials after drying for the acid digestion following standard protocols. Major, trace and rare earth elements were analyzed using quadrupole inductively coupled plasma mass spectrometry (Thermo Scientific Xseries 2 ICP-MS).

Textural analysis was carried out by dry sieving method using different sieves of ASTM mesh sizes- 5, 10, 18, 35, 60, 120 and 230. Separation of size fraction less 63 μm was not done.

3.2. Luminescence dating

Optically Stimulated Luminescence (OSL) dating has been widely used for fluvial sediments (Rades et al., 2016). It dates the event of last daylight exposure of the sediment and provides direct depositional date (Huntley et al., 1985; Aitken, 1998). In total, four samples were collected for OSL dating, 1 sample from T3 and 3 samples from T2. No sample could be collected from the T1 and T0. Samples for OSL dating were collected in galvanized iron (GI) pipes to avoid any accidental exposure to daylight, a routine method of sampling for OSL dating. All the samples were opened and processed in subdued red light conditions. The sediments were treated 3–4 times with 1N HCl and 30% H_2O_2 to remove the carbonates and organic materials respectively. The sediments were then sieved to obtain size fraction of 90–150 μm. This was followed by heavy liquid density separation using Sodium polytungstate (density = 2.58 gm/cm^3) to separate quartz and feldspar. Obtained quartz grain were etched with 40% HF for 80 min to remove alpha dose affected layer and feldspar contaminations present (if any after heavy liquid separation) followed by 12 N HCl treatment to dissolve the fluorides formed during etching. The sample preparation was done following Aitken, 1998. All samples were checked for feldspar contamination using Infrared stimulated luminescence (IRSL).

The obtained quartz grains were mounted on 10 mm stainless discs using Silko-Spray silicone oil. Standard single aliquot regenerative (SAR) protocol was applied to get the equivalent dose (Murray and Wintle, 2000). The optical luminescence measurements were carried out on Lexsygsmart TL-OSL reader (Freiberg

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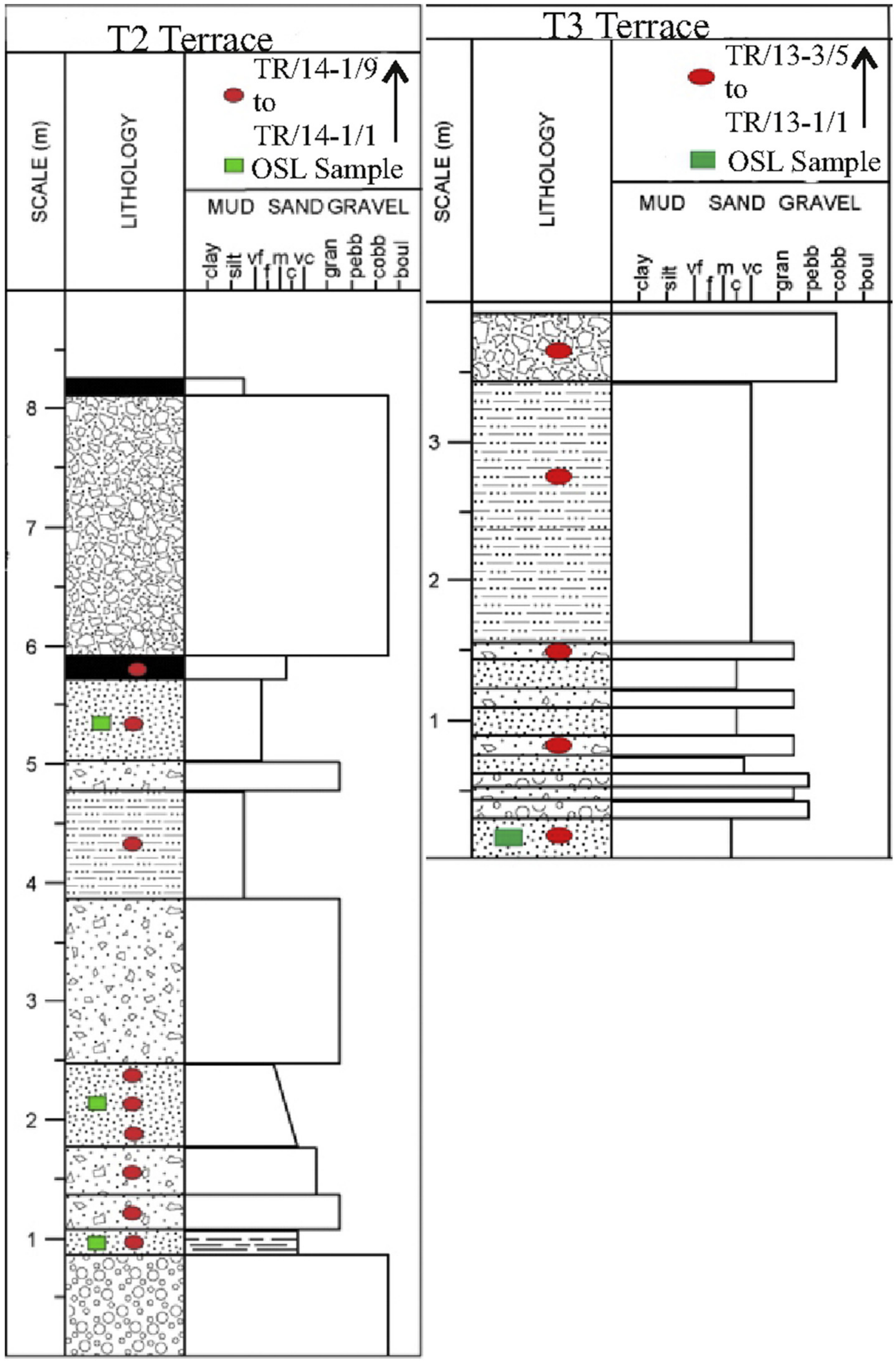

Fig. 3. Lithostratigraphy of the terrace T3 and T2 showing location of sediment samples collected for geochemical analysis and OSL dating.

Instruments, Germany) at Luminescence Dating Laboratory in IISER Kolkata. The instrument beta dose rate was calibrated using calibration quartz supplied from the Risoe National Laboratory, Denmark Technical University, Denmark. The instrument is equipped with blue light emitting LEDs ($\lambda = 458$ nm), the detection window consists of a combination of optical filters Hoya U340 and Delta BP 365/50 EX mounted on a solid state photomultiplier tube (PMT) designed to have very low background counts. A $^{90}Sr/^{90}Y$ beta source is used for irradiation. The concentration of radioactive elements was measured using Inductive coupled Plasma Mass spectrometry for dose rate determination (Table 1).

4. Results

4.1. Optically stimulated luminescence

All the samples have shown enough luminescence to background signal for dating and have shown wide dose distribution (as shown in the histogram of equivalent doses (Fig. 5) which can be accepted for old samples received in the present study. However, due to changing sensitivity and poor fitting of the luminescence data, many aliquots did not pass through the criteria of accepting (poor recycling ratio, high recuperation value and high test dose

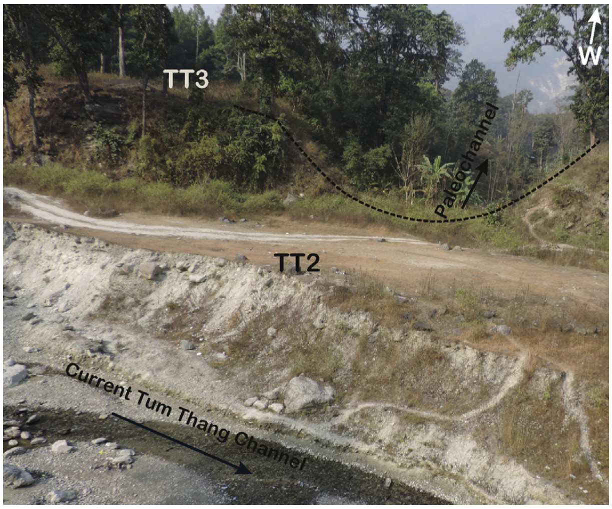

Fig. 4. Paleochannel of and present day channel of the Tum Thang Khola.

error) them for dating. The depositional age of the sand from T3 (TR/13/3/1) is 44.8 ± 8.4 ka. The samples from the T2 are TR/14-1/1, TR/14-1/4 and TR/14-1/8 are at a height of 1 m, 2.2 m and 5.6 m from the river bed respectively and have a depositional age of 23.9 ± 6.6, 21.2 ± 4.8 and 11.9 ± 3.1 ka respectively.

4.2. Textural analysis

Weight percent versus grain size of the sediment is plotted in the (Fig. 6). For the T3 terrace coarse sand is the dominant fraction. All the layers in T3 have shown almost similar distribution, may be due to the similar energy condition prevailing during deposition. For T2 terrace, grain size distribution shows wide range due to different layers of sand, pebble-cobble and clay layers. This is probably due to the different energy of deposition spanning over a large period of time. Bedload (BL1) of the Tista River which was collected near T2 terrace is predominantly coarse to very coarse sand having similar distribution as T3. Bedload (BL2) has higher percentage of fine to very fine sand because it was collected at mountain front where the Tista River enters plains.

4.3. Geochemistry

CIA values are used as an indicator of the intensity of chemical weathering (Nesbitt and Young, 1982). The index is calculated as CIA = [Al_2O_3*100/Al_2O_3+CaO + Na_2O + K_2O]. High values of CIA indicates the removal of mobile elements like Ca, Na, K relative to the static residual constituent (Al^{+3}) during weathering (Nesbitt and Young, 1982) while the low values of CIA indicate near absence of chemical weathering and consequently reflects cold or arid condition. CIA values of unweathered igneous rocks and fresh feldspar ranges from 40 to 50, whereas in intensely weathered residue rocks it approaches to 100 (Nesbitt and Young, 1982). CIA values of sediments present in a river terrace represent the overall weathering, i.e. in situ and during transportation.

Molar proportions of Al_2O_3 (A), CaO, Na_2O (CN), K_2O (K), FeO (F) and MgO (M) of the samples were plotted in the ternary A–CN–K diagram (Fig. 7a) and in the ternary A–CNK–FM diagram (Fig. 7b) (after Nesbitt et al., 1996) to deduce chemical weathering trends. Within the A–CN–K diagram sediment of T3 terrace plot on the plagioclase-K feldspar line showing its low chemical weathering while sediment of T2 terrace plot towards the A apex. It shows that these sediments are comparativel more chemically weathered and also calcium, sodium and potassium have leached out during weathering. This also indicates weathering trend towards illite and muscovite. In A–CNK–FM diagram T3 terrace sediments plot away from FM apex showing that mafic component is small but the T2 terrace sediments have some mafic source as they are clustering comparatively close to the FM apex. Aluminum, ferric iron, magnesium, and potassium are showing a clear decreasing trend as silica increases. Manganese, calcium, sodium, and phosphorus do

Table 1
OSL Age table showing elemental radioactive concentration and equivalent doses to compute final ages.

S.·No	Sample name	Terrace	U (ppm)	Th (ppm)	K (%)	ED (Gy)	Dose rate (Gy/ka)	Age (ka)	No. of discs
1	TR/13- 3/1	T3	6.0 ± 0.7	16.5 ± 2.0	3.1 ± 0.1	227.6 ± 39.6	5.1 ± 0.4	44.8 ± 8.4	19
2	TR/14- 1/1	T2	6.2 ± 0.3	18.8 ± 0.5	1.4 ± 0	83.84 ± 22.4	3.5 ± 0.2	23.9 ± 6.6	20
3	TR/14- 1/4	T2	3.1 ± 03	18.8 ± 0.6	2.4 ± 0	79.8 ± 17.6	3.8 ± 0.2	21.2 ± 4.8	15
4	TR/14- 1/8	T2	7.3 ± 0.3	26.6 ± 0.1	2.2 ± 0	59.5 ± 15.1	5.0 ± 0.3	11.9 ± 3.1	18

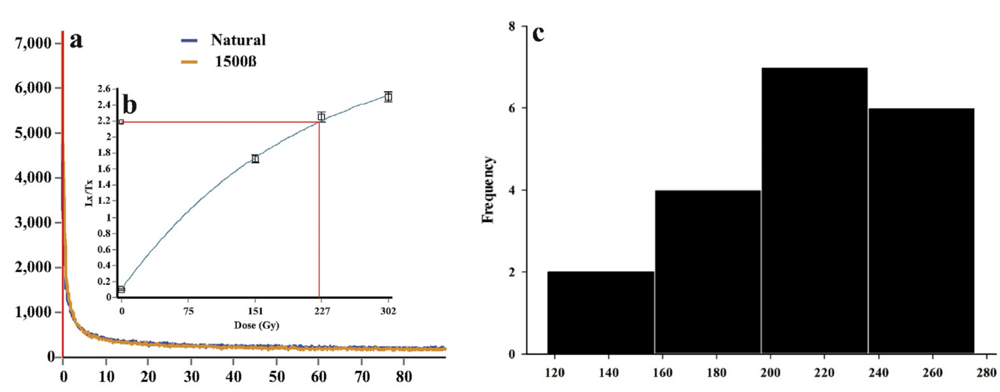

Fig. 5. Various curves related to OSL dating, (a) luminescence dose growth curve, (b) luminescence signal shine down showing enough photon counts and high signal to background ratio, (c) equivalent dose distribution as a histogram.

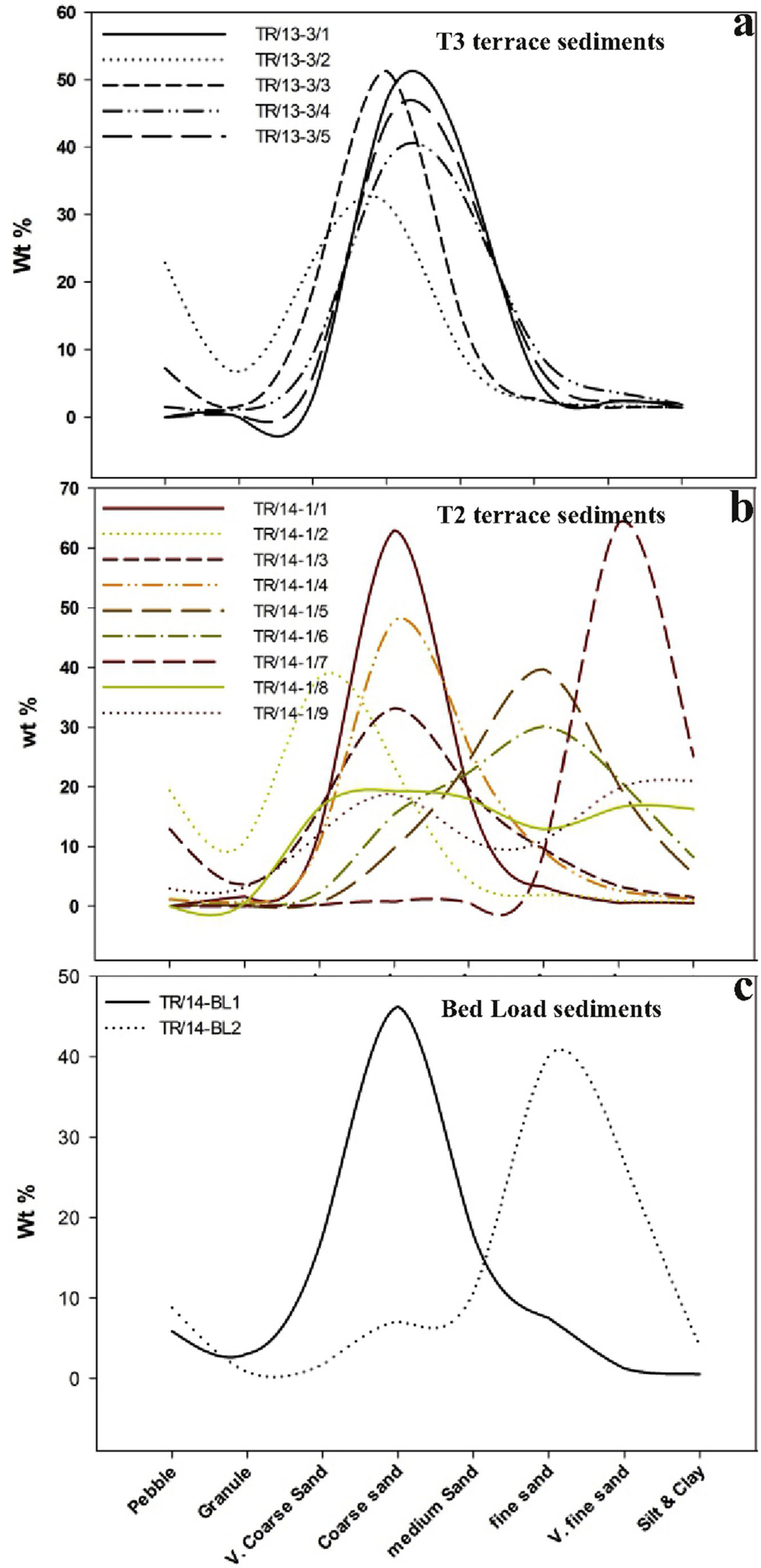

Fig. 6. Plots of various samples showing grain size distribution, (a) weight % of different grain sizes of sediments from T3 terrace (TR/13-3/1 to 3/5), coarse sand is the dominant size fraction, (b) weight % of different grain sizes of sediments from T2 terrace (TR/14-1/1 to 1/9), wide range of grain sizes are observed, (c) grain size of Bed Load samples.

not show any trend implying that these four elements are sensitive to more than one controlling factor.

5. Discussion

5.1. Tectonics and climate interaction

Studies by Mukul et al. (2007) between the MBT and MFT, near South Kalijhora Thrust (SKT) show that the terraces formed here are the manifestation of the neotectonics. This was based on their observations, which are: (i) exposure of bed rock in a section incised by Andherijhora khola, (ii) no lateral continuity, disjointed and unpaired nature of the terraces, (iii) terraces are far away from sea to be created by climate induced base level changes and (iv) no signature of landslides or glaciation induced formation of terraces. Meetei et al. (2007) have shown that the Tista River in Mangalbare locality has three tier terrace system, dominantly made up of four types of lithofacies. They showed that the formation of terraces in this locality is controlled by the dynamics of climate change and tectonics has no major role.

In the study area, 3 tier terrace system is found similar to that by Meetei et al. (2007). However, T3 is present only on the west bank in Mangalbare (Meetei et al., 2007) while it is present on both the banks in our study area. A section of the terrace T3 on the left bank of the Tista River in our study area (Fig. 2) is dominantly made up of thick sand beds with intermittent comparatively thin (few centimeters) layers of matrix supported sub-angular pebble and cobble (Fig. 3). The pebbles and cobbles are not sorted, lack any stratification and even preserve their fracture marks suggestive of very low physical weathering during transportation. This kind of situation could be achieved under two conditions- (i) either these rock fragments have been transported over a very small distance or (ii) are of glacio-fluvial origin (Hubbard and Glasser, 2005; Nývlt and Hoare, 2011). This kind of deposition could take place when the sediment discharge is very high under hyper-concentrated conditions (Sohn et al., 1999; Meetei et al., 2007) and the energy level was just enough to transport sand and pebbles. This is indicative that moderate monsoon conditions prevailed during the formation of this part of T3. A sample from T3 (TR/13/3/1) gives a depositional age of 44.8 ± 8.4 ka, suggesting the formation of T3 during the last interglacial (Meetei et al., 2007; Agrawal et al., 2012). T3 is a strath terrace with bed rocks exposed at places but has a thick alluvium cover; this could be because of change in base level induced due to tectonic movements which forced the river to incise (Hancock and Anderson, 2002). The tectonic movement occurred after ~45 ka which raised the T3 to its present level.

Terrace T2 is dominated by gravel facies with intermittent thin patches of sand beds (Fig. 3). The clast supported boulder bed which is more than a meter thick at the bottom of T2 comprises rounded, poorly sorted and well imbricated boulders. The bed shows irregular cross stratification also suggesting channel deposits (Meetei et al., 2007). This is overlain by medium to coarse textured; stratified thin sand bed dated 23.9 ± 6.6 ka. This shows decrease in turbulence of the river, probably due to decreased monsoonal activity during LGM. This is overlain by matrix dominated cobble pebble beds (~15 cm thick) of sub angular rock fragments, followed by a ~20 cm thick deposit of pebble with similar texture. This is overlain by a coarsening downward sand bed of ~60 cm thickness, giving a depositional age of 21.2 ± 4.8 ka. It suggests that these 3 beds were deposited in the initial phase of the Last Glacial Maximum (LGM), i.e. ~21,500 years ago due to decrease in monsoon which ultimately increased sediment/water ratio and thus helped in deposition (Bull, 1990; Pratt et al., 2002; Ray and Srivastava, 2010; Singhvi and Kale, 2010). The intermittent sand beds could be different parts of a meander in a wide valley but in narrow valleys such as of Tista, the river system has to aggrade to deposit different beds of sediments (Schumm, 1993).

Another sand bed at a height of ~5.5 m from the river bed is dated 11.9 ± 3.1 ka, a time of weaker monsoon during Younger Dryas event (Fleitmann et al., 2003; Sinha et al., 2005; Dutt et al., 2015). It is observed that sand beds of T2 (channel deposits) were deposited during the cold phases (LGM and Younger Dryas) whereas the cobble and boulder beds were deposited during humid phases. This sand bed is overlain by a black colored layer which is a mixture of sand and clay and contains some organic material, which is similar in appearance and texture to the present day soil layer at the top. This layer represents a hiatus in the deposition followed by incision. The black layer is overlain by matrix supported sub angular bed of cobbles and boulders (~2.5 m thick deposit) having no signature of sorting or stratification and could be interpreted as a hyper-concentrated flow deposits. This layer must had formed during intense monsoon around 10 ka (Bookhagen et al., 2006) which mobilized local weathered material produce during drier phase (Singh, 1996; Pratt et al., 2002).

The T2 is warped (Fig. 8a) showing signatures of tectonic activity, the black layer bends at ~23° from the horizontal. The height of this black layer is ~6 m above the river bed which is overlain by a matrix supported boulder layer of ~2.5 m and moving downstream

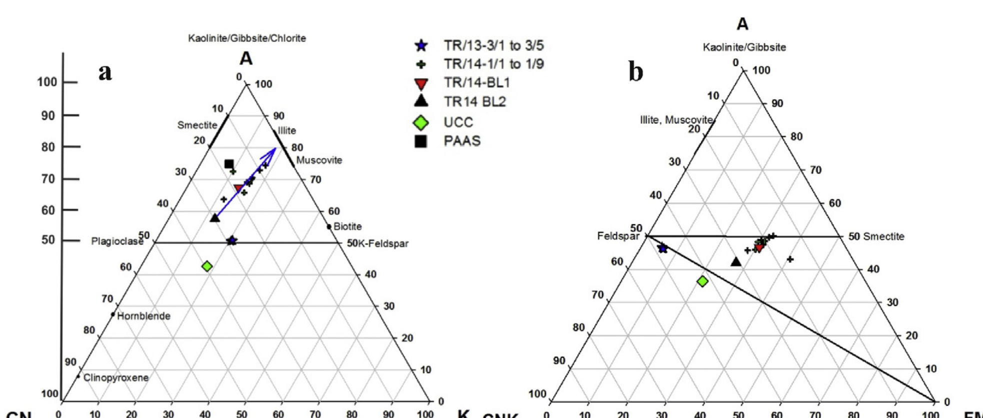

Fig. 7. (a) The A–CN–K diagram sediment of T2 terrace (TR/14-1/1 to 1/9) plot on the plagioclase-K feldspar line showing its low chemical weathering while sediment of Tista river terrace (TR/13-3/1 to 3/5) plot towards the A apex. It shows that these sediment are comparatively more chemically weathered and also calcium, sodium and potassium has leached out during weathering. (b) In A–CNK–FM diagram T3 terrace sediment plot distant from FM apex suggesting mafic component were minute (less than 10%) but the T2 terrace sediments have some mafic source (~30–40%).

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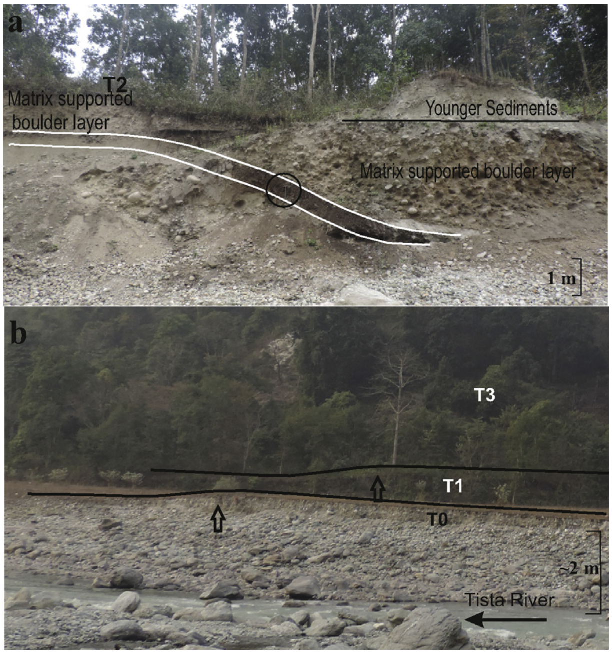

Fig. 8. Warping of T2, T1 and T0 surfaces. (a) The warping in the T2 terrace is shown by bending of organic rich black mud layer. On the left side of the figure the height of this black layer is ~6 m above the river bed which is overlain by a matrix supported boulder layer of ~2.5 m and while moving downstream (to the right), the height of this black layer decreases and finally merges with the river bed. Another important feature is that the boulder layer on the left is overlain by soil whereas on the right a younger layer of sediments overlie the boulder layer. (b) Similar kind of warping is also observed in the T1 and T0 surfaces.

(to the right) the height of this black layer decreases and finally merges with the river bed. Another important feature is that the boulder layer on the left is overlain by soil layer whereas on the right a younger layer (light grey in color) of sediments overlies the boulder layer. The OSL sample below the black layer gives an age of 11.9 ± 3.1 ka suggesting that the deformation event which raised the T2 to its present level occurred after 11.9 ka. The light grey colored deposits on the right (Fig. 8a) show that the Tista River has went through another phase of aggradation but as the section on the left (Fig. 8a) was uplifted so no further sedimentation could take place over it. The Tum Thang khola was affected by this activity and was forced to shift its course and flow in opposite direction (Fig. 4). The T1 could not be studied due to inaccessibility to exposure. The T0 is made up of cobble and pebble beds and hardly has any vegetation cover compared to all other surfaces which are under thick vegetation cover. The T1 and T0 are also warped up showing signatures of deformation (Fig. 8b); however, it is based only on distant observation and needs further detailed study. The T0 has formed in recent years and its warping suggests that the area under study is tectonically active also supported by studies from Bilham et al. (2001) and Mukul et al. (2007). The satellite image shows that the inhabitation of this area has increased significantly in the last decade, due to tourism activity and could prove fatal for the region.

5.2. Hydrodynamic control of sediment sorting

During the course of transportation, sediments get sorted based on their grain size, shape and density which accounts for the chemical and mineralogical differentiation of the sediments (Singh and France-Lanord, 2002; Garzanti et al., 2011; Lupker et al., 2011, 2013). The mineralogical composition of sediments of the rivers draining through Himalaya is predominantly quartz, micas and feldspar, with presence of other phyllosilicates, clay assemblages and hydroxides in the finer fraction (Lupker et al., 2013 and the reference therein). The energy condition is different in different segments of river which results in enrichment of coarse grained

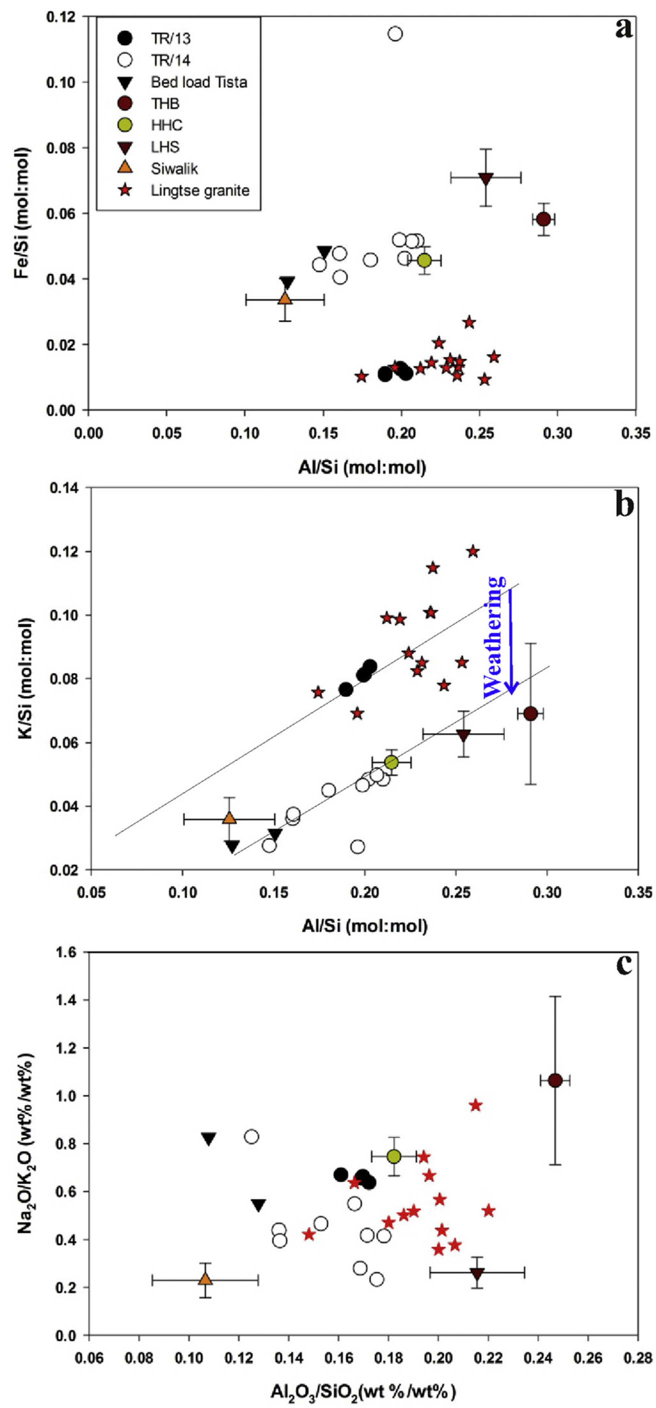

Fig. 9. (a) The immobile element ratios of Fe/Si versus Al/Si, the sediments of T3 terrace (TR/13) are plotting close to the Lingtse granite (shown by red star) showing that they have similar source. The present day bed load samples of Tista River (black inverted triangles) are plotting close to the T2 terrace sediments (open circles) showing similar source.(b) Evolution of K/Si, the concentration of mobile element (K) in T3 terrace sediment is higher compared to T2 and bed load samples showing that these are more weathered. and (c) Na_2O/K_2O ratio with respect to Al_2O_3/SiO_2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

quartz in the bedload and at bottom while micas and clays are enriched in the shallow surface waters. This result in chemical differentiation of sediments within a single reach of river (Lupker et al., 2013) Ratios of immobile elements such as Fe/Si and Al/Si are helpful to highlight it (Fig. 9). Fe, Al and Si are immobile to a first order during Himalayan erosion and remain notably unaffected by chemical weathering (Galy and France-Lanord, 2001). Al/Si and Fe/Si are directly correlated to the bulk sediment grain-size and are a proxy of mineral sorting (Lupker et al., 2013 and the reference therein). The degree of chemical weathering experienced by sediments in the Himalayan system can be traced using mobile to immobile elemental ratios of river sediment such as K/Si. Sediment sorting also applies for the immobile element such as K. The K/Si ratio is dominantly controlled by the grain size of the sediments, i.e. clay to quartz mixing. Less K/Si values for the T2 terrace indicate higher weathering than the T3 terrace sediments (Fig. 9). A line in the (Fig. 9b) indicates of increasing trend. The HHCS rocks is found to have similar or higher Na_2O/K_2O ratio in comparison to the sediments (Singh, 2009, 2010) (Fig. 9c) and therefore could be the source of terrace sediments.

In all the above plots samples of T3 terrace are plotting distinctly from that of T2 terrace. The explanation for this observation is that the sources of the sediments from these two terraces are different. Also, it was noticed that the rock fragments of the T3 terrace are mainly granite but the present day bedload consists mainly of phyllite, schist and quartzite which is typically found in Daling group. We expected that Lingtse granite may be the probable source of these deposits. To confirm it we plotted composition of Lingtse granite in the different geochemical plots (Fig. 9). The instrumental data also shows that probably Lingtse granite is exposed in some part of basin and thus contributed to terrace sediments, which has not been mapped. Further studies are required to establish this fact.

6. Conclusions

It can be observed that the terraces formed in the study area are controlled by climate and tectonics both. Climatic control provides the essential sediment supply and discharge, whereas tectonic movement provides accommodation and preservation. The present work provides a scope for future work to do a detailed structural and seismological study to understand the nature of the fault and its behavior, present (if any) as shown by deformed layers in terrace T2 and shifting in the course of Tum Thang khola. The terrace on the right bank of the Tista River could not be studied due to inaccessibility, is a potential site to understand past climate. We conclude with the following -:

(i) Three sets of terraces were formed; highest being paired and rest unpaired showing climate and tectonic control during formation.
(ii) Highest terrace (T3) formed ~44 ka which was a time period of moderate monsoon conditions as shown by the lithostratigraphy and supported by past climate record.
(iii) A major tectonic uplift took place after 45 ka, which raised the T3 to its present level.
(iv) Another tectonic movement took place after 11.9 ka which warped the T2 terrace and one such movement is active which is responsible for the warping of T1 and T0. The Tum Thang khola has witnessed a major shift in its course due to tectonic movement after 11.9 ka.
(v) The sand beds of the channel deposit (T2) were deposited during cold phases (LGM and Younger Dryas) while the pebble and boulder beds were deposited during humid phases.
(vi) Less K/Si values for the T2 terrace indicate higher weathering than that of T3 sediments.

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