Late Quaternary glaciation and seismicity in the Higher Central Himalaya: evidence from Shalang basin (Goriganga), Uttaranchal

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The Shalang basin, which is a tributary basin of the Goriganga in the higher central Himalaya, is endowed with record of late Quaternary glaciation and seismicity. Three distinct glaciation events in the form of lateral moraines have been identified and are used to reconstruct the palaeo-Equilibrium Line Altitudes (ELA). Maximum ELA depression (~ 600 m) was associated with the oldest and longest Stage-I glaciation. Subsequent glacial advancements were limited in extent and remained above 3500 m. Luminescence dating of glaciogenic sediments suggests that the oldest Stage-I glacial event is equitable to Marine Isotopic Stage-4 (MIS-4), whereas stages-II and III are assigned MIS-2 and little ice age respectively. Morphology of the moraines and presence of seismites in a lake sequence suggest tectonic activity along the Trans-Himadri Fault during the late Quaternary.

Keywords: Equilibrium line altitude, Late Quaternary glaciation, luminescence dating, Relict lake.

THE Himalaya and Tibetan plateau have considerable influence on global climate and may have played a key role in the onset of the Quaternary glaciation[1,2]. The elevated topography paved the way for glaciers[3], and records of past glaciation that are preserved in the region can be used to reconstruct the temporal and spatial variations in climate[4]. It has been suggested that the extent of glaciation in the northwestern and Trans-Himalaya was sensitive to northward penetration of monsoon-driven moisture[5]. Thus, the moraine successions in the glaciated valleys along the entire length of the Trans-Himalaya may have responded to changes in moisture and temperature conditions in the past[6]. It has been argued that a detailed history of the Last Glacial Stage (LGS) would provide a good framework for greater understanding and modelling of climate fluctuation during the Pleistocene[7]. In glacial geomorphology, past temperature and precipitation can be estimated using the equilibrium line altitude (ELA) of glaciers. In the field, ELA is associated with the emergence of lateral moraines[8] and defines the boundary between the zone of accumulation from that of ablation. Considering this, the magnitude of past climatic changes can thus be ascertained by estimating the altitudinal difference between the past and present ELAs[7]; also known as ELA depressions.

This article presents the observations made in the Trans-Himalayan region of the Shalang glacier (Goriganga basin), central Himalaya (Figure 1 *a*), with a view to reconstruct the glacial history and palaeoclimate during the late Quaternary. Further, moraine morphology and relict sediments have been used to ascertain the role of Trans-Himadari Fault (THF) during the late Quaternary glaciation.

Geology and geomorphology

The Shalang glacier (30°15′–30°20′N; 80°5′–80°10′E), one of the major glaciers, emerges from the northeastern slope of the Nandadevi massif (Figure 1 *a*). The Shalang basin is bound by Main Central Thrust (MCT) in the south and THF in the north[9] (Figure 1 *b*). The basin is represented by rocks of Vaikrita Group/Central crystalline (quartzite, quartz schist, calcsilicate, gneisses and migmatite) and Martoli Formation Tethyan sedimentary (bedded black shale, slate and phyllites)[10]. Rocks of Vaikrita Group are exposed in the southern part of the basin, whereas rocks of Martoli Formation are in the north (Figure 1 *b*). The presence of U-shaped valley, abrupt termination of terminal moraine, and a near straight course of Goriganga river with occasional point bar immediately northwest of Rilkot suggest structural control on landscape evolution. We attribute this to the presence of THF that runs parallel to the Goriganga till Martoli (NW–SE) and then takes a northwesterly turn (Figure 1 *b*). The U-shaped valley developed on the hanging wall (NW), whereas the V-shaped valley was carved on the footwall (SE) of the THF (Figure 2). Compared to the Goriganga basin, the tributary Shalang basin is wider in its upper reaches (southern part) and becomes progressively narrow towards the northern part till it joins the Goriganga (Figure 3). The Shalang basin is surrounded by Shalang Dhura (Dhura = ridge), Shalla

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Dhura and Martoli peak (4586 m) in the east and Kuchela Dhura, Samjang Dhura and Nanda Kot (6861 m) towards the west (Figure 3).

The Shalang glacier flows proximal to the steep western flank. Relict glacial basin floor is exposed towards the eastern flank, where degraded conical mounds of calcsilicate rocks are exposed (Figure 4). Evidence such as polishing, striations and rounding of the crescentic head wall of the relict basin suggests past glacial activity that was confined to ~ 1000 m east of the modern glacier. The oldest moraine is dominated by lithified calcsilicate clasts that emanate at the base of the relict glaciated basin located farthest from the modern glacier (Figure 4). Subsequent lateral moraines run parallel to the modern glacier.

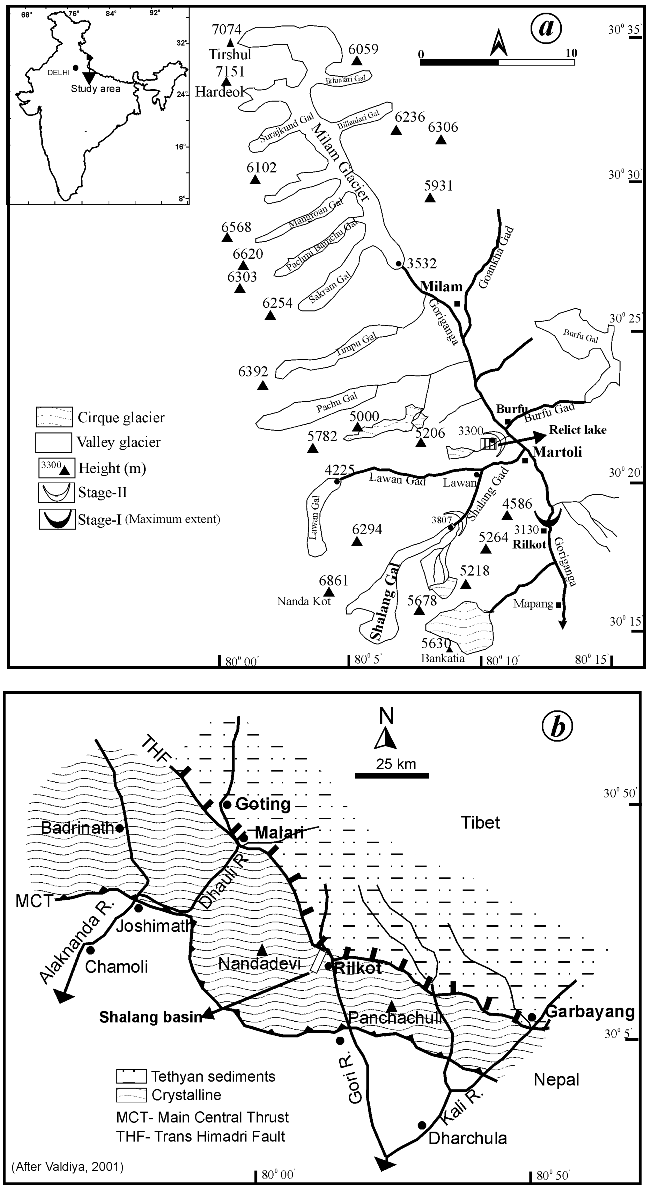

Figure 1. *a*, Map showing distribution of major valley glaciers and active cirques in the Goriganga basin. *b*, Generalized lithological and structural map of the study area (after Valdiya[9]).

The Shalang glacier follows the western escarpment of Shamjang Dhura. As a result, no lateral moraine ridges are preserved on this flank (Figures 5 and 6). The valley narrows down north of the snout (3700 m), and Shalang Gad (Gad = stream) emerges from the glacier melt incising a deep gorge (~ 100 m) through the lithified moraine and bedrock (phyllite) at the base of Shamjang Dhura before meeting Goriganga (Figures 5 and 6). Downstream valley opens up and good exposures of moraine deposits can be seen between the villages Martoli and Rilkot (Figure 6).

Moraine stratigraphy

Based on the relative dating technique such as moraine morphology, degree of cementation/compaction and soil

Figure 2. Field photograph showing glaciated basin above Rilkot and terminal moraine. Also indicated is the position of THF that roughly demarcates the glaciated U-shaped valley in the north and V-shaped fluvial valley in the south.

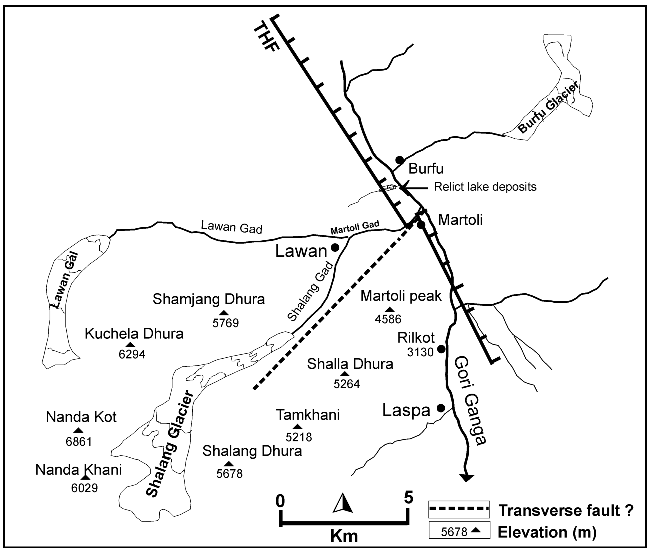

Figure 3. Structural map of Shalang basin showing position of THF (modified after Valdiya[9]) and inferred transverse fault with respect to the Shalang glacier (present work). Major peaks surrounding the basin are also marked.

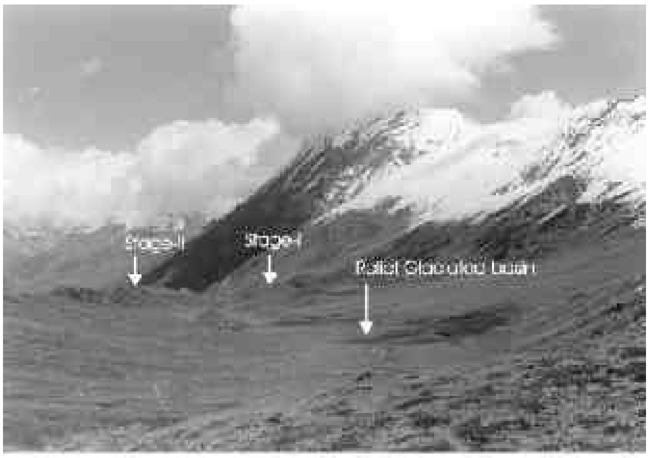

Figure 4. Field photograph of relict glaciated basin along with Stage-I and Stage-II moraines. Photograph facing north taken from modern accumulation area.

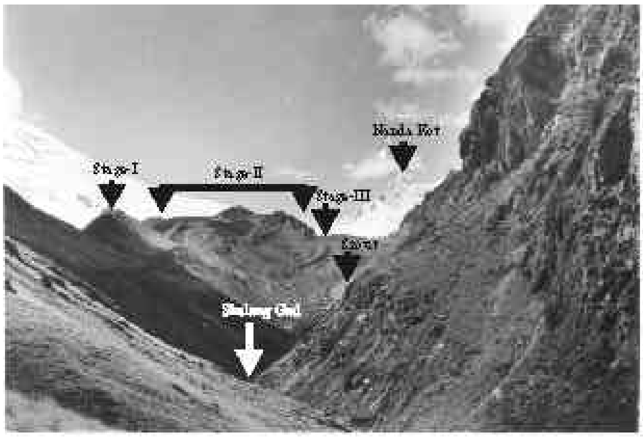

Figure 5. Field photograph showing lateral moraines of stages-I to III. Stage-I moraine is rounded, whereas Stage-II and Stage-III moraines have sharp crests. Photograph looking south (after Chamyal and Juyal[23]).

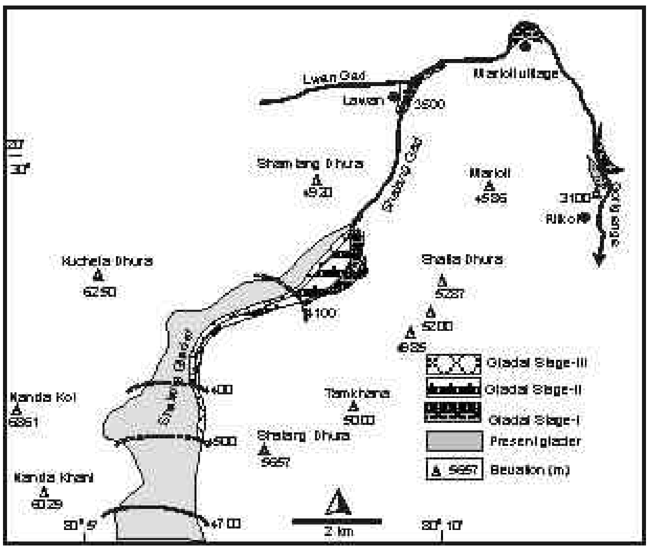

Figure 6. Geomorphological map of moraines preserved in the Shalang and Goriganga basin. Palaeo ELAs, dashed line; present-day ELA, solid line (after Chamyal and Juyal[23]).

formation, the moraines have been classified into three glacial advancements as stages: Stage-I being the oldest and Stage-III the youngest (Figures 5 and 6).

The moraine of Stage-I is exposed on the eastern flank of the relict basin and is over-ridden by the moraine of Stage-II in the middle part of the basin. The moraine of Stage-I is a rounded ridge (Figure 5), buff-coloured and well-cemented, supporting good vegetation of juniper. Lithology of moraine is dominated by calcsilicate clasts that vary in size from pebbles to boulders. Maximum size of the boulder measured at the distal end of the moraine is $2.5\ \text{m} \times 1.5\ \text{m} \times 1.2\ \text{m}$, with polishing (desert varnish) and glacial striations (Figure 7). The Stage-I moraine extends up to ~ 15 km from the point of emergence (at 4100 m altitude) and terminates at Rilkot (at 3100 m altitude; Figure 6). At Rilkot, a weakly developed 20-cm thick, dark grey Ah horizon covers the moraine.

The moraine of Stage-II is a complex suite of curvilinear sharp crested ridges (Figures 5 and 6) moderately compact and sparsely vegetated. A veneer of immature brownish-grey soil has developed on the top of the Stage-II moraine. The largest clast fresh in appearance is $1\ \text{m} \times 0.7\ \text{m} \times 0.3\ \text{m}$ in dimension. The Stage-II moraine ridges run in S–N direction before turning NE and finally curving towards NNE. The moraine begins with a single ridge at an altitude of 4400 m asl and spreads into seven well-spaced ridges below 4000 m asl, where they curve sharply towards the northwest (Figures 4 and 5). The middle and lower part of Stage-II moraine overrides Stage-I moraine that can be traced beyond 6 km from the point of emergence (4400 m asl) in the south to 3500 m asl in the north near Lwan village (Figure 6). Compared to Stage-I, the lithology of Stage-II moraine is dominated by phyllite, schists, gneisses and basic intrusive rocks. These rocks are also found in the accumulation zone of present day Shalang glacier. The lithological contrast between Stage-I and Stage-II moraine implies the change in source area of the moraines after Stage-I glaciation.

Figure 7. Calcsilicate boulder at Martoli village showing glacial striations and desert varnish.

Stage-II and Stage-III moraines run parallel to the present-day glacier. Stage-II moraines lie around 10–20 m above the present-day glacier, whereas the Stage-III moraine is only 3–5 m above the present-day glacier. Stage-II and Stage-III moraines have identical lithology; however, the latter is razor-sharp crested (Figure 5). Additionally, the lithoclasts are diminutive, fresh in appearance and devoid of soil cover. The moraine ridge extends up to 8 km from the point of emergence at 4500 m asl to its terminus at 3700 m asl.

Neotectonic activity

Presence of geological evidences of relict glaciated basin in the east, preferential preservation of lateral moraines on the eastern flank and juxtaposed Shalang glacier towards Shamjang Dhura (western flank), collectively suggest westward tilt in the basin (Figures 6 and 8). The THF runs NW–SE and demarcates the northern limit of the Shalang basin. A lateral displacement of the THF is observed near Martoli village and is attributed to the presence of a NE–SW trending transverse fault (Figure 3). Valley entrenchment and formation of deep gorge immediately west of Martoli village by Shalang Gad are attributed to the activity associated with the movement of the transverse fault. Thus, it is suggested that a lateral shift in the Shalang glacier is related to the differential movement along the transverse fault that took place after the Stage-I glaciation. The isostatic recovery due to decrease in ice volume after Stage-I glaciation reactivated the transverse fault. Such reactivation of pre-existing faults in tectonically active basins has been reported during deglaciation[11]. Besides, evidences of seismicity are obtained from a relict lake succession exposed by Kharkhan Kholta Nala, south of Burfu village (Figure 9). Field evidence suggests that terminal moraines of a north-facing cirque glacier located at 4000 m facilitated the impounding of glacial melt during the phase of recession in which ~ 23 m thick lacustrine succession was deposited. The lake sediments resting over the ground moraine of Stage-II have preserved four seismically deformed horizons. These horizons are represented by contorted bedding, flame structure, sand dyke and normal sense of faulting (Figure 9). Relict lake deposits lay on hanging wall of the THF and presence of deformation structures suggests episodic seismic activity along the THF. The evidences suggest that the THF has been active during the Quaternary[9] and has played an important role in landscape evolution[12]. Preliminary luminescence chronology bracketed these events between 16 and 11 ka (Figure 9), implying that the terrain has been seismically active during the late Quaternary.

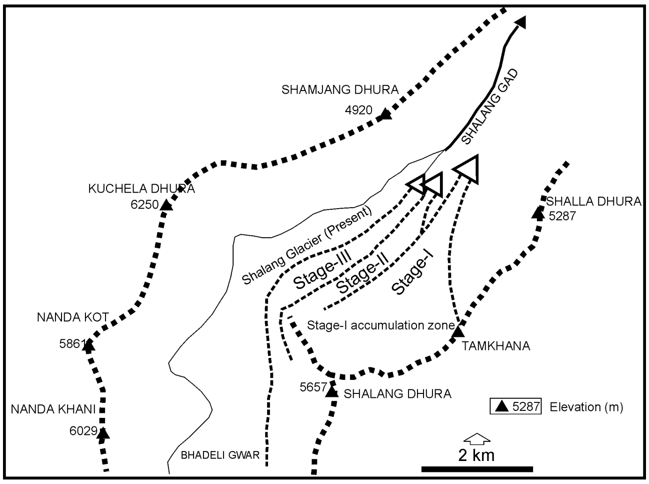

Figure 8. Map showing progressive westward shift in lateral moraines from Stage-I to Stage-III.

ELA and palaeoclimatic implications

Shalang is a single-valley glacier (simple glacier) and free from snow and debris avalanche. Hence it is ideal for the reconstruction of present and past ELAs (Figure 1 *a*). This is important since complex glaciers were found to overestimate the present and former ELAs[7]. The modern ELA and accumulation area ratio (AAR) of Shalang glacier are determined using the ten years IRS LISS-II cloud-free (September and October) False Colour Composites (FCC) data. AAR is the ratio of accumulation area that lies above the equilibrium line to the total area of the glacier (accumulation plus ablation)[13] and it is being used quite extensively for mass balance studies in the Himalayan glaciers[14].

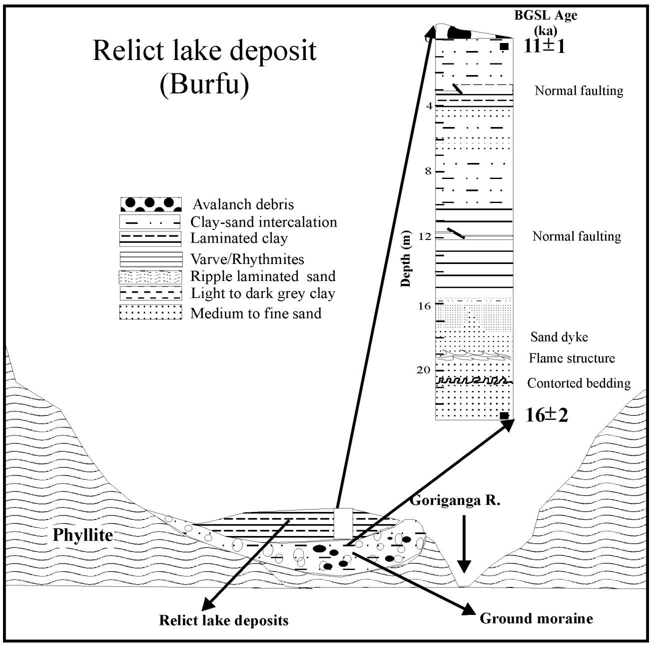

Figure 9. Stratigraphic succession of the relict lake sediments near Burfu village. Note deformation structures. Blue-green light Stimulated Luminescence (BGSL) ages are shown alongside. Valley cross-section is schematic.

Table 1. Past temperatures and relative ice volume estimates

Glacial stage	ELA (m)	ELA-decline (m)	Temperature decline (°C)	Glacier volume (km^3)	Times increase (in volume)
Modern glacier	4700	–	–	0.05	–
Stage-III	4500	200	~ 1	0.1	2
Stage-II	4400	300	~ 2	0.4	8
Stage-I	4100	600	~ 4	0.8	16

The IRS FCCs provide a visual demarcation separating the glacier accumulation zone from ablation, which can be used to calculate AAR and delineate ELA of the modern glaciers[15]. In the Goriganga basin, an AAR value of 0.45 was arrived at with respect to six glaciers, including the Shalang glacier. This compares well with the value calculated for modern Himalayan glaciers[13]. This value was then translated onto the Survey of India topographic map, which enabled the marking of the ELA of Shalang glacier at 4700 m altitude (Figure 6). To determine the palaeo-ELAs, maximum elevation, or as in the present case, emergence point of lateral moraines was considered[8]. This assumption seems valid considering the emergence of lateral moraine at the boundary demarcating the zone of dirty and white ice as seen in the FCCs and in the field[15]. Due to the preferential westward shift in the Shalang glacier, relict moraine ridges are located in the eastern flank and are away from the influence of avalanche and landslide activity. This is important because palaeo AAR and ELA estimation relies on the assumption that no significant modification occurred after the lateral moraine deposition. The well-preserved lateral moraine and basin morphology helped in the geometrical reconstruction of the relict basins, which in turn were used to estimate the ice volumes associated with Stages-I to III glaciation. Though the basins may have undergone deformation with time, gross estimates can still be made to visualize the apparent quantum of ice these basins may have supported during different glacial stages. Thus some estimate of past moisture and temperature regimes can be made. However, palaeo-temperature estimation would require reliable data on adiabatic lapse rates (temperature) for which no unique method exists due to the inherent complexity of the glacier system[16,17]. A heat and mass-balance approach as a probable solution to this problem has been suggested[17]. In the absence of such studies, temperature estimates are made by multiplying ELA depression by a lapse rate. The adiabatic lapse rate used is an intermediate between a moist (5°C/km) and dry (10°C/km), or by taking actual field measurements[17]. We have assumed a value of 6.5°C/km based on limited meteorological data available from the Dokriani Bamak glacier in the central Himalaya[18]. This value represents the lapse rate for the beginning of the ablation period in the Dokrani Bamak glacier. Comparing the modern ELA with that of the reconstructed palaeo-ELA, tentative estimates of past temperatures and relative ice volumes were calculated (Table 1).

Clearly, maximum temperature decline and increase in ice volume was associated with Stage-I advancement. Given the suggestion that maximum accumulation and ablation in the Himalayan region occur simultaneously during the summer southwest monsoon[13], it can be suggested that the Shalang basin experienced enhanced moisture condition during Stage-I.

Discussion

Three glacial advances are documented in the Shalang basin (Goriganga) that have provided a relative chronology on the available data from the adjoining areas and luminescence ages obtained on the relict lake sediments near Burfu village.

Some estimate on the timing of the maximum advancement of the valley glacier in the Shalang basin (Stage-I) is obtained by dating the relict lake sediment exposed along Kharkhan Kholta Gad near Burfu village (Figure 9). Considering luminescence dating of the bottom-most relict lake sediment (~ 16 ka age), it can be safely postulated that Stage-I is significantly older. Recent studies[12] in the Kaliganga basin suggest that maximum extent of valley glacier occurred during the Marine Isotopic Stage-4 (MIS-4) or early part of MIS-3. The longest glacial advancement called Bhagirathi Glacial Stage (BGS) that extended 40 km beyond the glacier snout was dated[19] to 63 ka and equated with the MIS-4, when cold and humid climate may have caused more atmospheric humidity to affect large-scale glacial advancement[20]. A recent review[21] of global Quaternary glaciation suggested that the last maximum glacier advance predates the Last Glacial Maximum (LGM) ~20 ka. The maximum ELA depression (~ 600 m) and 16 times increase in ice volume (compare to present) during Stage-I glaciation accords well with the suggestion that this event corresponds to the cold and moist MIS-4 (Table 1).

In the Shalang basin, Stage-II glaciation was less extensive as indicated by its terminus around 3500 m. Evidence similar to this was obtained from the adjoining Kaliganga basin, where absence of moraine intercalation in relict lake sediments at Garbayang that formed after the retreat of Stage-I glaciation confirms that glaciers remained much above the limit of the penultimate glaciation (MIS-4)[12]. During Stage-II glaciation, ELA was lowered by 300 m and the ice volume increased by eight times, suggesting enhanced atmospheric aridity compared to Stage-I. Considering that the Stage-II moraine underlies the lake sediments that are luminescence dated to 16 ka, it is reasonable to assume that Stage-II glaciation occurred during the Last Glacial Maximum (MIS-2). This period corresponds to regional cooling and weak southwest monsoon in the central Himalaya[5].

Reconstruction of ELA depression and ice volume during Stage-III glaciation indicates that compared to the present, the snow line has lowered by ~ 200 m and ice volume has increased marginally (Table 1). We attribute this event to the neoglacial stage corresponding to the Little Ice Age, as observed in the Milam glacier, Goriganga basin[22].

The study further indicates that THF played an important role in the landscape evolution, particularly restricting the southern extension of the valley glacier that terminated near Rilkot. Differential movement along the transverse fault not only led to lateral displacement of the THF near Martoli, but also facilitated preferential westward shift in the Shalang glacier. Chronologically constrained seismically deformed horizons in the relict lake sediments suggest that activity along the THF continued till around the beginning of Holocene. This is in accordance with the observations made in the Kaliganga basin[12,23], implying regional tectonic instability in the vicinity of the THF during the last glacial stage.

The evidences presented above are preliminary in nature and a more definite inference would await further field and laboratory data from chronologically constrained sequences in the Himalayan region.

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