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RECONSTRUCTION OF LATE QUATERNARY NEOTECTONIC MOVEMENTS AND FLUVIAL ACTIVITY IN SIKKIMESE-BHUTANESE HIMALAYAN PIEDMONT

Abstract. In the part of Sikkimese-Bhutanese Himalaya the youngest Siwalik overthrust had not developed, and the piedmont zone with extensive fans forms a semicircular gulf dismembered by several faults and minor overthrusts. Some uplifted parts of older deformed alluvial fans contain the lenses of organic clays which were earlier dated at 22–34 ka BP by ^{14}C method. Various elevated levels differ also in soil maturity. It means that the main tectonic activity with overthrusting could occur later.

To distinguish various alluvial formations and phases of tectonic activity the authors dated older levels in several localities by OSL method as well as investigated soil profiles. Most mature soils over elevated blocks built of coarse alluvia were dated between 50 and 60 ka BP. Probably the previous ^{14}C dates from clays are too young, and on the contrary OSL dates are overestimated. The younger generation of fans (10–15 m high) dated at about 14 ka coincide with the start of monsoonal pre-Holocene activity. The authors try to correlate these phases with terraces and tectonic activity in the most eastern part of the Himalayas (two phases of overthrusting: after 50 ka and 10–5 ka BP) as well as with events outside the piedmont zone: glacifluvial aggradation in the Tista valley during advance of glaciers in Sikkim and with sequence of deposits in the Brahmaputra delta.

Key words: neotectonic movements, maturity of soils, OSL dating, Sikkimese-Bhutanese Himalayan piedmont

INTRODUCTION

For the great Himalayan range several overthrusts are characteristic. The youngest of them and the outermost — the Siwalik belt, built of Neogene-Quaternary products of degradation of the Himalayas — is still expanding by folding and overthrusting over the Quaternary alluvia of Sub-Himalayan foredeep (G a n s s e r 1964; Va l d i y a 1998). At the steep front of the eastern Himalaya, the Siwaliks are very narrow and even between the Tista and the Torsa rivers are totally missing at frontal part of main Himalayan thrust (Fig. 1; N a k a t a 1972; D a s, C h a t t o p a d h y a y 1993a; G u h a et al. 2007).

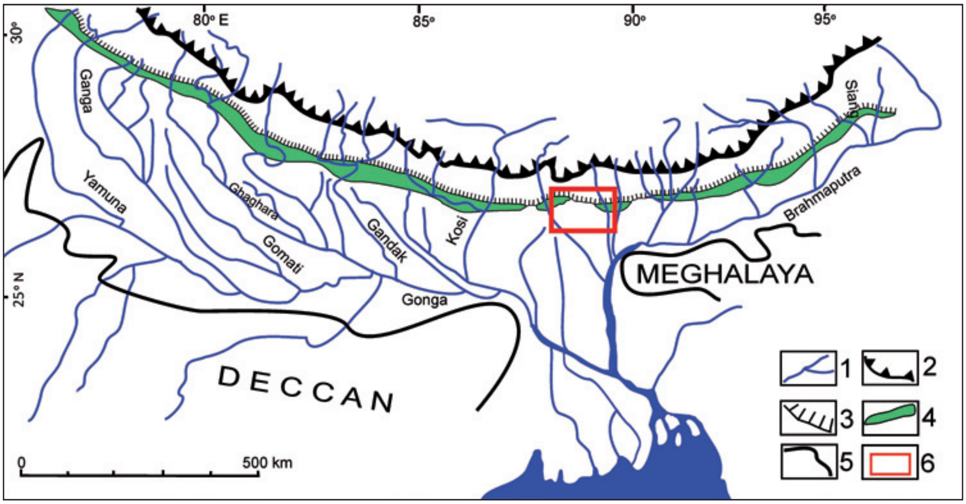


Fig. 1. Himalaya and sub-Himalayan foredeep. 1 – rivers, 2 – main central Himalayan thrust, 3 – main boundary thrust, 4 – Siwalik belt, 5 – margin of Deccan and Meghalaya uplands, 6 – research area

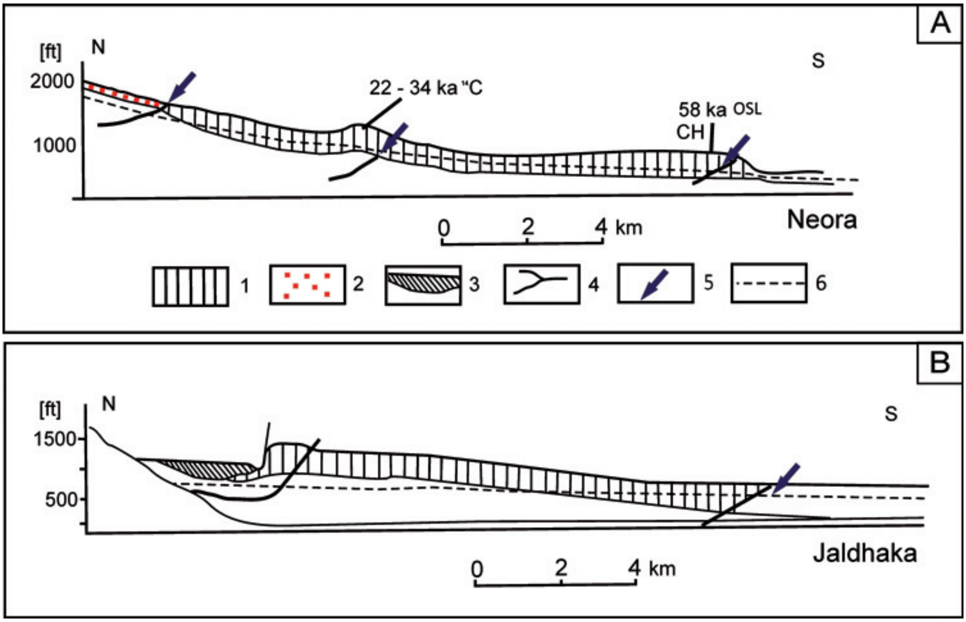


Fig. 2. Geological transect of Himalayan piedmont. 1 – Matiali formation, 2 – terrace 30 m, 3 – young alluvia, 4 – overthrusts, 5 – active overthrusts, 6 – river channel; CH – Chalsa site (Tab. 1, Fig. 3), (based on D. G u h a et al. 2007)

The oldest products of degradation were discovered at the margin of the mountains on small flattenings where large boulders were lifted to elevation ca. 100–350 m above river beds, like Rangamati and other surfaces (N a k a t a 1972;

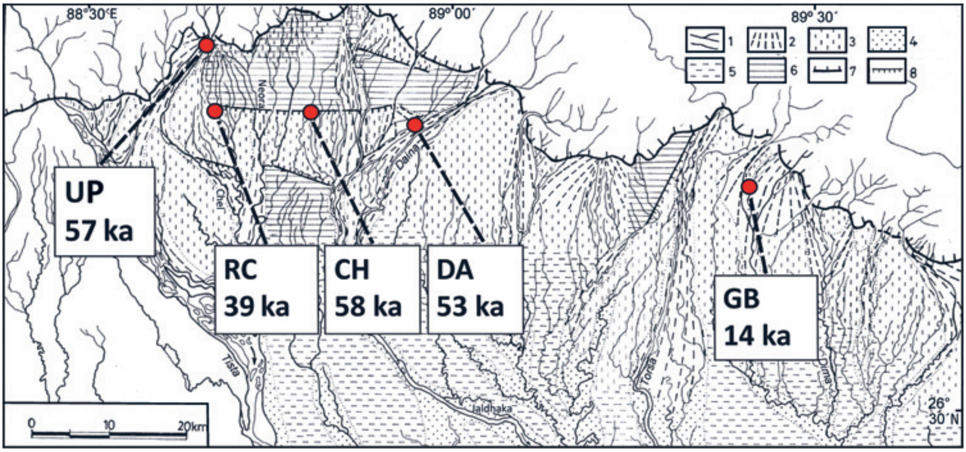


Fig. 3. Geomorphological map and places of sampling (after S t a r k e l et. al. 2008). 1 – river, 2 – alluvial fan, 3 – older fan, 4 – floodplain (downstream), 5 – low terrace, 6 – elevated blocks, 7 – edge of Himalaya, 8 – fault scarp

B a s u, S a r k a r 1990). The steep front of the mountains stands there back up to 10 km to the north and forms a semicircular gulf (S t a r k e l et al. 2008). Just in this section of piedmont, composed mainly of systems of gradually lowering alluvial fans, we observe several W-E elongated blocks bordered by overthrust or fault scarps up to 40–60 m high (Figs. 2 and 3). Some of these scarps built of coarse alluvia have a structure of a thrust anticline (G u h a et al. 2007). Some streams flowing directly from the Himalayas towards south cut across these elevated block in narrow antecedent gaps.

STATE OF RESEARCH

In the sub-Himalayan piedmont zone, T. N a k a t a (1972) and later A. D a s and G. S. C h a t t o p a d h y a y (1993b) have mapped several levels of fans and terraces putting them in stratigraphic order after their elevation, maturity of soil cover, and later also taking into consideration their tectonic deformation (N a k a t a 1989). They distinguished the higher levels with brown-red colour soils, middle terraces with yellow soils and the lowest with shallow gray soils. At the beginning of the 21st century the geologists from Calcutta (G u h a et al. 2007) documented the presence of series of faults and overthrusts, mainly parallel to the main Himalayan front. In their paper on tectonics of Jaldhaka river segment, they described elevated blocks (to 60 m high) built of gravels of Matiali formation with distinct thrusts, bordered by fault-lines and dissected by antecedent streams. There, in some localities among gravel beds they have found dark clays rich in fine organic material. They separated mostly pollen and spores from it and dated by ^{14}C method (Fig. 2).

The first sample was obtained from a S-exposed footwall of Gorubathan thrust east of the Neora River and dated at 33,875 ± 550 years BP. The second sample originated from the northern scarp separating the elevated Nagrakata block from Jiti depression at the direct foreland of the Himalayas. It was dated at 27,210 ± 240 years BP. Both dates indicate that the overthrusting and uplift occurred later in time. The third clay sample rich in fine organic detritus was dated from the top of the southern scarp of Chalsa largest overthrust block (closely to our OSL dating site). It topmost part was dated at 22,030 ± 130 years BP. The authors suggested that this horizon was formed probably after overthrusting.

Unfortunately the sites and profiles with analyzed samples were not described in detail. In the opinion of the authors it is not excluded that the age of samples has been rejuvenated (Guha et al. 2007).

The thick series of the huge megafan of the Tista river located west of the semicircular gulf (of the Himalayan front) was dated by ^{10}Be and OSL methods (see Abrahami et al. 2013) between 30 and 5 ka BP. The megafan was later uplifted and dissected.

METHODS

In first years of the 21st century the team of geomorphologists from the Department of Geomorphology and Hydrology in Krakow (a part of the Institute of Geography and Spatial Organization of Polish Academy of Sciences) after extensive studies on landslides and floods in the Darjeeling Himalaya (Starkel, Basu 2000) started to survey the foreland of the Himalayas between outlets of the Tista and the Torsa rivers. We concentrated on a problem of progressing aggradation over extensive alluvial fans (Starkel et al. 2008). During that survey we concluded that this part of the Himalayan foredeep has a complicated structure. From the subsiding plains, the blocks are rising, which frequently show distinct signs of active tectonics. L. Starkel compiled the geomorphological map (Fig. 3) showing different age of fans, fault-lines etc.

The above mentioned papers of A. Das and G. S. Chattopadhyay (1993b), T. Nakata (1983) and D. Guha et al. (2007), on the relatively young age of the deposits building the blocks elevated along faults and overthrusts, turned our attention and pushed us to date several terraces and fans. We selected two methods: OSL dating as well as a study of maturity of soil profiles.

For OSL dating and for soil analyses we collected samples from four outcrops at the elevated block (Chalsa, Daina, Ranichera and Upper Phagu) as well from a 12 m high terrace of the Gabur Basra stream. Samples were collected in November 2009 and November 2010.

In the laboratory of Institute of Physics, Silesian University of Technology in Gliwice all samples were dried before performing high-resolution gamma spectrometry. For this purpose a HPGe detector manufactured by Canberra was used.

The collected spectra allowed determining U, Th and K contents in the samples. Prior to measurements, the samples were stored for ca. 3 weeks to ensure equilibrium between gaseous ^{222}Rn and ^{226}Ra in the ^{238}U decay chain. The activities of the isotopes in the sediments were determined using IAEA standards RGU, RGTh, RGK. Dose rate conversion factors of G. Adamiec and M. J. Aitken (1998) were used to determine annual doses.

The cosmic ray dose-rate at the sample depth and location was determined according to J. R. Prescott and J. T. Hutton (1994). An average water content no higher than 22% was assumed and the value of (18 ± 4%) was used in further calculations. Based on these data, the average dose rates for grain sizes of 90–125 μm were calculated.

Coarse grains of quartz (125–200 μm) were extracted from the sediment samples for OSL dating. The routine treatment with 20% hydrochloric acid (HCL) and 20% hydrogen peroxide (H_2O_2) was applied. Sodium polytungstate solutions were used for density separation of the quartz grains with densities between 2.62 g/cm^3 and 2.75 g/cm^3. Sieving before and after the 60 min etch with concentrated hydrofluoric acid (HF) was performed.

Multi-grain aliquots were prepared by spraying silicone oil onto the 10-mm-diameter stainless steel discs through a mask with 6 mm in diameter holes and attaching the grains to the oil-covered areas. For the OSL measurements an automated Daybreak 2200 TL/OSL reader (Bortolot 2000) was used. The blue light stimulation was performed using an array of LEDs (470 ± 4 nm) delivering to the sample about 60 m W/cm^2. The calibrated, integrated in the reader $^{90}Sr/^{90}Y$ beta source was used in the laboratory irradiations. The source delivered a dose rate of ca. 5.27 Gy/min. The equivalent doses were determined using the single-aliquot regenerative-dose (SAR) protocol (Murray, Wintle 2000).

The analyses of soil samples were performed at the laboratory of the Institute of Geography and Spatial Organization PAS in Krakow. Grain size distributions were determined using the combined sieving method (for grains of diameter larger than 1 mm) and a Fritsch laser particle sizer Analysette 22 (for grains of a diameter smaller than 1 mm), after pre-treatment with H_20 and ultrasonic disaggregation. Organic matter content was determined using the wet digestion method of Tiurin, using $K_2Cr_2O_7$ for oxidation of organic carbon. The pH was determined using field colorimetric method. Soil colours were described according to the Munsell system scale.

RESULTS OF OSL DATINGS AND SOIL ANALYSES FOR SELECTED LOCALITIES

Table 1 summaries information on the samples used for OSL datings. The parameters of soils are characterized separately for the analysed profiles (Figs. 4, 5, 7, 8 and 10).

Table 1

OSL dating from terraces at piedmont zone (see Fig. 3)

Number of sample	Locality	Terrace level in meters	Depth of sampling horizon	Age in ka BP
CH2	Chalsa	65	1	58.1 ± 2.4
DA2	Daina	12	1	52.8 ± 2.5
UP1	Upper Phagu	30	5	57.4 ± 4.4
RC1	Ranichera	20	5	38.6 ± 1.5
GB1	Gabur Basra	12	5	13.8 ± 1.4

CH2 Chalsa site is located at the southern margin of the elevated horst just above a scarp about 65 m above the river channel (Fig. 4). The OSL date from 1 m depth is 58.1 ± 2.4 ka BP. At least 2 m deep uniform sandy soil of red and yellow colour (10YR in Munsell colour scale) indicates an advanced maturity of soil. The opposite NE margin of this flat level, in about 15 km distance, was dated earlier by ^{14}C at 22–34 ka BP (G u h a et al. 2007).

DA2 Daina site is located at the most eastern part of the same Chalsa thrust, but is elevated only 12 m above the floodplain of the Daina river, the left tributary of Jaldhaka (Fig. 5). The OSL date from 1 m depth is similar to the former one; 52.8 ± 2.5 ka BP. The soil was developed on gravely substrate and is also yellow-red in color (10YR), like in Chalsa.

UP1 similar age is assigned also to sands with gravels from 5 m depth at lower, 30 m high, terrace of the Chel river in a higher mountain course at Upper Phagu Tea Garden (UP1), north of the marginal Himalayan overthrust (Fig. 6). The OSL date: 57.4 ± 4.4 ka BP may indicate that the uplift rate was probably of similar order on both sides of the main Himalayan overthrust.

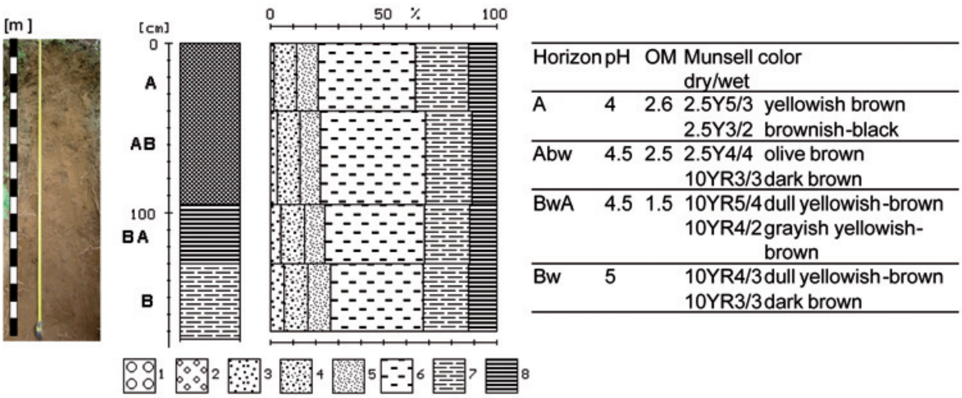
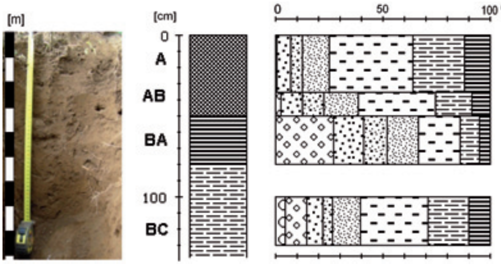


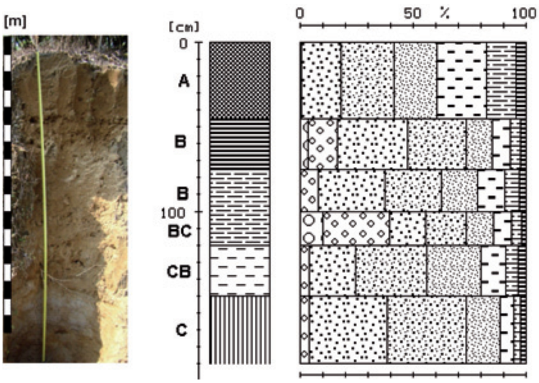
Fig. 4. Properties of soil profile CH2. Grain size composition: 1 – coarse gravel (> 16 mm), 2 – fine gravel (2–16 mm), 3 – coarse sand (0.5–2.0 mm), 4 – medium sand (0.25–0.50 mm), 5 – fine sand (0.063–0.25 mm), 6 – coarse silt (0.02–0.063), 7 – fine silt (0.004–0.02 mm), 8 – clay (< 0.004 mm)



Horizon	pH	OM	Munsell color dry/wet
A	4	3.6	10YR4/2 gray yellowish brown 10YR2/1 black
Abw	4.5	2.4	10YR4/3 olive brown 10YR2/2 brownnish black
BwA	4.5	1.5	10YR5/4 dull yellowish-brown 10YR3/3 dark brown
BwC	4.5		2.5Y4/4 olive brown 10YR2/2 brownnish black

Fig. 5. Properties of soil profile DA2. (Grain size composition see Fig. 4)

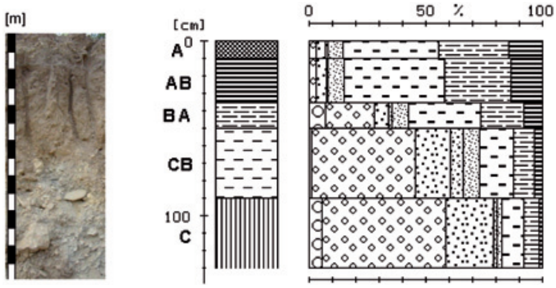
Fig. 6. High terrace of the Chel river, close to profile UP1



Horizon	pH	OM	Munsell color dry/wet
A	4	1.3	2.5Y5/3 yellowish-brown 2.5Y3/2 brownish-black
Bw	4.5	0.2	2.5Y5/4 yellowish-brown 10YR4/3 dull yellowish-brown
Bw	4.5	0.2	2.5Y6/3 dull yellow 10YR4/3 dull yellowish-brown
BwC	4.5		2.5Y5/3 yellowish-brown 10YR3/3 dark brown
CBw	4.5		2.5Y6/3 dull yellow 10YR4/2 grayish yellowish-brown
C	5		2.5Y7/3 light yellow 2.5Y4/2 dark grayish yellow

Fig. 7. Properties of soil profile RC1 (Grain size composition see Fig. 4)

RC1 Ranichera site is located at the fan surface of the Chel river much lower than the previous ones (about 20 m above river channel; Fig. 7). The sample from about 5 m depth, from sands with gravely intercalation, was dated at



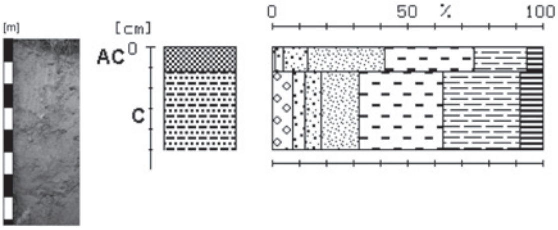
Horizon	pH	OM	Munsell color dry/wet	
A	4.5	3.1	2.5Y4/3	olive brown
			2.5Y3/2	brownish-black
Abw	4.5	2.6	2.5Y4/4	olive brown
			2.5Y2/3	brownish-black
BwA	5	2	2.5Y4/4	olive brown
			2.5Y3/3	dark olive brown
CBw	5		2.5Y6/4	dull yellow
			2.5Y3/3	dark olive brown
C	5		5Y7/2	Light gray
			5Y5/2	grayish olive

Fig. 8. Properties of soil profile GB1 (Grain size composition see Fig. 4)

Fig. 9. Alluvial fan, 15 m high along the Gabur Basra creek

38.6 ± 1.5 ka BP. The colour of soil varies between 10YR and 2.5Y – cambic horizon is more yellow. It indicates a less advanced stage of soil evolution. Also maps produced by T. N a k a t a (1972) and D. G u h a et al. (2007) show this fan as a separate middle level.

GB1 the lowest and the youngest among the dated sites is from Gabur Basra creek site. It is located at the margin of 10–15 m high fan of the small Gabur Basra creek, only about 5 km from its outlet from the Himalayas. This fan is built



Horizon	pH	OM	Munsell color dry/wet	
AC	5.5	0.5	5YR6/2	grayish olive
			2.5Y4/2	dark grayish olive
C	5	0.1	5Y6/2	grayish olive
			2.5Y4/2	dark grayish olive

Fig. 10. Properties of soil profile from floodplain of the Chel river (Grain size composition see Fig. 4)

of alternated layers of sands and gravels with single boulders. The chaotic sedimentation presents the deposition during flash floods with probable supply from debris flows (Fig. 8. 9). The sample from 5 m depth was dated at 13.8 ± 1.4 ka BP. This fan has a similar elevation as many fans at the outlets of small creeks, which are no more flooded.

All the described soils of the overflooded terraces represent Inceptisoils differing mainly in a stage of evolution. These soils are used for tea plantations or forests. On the floodplain of a parallel valley of the Pana river and of the westernmost Gish river, the soil profiles, which have the character of typical Entisoils (Fig. 10), have been analyzed. They are gray in colour with visible fluvial lamination. The soils in question are covered by grass or cultivated as rice fields. They are still flooded during greater floods.

DISCUSSION AND CONCLUSIONS

The active neotectonics in the piedmont zone differentiated previous altitudes of generations of alluvial fans. Therefore, the OSL datings supported by references to various maturity of overlying soils help to distinguish several generations of upper Quaternary terraces, disturbed by overthrusts and fault-lines and in general confirm previous datings by ^{14}C as well general characteristics of sequence of soils (Nakata 1989; Das and Chattopadhyay 1993a; Guha et al. 2007). But, there is a distinct difference in age between ^{14}C and OSL dates. It is not excluded that ^{14}C dates from organic dust are too young (20–30 ka BP) comparing with the termoluminescence older age (50–60 ka BP). In any case, the dates mean very young overthrusting and older folding during a relatively short period as well as a very rapid downcutting before formation of new fills of extensive fans dated about 15–12 ka BP (Gabur Basra profile – Fig. 8). That new phase of aggradation seems to coincide with reactivation of a strong monsoonal activity in Southern Asia (Overpeck et al. 1996; Kale et al. 2003).

Our results may be well correlated with the OSL datings of alluvia in the most eastern part of the Himalayas, in Arunachal Pradesh, building the strath terraces tectonically deformed along the Himalayan Frontal Thrust (HFT), Main Boundary Thrust (MBT) and transversal faults (Srivastava et al. 2009; Lui r e i et al. 2012). The elevated terraces are dated there between 56 and 47 ka BP and colluvial deposits at the base of the frontal edge of MBT are dated at 54 ka BP. It indicates that after 50 ka BP there was the phase of neotectonic activity. The lower strath terrace-fans at outlets of the Himalayan rivers are dated between 11.5–9 ka BP, what was interpreted as reflection of tectonic phase about 10–8 ka BP. The lowest terraces (above floodplain) got the dating 6–4 ka BP. This again coincides with the youngest dates from the Tista megafan, which was lifted up and dissected in last 5 ka BP (see: A b r a h a m i et al. 2013).

The role of climatic fluctuations manifested themselves during the last cold stage in the aggradation in the mountain part of the great Himalayan Tista river valley draining the Sikkimese Himalaya. Several kilometers upstream of the narrow canyon-like outlet of the Tista from the mountains at Kalijhora site, there is a 55–60 m high terrace shelf of about 40 m thick sequence of sands and fine gravels (unusually finer for this mountain segment) which were dated by TL method between 47 ± 6 ka at the base and 17 ± 6 ka BP at the top (B l u s z c z et al. 1997; S t a r k e l , B a s u 2000). The rocky shelf below suggests that downcutting in the bedrock occurred later. Such sequence of events could be explained by a very intensive glacifluvial aggradation at front of 30–50 km long valley glaciers during a cold pleniglacial phase. It seems that neotectonic activity in the foothills occurred before that coolest phase. On the great fan – delta of the Brahmaputra river, downstream of the junction with its tributary – Tista, at about 110 m depth below the clay horizon, there was found wood dated at 28320 ± 1750 – 1440 years BP (U m i t s u 1987). That clay layer, at least 5 m thick, could be an expression of the coolest phase (advance of mountain glaciers and lowest niveau of the Indian Ocean). Above it, in thick series of sandy deposits, at about 85–75 m depth, a gravely horizon indicating frequent heavy floods appears. We suggest that it is probably the marker of reactivation of monsoonal activity 15–12 ka BP (corresponding with formation of 10–15 m high fans at the outlets of small creeks dissecting the front of the rising Himalayas). The neotectonic factor played also a distinct role in this sequence of changes in fluvial activity, causing the dissection of middle terraces, followed by formation of youngest fill, still continuing.

The differentiated tectonic movements were probably concentrated in two main phases: the first one after deposition of alluvia dated 58–52 ka BP and the second after deposition of extensive alluvial fans dated in Gabur Basra 13.8 ka BP, later dissected and rejuvenated after 5 ka BP.

Similar ages of two distinct groups of forms in the Sikkimese-Bhutanese Himalaya and Arunachal Pradesh show that the main phases of tectonic activity were probably synchronous along the whole edge of the eastern Himalayas, but the stage of evolution of the Himalayan overthrusting was different. The sector between the Tista and the Torsa is still undeveloped.

The preliminary datings of alluvia, supported by various maturity of soils, in the tectonically active piedmont of Sikkimese-Bhutanese Himalaya put in the context of climate changes in the transect from Himalayas to Brahmaputra delta help to construct a hypothetical sequence in evolution of fluvial activity during the last cold stage in this part of Himalayan foredeep. It has been shown also that in case of differentiated tectonic movements single morphological method is not sufficient for establishing a chronological sequence of evolution of fluvial systems.

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