Landslide-dammed lakes in the Alaknanda Basin, Lesser Himalaya: Causes and implications

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We present observations on landslide-dammed lake deposits located in the vicinity of the E–W and NW–SE trending, south-dipping North Almora Thrust, in the Alaknanda Basin around Srinagar Garhwal. Preliminary observations suggest that activation of crumpled and unstable phyllite dominated slopes led to temporary damming of second and third order tributaries of the Alaknanda river. Sedimentary styles of the succession indicate deposition under the transient lacustrine environment, with seasonality. Luminescence chronology suggests that the lakes were formed after the Last Glacial Maximum (LGM) and probably continued till the Mid-Holocene. Lake formation is attributed to the reactivation of phyllite-dominated slopes following the reestablishment of the southwest monsoon after the LGM. Presence of contorted laminas is interpreted as episodic events of seismic activity. Finally the lakes disappeared due to large-scale slope reactivation around Mid-Holocene.

Keywords: Alaknanda Basin, landslide-dammed lakes, optical dating.

CLIMATE change at variable timescales exerts profound control on hill slope and fluvial transport processes and hence the landscape development[1,2]. However in the case of the Himalaya, additionally the role of tectonics remains equally important[3]. Climatic and rainfall variations are major forcing factors behind orogenic deformation in the Himalaya[4]. Therefore, it is important to understand the past climatic changes and associated sediment generation and deposition in different climato-tectonic domains of the Himalaya.

In the Alaknanda Basin evidences pertaining to the landslide damming of the rivers are limited to the Higher Himalayan ranges around the Main Central Thrust (MCT). The zone of the MCT is not only seismically active, but also coincides with the zone of intense southwest monsoon[5]. Away from the MCT towards the south, there is no reported evidence for river damming in the geological past. In view of this, the observations presented here are important.

Activity along the North Almora Thrust (NAT) is manifested by the presence of highly fractured phyllites that are precariously resting on moderate to steep slopes around Srinagar town. During the prolonged monsoon phases, increased pore-water pressure creates favourable conditions for deep-seated landslides, which are evidenced along National Highway no. 58. Here, the results of our preliminary investigations on four lake sequences coupled with geochemistry and Optically Stimulated Luminescence (OSL) chronology have been used to determine the timing of landslides and to explore the records of palaeoclimatic changes.

The area investigated lies in the Alaknanda Basin of Garhwal Lesser Himalaya (lat. 30°15′–30°18′32″N and long. 78°42′–78°50′E). After traversing a narrow valley, the Alaknanda river enters the wide open valley (~6 km long) around Srinagar town, where six levels of aggradational river terraces can be seen. Geomorphic features, viz. fossil river course, entrenched meanders, river gorges, raised aggradational and degradational terraces, and slip-off slopes indicate tectonic activity in the past[6]. Climatically the area bears subtropical climate with a mean annual rainfall between 1000 and 1500 mm, of which 80% occurs between mid June and mid September. During this period the Alaknanda river and its tributaries carry maximum water and suspended load. The vegetation is dominated by *Pinus roxhburghi* (1400–700 msl), *Dalbergia sissoo* and *Acacia* spp. (700 m) and its distribution is governed by the altitude and slope aspect.

The dominant lithology in the study area is low-grade upper Proterozoic phyllites and flaggy quartzites equivalent of Garhwal Synform[7] (Figure 1 *a*). The phyllites are

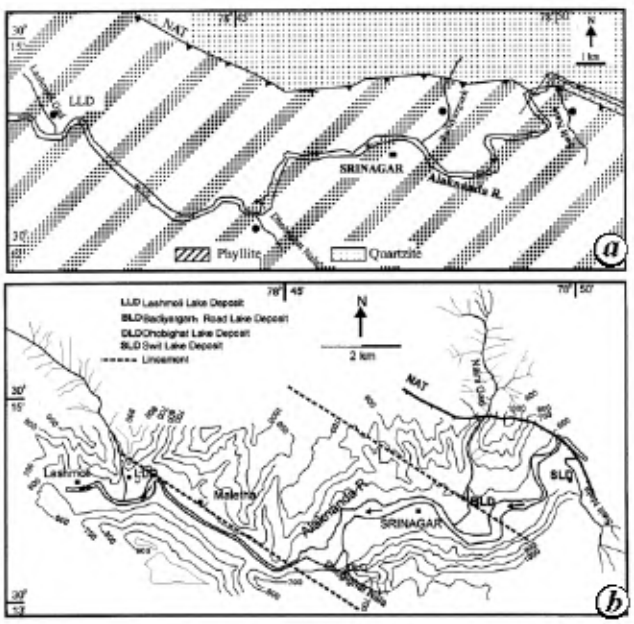

Figure 1. *a*, Major lithology of the study area along with location of lake deposit sites. *b*, Map showing the valley morphology, major lineaments and location of lake deposits.

*For correspondence. (e-mail: pradeep@wihg.res.in) tightly folded, and fractured with intercalated sills and dykes of metabasics. Contact between the phyllite and flaggy quartzite is demarcated by 45°–60° southerly dipping E–W and NW–SE trending NAT and is characterized by wide shear zone around Srinagar[7]. At places, the NAT becomes vertical or even north-dipping[6].

Two types of slopes are discerned around Srinagar, the upper precipitous slopes (above 1500 m), and the lower undulating slopes covered with ancient landslide debris (between 1500 and 700 m). The Alaknanda river enters into the basin through a gorge near Koteshwar. After flowing 500 m towards south, takes a westward course around Srinagar and flows as a braid, meandering river with the development of channel bars (Figure 1 *b*). The abrupt change in river course is attributed to the activation of lineaments[6]. Six generations of fluvial terraces along the meandering loops on either side of the Alaknanda river could be seen around Srinagar (Figure 2 *a*). These are differentiated by vertical offsets ranging from 3 to 10 m, which is attributed to reactivation of the WNW–ESE, NE–SW and E–W trending faults (strike–slip to oblique slip displacements) in the recent and sub-recent times[8–10]. A recent study based on detailed geomorphological investigation around Srinagar has suggested that the area was seismically active during the Late Quaternary[6].

Figure 2. ***a***, Field photograph showing six levels (T_6–T_1) of terraces along the meandering loop of the Alaknanda. Majority of the lake deposits occur on terrace T_5, except for the Lashmoli and Swit Nala Lake deposits that exist on terrace T_4. ***b***, Photograph showing seismically induced sand dyke located in Badiyargarh lake sequence.

Four lake profiles were studied using lithofacies, geochemistry and OSL chronology. Identification of lake sequences was based on lithofacies determination using grain-size pattern, vertical and lateral association of individual depositional units, colour and bioturbation. For geochemical analysis samples were collected both from fine sand and clayey silt units, where samples for OSL dating were collected from the sandy horizons.

Samples for geochemical characterization of sediments were collected from the two lake sequences located on Badiyagarh road (BLD) and Dhobhighat (DLH). Four kilograms of each sediment sample was collected, air-dried and homogenized. One kilogram of homogenized sample was crushed to 250 μm. Out of the 1 kg sample processed and crushed, about 200 g of each sample was ground to 75 μm size for geochemical analysis.

The major elements were analysed by XRF (Siemens) on fused glass disc using the method proposed by Norrish and Hutton[11]. The precision of the analysis for major and trace elements was monitored using USGS rock standards (SGR and MAG-1) and it was better than 1.5 and 5% respectively. Molar proportions of Al_2O_3 (A), CaO (C), Na_2O (N) and K_2O (K) were used to calculate the Chemical Index of Alteration (CIA). The calculation was done using chemical data on carbonate-free basis[12,13].

For OSL dating the samples were collected in opaque pipes in order to protect them from exposure to sunlight. This technique relies upon the fact that prior to burial geological luminescence stored in the mineral lattice gets zeroed by daylight exposure during the process of erosion and transportation[14]. There are increasing evidences to suggest that the geological luminescence of quartz sufficiently bleached during fluvial transportation[15,16]. Six samples were dated, two each from Badiyagarh, Dhobhighat and Lashmoli lake sequences. Quartz fraction from the samples was extracted by treating them sequentially with HCl, H_2O_2 (to remove carbonate and organics respectively) and heavy liquid separation using sodium polytungstate (density = 2.58 g/cubic cm). These grains were then sieved to get 90–150 μm size range and etched using 40% HF for 80 min, followed by 12 N HCl treatment for 40 min to remove any contribution from alpha irradiation. The purity of quartz vis-à-vis feldspar contamination was tested using Infrared Stimulated Luminescence. The grains were mounted on stainless-steel disks using Silkospray™. Luminescence measurements were made on a Riso TL/OSL-12 system with a halogen lamp source for stimulation.

OSL was recorded for 100 s at 125°C. The signal was recorded through the filter combination of BG-39 + U-340. A $^{90}Sr/^{90}Y$ beta source delivering a dose rate of 3.6 Gy/min was used for irradiation. The five-point single aliquot regeneration protocol suggested by Murray and Wintle[17] was applied on all the samples. Three regeneration dose points were used to construct the dose growth curve and two points were used to check for recuperation effect and sensitivity corrections (recycled point) respectively. A preheat of 240°C/10 s for natural and regeneration doses and a cut heat of 160°C for test doses were used. Dose growth curves having <10% variation in recycling ratio were selected. For dose rate estimation uranium, thorium and potassium concentrations were determined by XRF analysis.

Evidences of landslide-induced stream damming were identified at four locations in the study area on either side of the valley (Figure 1 *b*). These streams not only incise the host lithology, but also the fluvial terraces before meeting the Alaknanda river obliquely or at right angles (Figure 1 *b*). Longitudinal profile of the streams shows a distinct knick point, above which remnants of ancient lake deposits were found. Knick-point development in seasonal streams has been attributed to brisk rate of upliftment in the region[9]. Distribution of relict lake sediments in the study area suggests that damming of streams occurred after the development of the second (T_5) and third oldest terraces (T_4). The lithofacies architecture of the lake sequence indicates three major facies, viz. matrix-supported gravels of debris flow origin; greyish, fine sand, and bioturbated clayey silt. The start of the sequence is generally marked by the presence by debris flow followed by the greyish, fine sand facies, which indicates the initiation of landslide-dammed lake. This is overlain by bioturbated clayey silt facies, indicating deeper conditions in the lake during the warm and wet climatic conditions. The sequence is often punctuated by debris flow indicating reactivation of the landslide, and at places fine sand facies shows the presence of seismically induced liquefaction features indicating seismic activity penecontemporaneous to lake sedimentation (Figure 2 *b*).

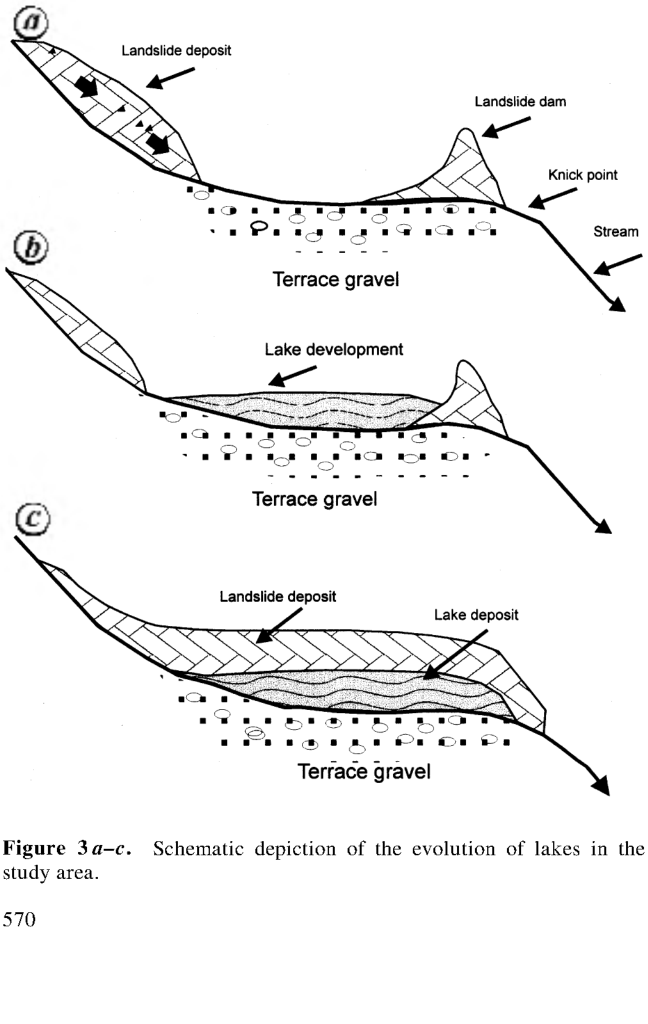

Figure 3 *a–c*. Schematic depiction of the evolution of lakes in the study area.

Figure 3 depicts the process involved in the formation of landslide-dammed lakes in the study area. Damming of streams involved a triggering mechanism for slope activation (Figure 3 *a*), transportation of debris and entrapment at a narrow course giving rise to ponding (Figure 3 *b*) and finally termination of lakes by renewed landslide activity (Figure 3 *c*). Crude orientation of the platy rock fragment and reworked fluvial gravel indicates their transportation under the influence of water aided by gravity. Among the various factors that govern the durability of a landslide-dammed lake along the streams the rate of sedimentation, hydraulic pressure and thickness of the landslide barrier are important. The stratigraphy of individual lake sequences is described below.

The lake succession at Lashmoli (78°45.90′E, 30°12.67′N) is 3.5 m thick, dominated by greyish, fine sand and clayey silt. This sequence is located in the vicinity of a seasonal stream that meets the Alaknanda river on the right flank near Lashmoli village (Figure 4). The succession rests on fluvial terrace (T_4). From the base upwards, the succession begins with the deposition of 20 cm thick, internally laminated brown, clayey silt followed by 60 cm thick, mottled, fine, greyish sand. The upper part of this horizon shows contorted contact with the overlying 20 cm thick light to dark grey clayey silt. The upper part of this unit shows desiccation cracks which are filled by the overlying 60 cm thick fine sand containing clay lenses. This is followed by 45 cm thick, massive, fine-to-medium grey-yellowish sand. A 50 cm thick, internally laminated, light-brown fine silt overlies this horizon. Finally a thick pile of debris flow containing moderately oriented phyllite and reworked fluvial gravel marks the termination of the lacustrine sedimentation.

A 3.5 m thick section of lake deposit was studied along Badiyargarh road (78°47.75′E, 30°13.79′N). The sequence rests on terrace T_5 (Figure 5). The site is located at the right bank of the Alaknanda river and is incised by a rain-fed stream that has developed a 700 m wide alluvial fan at the confluence with the Alaknanda river. Ponding of the seasonal stream occurred on the T_4 gravel by a landslide that originated from the northern flank. From the bottom upwards, the sequence began with the deposition of 30 cm thick, laminated-to-massive medium sand. The upper part of the horizon intrudes into the 20 cm thick, overlying, chaotically mixed fine silt. This is overlain by 30 cm thick, internally laminated medium sand. A massive 140 cm thick, compact coarse sand horizon overlies this. This in turn is succeeded by a 15 cm thick, bioturbated, sandy clay horizon. This horizon is overlain by 15 cm thick, fine-grained massive sand, which is overlain by a 80 cm thick, internally laminated silt horizon. Finally phyllite-dominated colluvium and reworked terrace gravel terminate the succession.

Another 1.7 m thick sequence at Dhobighat (78°45.92′E, 30°12.67′N), located on the right flank of the Alaknanda, (~2.5 km from Srinagar along the Srinagar–Pauri road) was studied (Figure 6). Geomorphic relationship of the lake sequence with that of the terrace indicates that ponding occurred after the deposition of terrace T_5. A trench was excavated from the surface to the underlying terrace gravel in which 12 distinct fining upward units of greyish, fine sand and silty clay of varying thickness were encountered. Sedimentation began with the deposition of 60 cm thick, fining upward sand, the lower part of which shows cross-lamination. This horizon is overlain by 18 cm thick, crudely laminated silt, which in turn is succeeded by 22 cm thick coarse sand intruding into the 18 cm thick overlying silt (Figure 6). This is followed by 10 cm thick fine sand, which is overlain by 8 cm thick silt deposit and is succeeded by 30 cm thick massive clay horizon. Finally thick colluvium dominated by phyllite clasts marks the termination of the lacustrine environment.

A section was studied in the vicinity of Swit Nala (78°49.44′E, 30°13.85′N), a tributary to the Alaknanda river. A 2.8 m thick lake succession punctuated by landslides overlies T_4 terrace (Figure 7). From bottom upwards, the

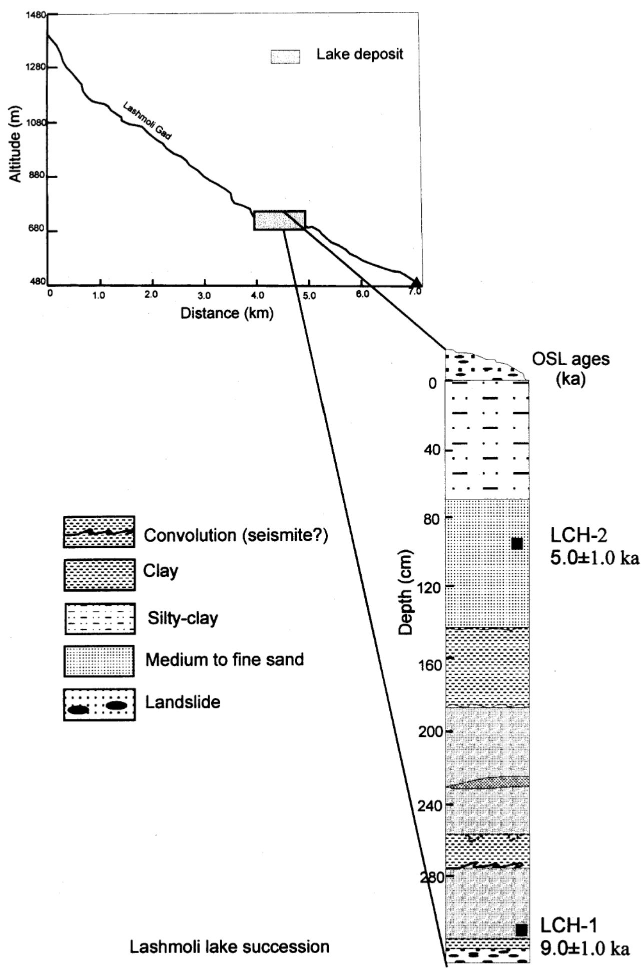

Figure 4. Longitudinal stream profile and lake succession exposed at Lashmoli. Optical ages on the samples LCH-1 and LCH-2 are shown alongside the stratigraphy.

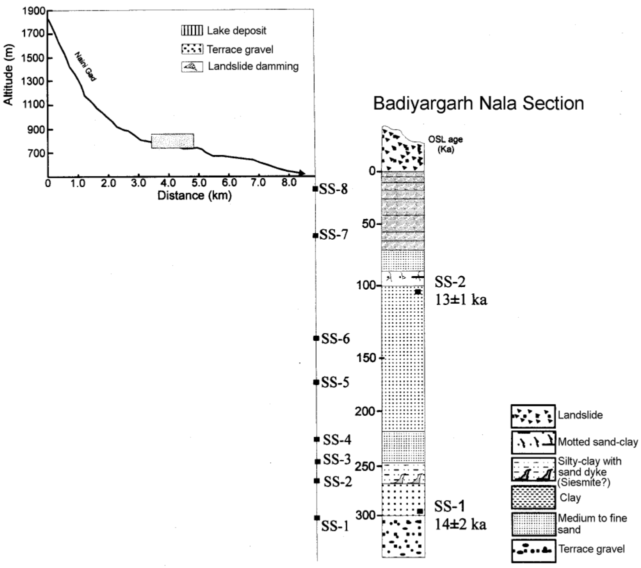

Figure 5. Longitudinal stream profile and lake succession exposed at Badiyargarh road lake section. Bar on the left of the litholog indicates position of the samples (SS-1, SS-2, etc.) collected for geochemical analysis. OSL ages given are in ka.

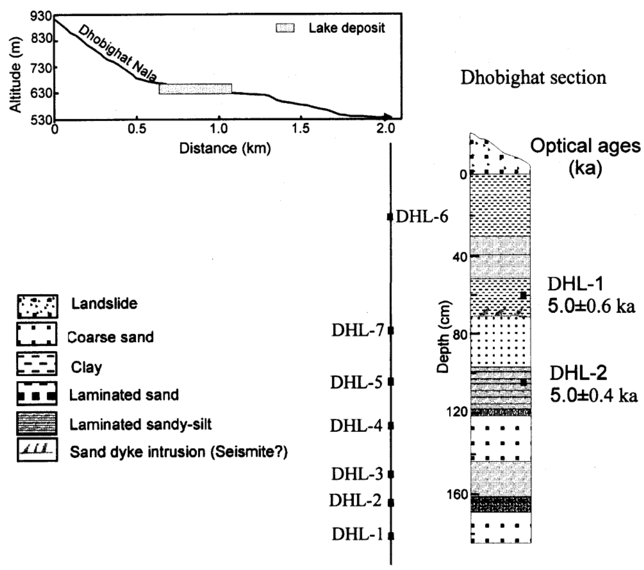

Figure 6. Longitudinal stream profile and lake succession exposed at Dhobighat Nala. Bar on the left of the litholog indicates position of the samples (DHL-1, DHL-2, etc.) collected for geochemical analysis. OSL ages on samples DHL-1 and DHL-2 collected from dating are given in ka.

succession begins with the deposition of 80 cm thick, coarse-to-medium, greyish sand, which is overlain by a thin (5 cm) silty clay lamina. A temporary hiatus in sedimentation is inferred by the presence of a 20 cm thick, locally generated debris flow deposit. Resumption in lacustrine sedimentation followed with the deposition of 45 cm thick, clayey silt followed by a debris flow event. This debris flow event was succeeded by a short-lived lacustrine phase, as indicated by the deposition of 40 cm thick, clayey silt showing convolute bedding capped by 10 m thick colluvium containing oriented clasts of phyllite and reworked terrace gravels.

Geochemical analysis on the samples collected from different sedimentary units of the sequences at Badiyargarh and Dhobhighat was conducted to ascertain weathering conditions in the lake catchment. Major oxides and trace element concentrations were determined for each sample using XRF. The extent of weathering defines the nature of the sediments, which is controlled by the climate and tectonics of the hinterland. CIA of the sediments, which is a measure of the extent of chemical weathering and gives an insight into the weathering trends and therefore the tectonic and climatic condition of the provenance[17], was calculated.

CIA of greyish sand and clayey silt units of the lake sequences at Badiyargarh and Dhobhighat was calculated separately and is plotted in Figure 8. The finer sediments of lake deposits show high CIA values with an increasing upward trend. However, the sequence profiles do not show any sign of *in situ* weathering. The sandy units show small changes initially, but have nearly constant CIA values in the later deposits. The increasing CIA values in finer sediments indicate that weathering of sediments took place in the lake catchment under humid and warm conditions and then these weathered sediments with high CIA value were deposited into the lake[18]. These conditions prevailed prior to sedimentation, and the constant CIA value of coarse sediments in the upper part is due to the fractionation of unweathered grains into the coarse fraction during high flow (rainy seasons).

The OSL chronology indicates that Lashmoli lake was formed at 9 ka and sedimentation was terminated after 5 ka. The lake at Badiyargarh was formed around 13.9 ka and sedimentation terminated at ~12.7 ka. The two samples from the lake sequence at Dhobhighat Nala indicated continued sedimentation ~5 ka. This suggests that landslide-dammed lakes around Srinagar possess fragmentary record of sediment generation and deposition from 14 to 5 ka. Table 1 provides the age and radiometric data for the samples collected.

In the lesser Himalaya, tectonics, lithology and climate play a major role as preparatory causal factors for slope failures, which at times leads to the formation of lakes.

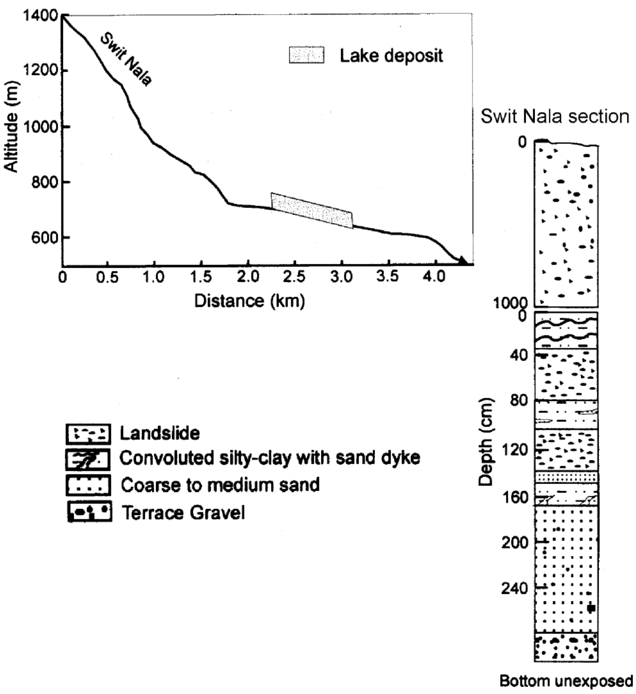

Figure 7. Longitudinal stream profile and lake succession exposed at Swit Nala.

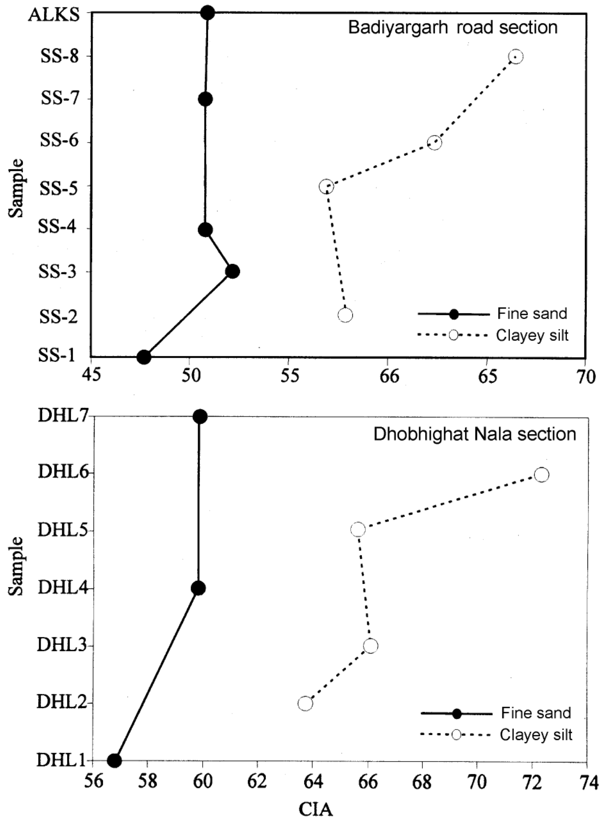

Figure 8. Up section variation in Chemical Index of Alteration (CIA) values as a function of depth in Badiyargarh and Dhobhighat lake sections. Samples from fine sand and clayey silt horizons were plotted separately because fine sand is mainly composed of quartz that may not be sensitive to weathering compared to clayey silt.

Table 1. Age and radiometric data for samples collected

Sample	Depth (m)	U (ppm)	Th (ppm)	K (%)	Dose rate (Gy/ka)	Palaeodose (Gy)	Age (ka)
SS-1	0.90	2.4 ± 0.2	14.2 ± 1.4	2.1	3.2 ± 0.3	41.2 ± 1.5	12.7 ± 1.2
SS-2	3.10	2.4 ± 0.2	11.9 ± 1.2	1.6	2.7 ± 0.3	37.2 ± 2.2	13.9 ± 1.6
DHL-1	0.60	4.9 ± 0.5	19.4 ± 1.9	3.1	4.9 ± 0.4	23.9 ± 1.8	4.9 ± 0.6
DHL-2	1.00	5.1 ± 0.5	22.4 ± 2.2	2.4	4.9 ± 0.4	23.6 ± 2.2	4.8 ± 0.4
LCH-2	0.40	4.5 ± 1.0	19.0 ± 5.0	2.6	4.6 ± 0.5	22.0 ± 3.0	5.0 ± 1.0
LCH-1	2.90	5.0 ± 1.0	20.0 ± 6.0	1.5	3.8 ± 0.5	36.0 ± 1.0	9.0 ± 1.0

SS samples are from Badiyargarh section; DHL samples are from Dhobhighat Nala section; LCH samples are from Lashmoli section; Water content: 15 ± 5%; Cosmogenic gama: 150 ± 30.

Such lakes provide an opportunity to understand the role of the above forcing factors in their evolution. In the present case, these deposits were located either in the vicinity of E–W trending lineament (e.g. Lashmoli, Badiyargarh and Dhobighat) or on the hanging wall of NAT (e.g. Swit). Geomorphic expression of these structures is well preserved in the form of deeply incised phyllites and invariable presence of knick points (Figures 4–7). These features suggest that the area was tectonically active in the past and probably continued till the present. As depicted in Figure 3 *a–c*, slope failure in the upper reaches generated assorted sediments that far exceeded the carrying capacity of the streams. These were arrested at the gorge section above knick points forming a sediment barrier behind which lakes of various dimensions were formed.

Lashmoli and Swit Nala sections are located on terrace T_4 of Alaknanda river, while others (Badiyargarh and Dhobighat) are developed on terrace T_5. There is no evidence to suggest that landslides extend onto the lower terraces. Considering this and the cross-cutting relationship of streams with the terraces suggests that events of lake formation at least post date terrace T_5 aggradation, and in Lashmoli post date terrace T_4. Sedimentary structures and texture of the lake sediments further indicate that lakes were unconfined (open type), except during periods of silty-clay deposition. In addition, sedimentation was near continuous during their existence with the exception at the Swit Nala section, where the lacustrine sedimentation was temporarily punctuated by landslide events. Finally, a widespread landslide event led to their disappearance from the area.

Though limited in their distribution, at places soft sediment-deformation structures (contortion and convolution) in otherwise planar laminae were observed. Although the generation of such structures is attributed to palaeoseismic events[19], it is often difficult to confidently establish their relationship with seismic shaking[20]. Among all the features of soft sediment deformation, liquefaction features such as sand blows are considered most diagnostic of seismic shaking[21]. In our case we have observed scattered sand patches in otherwise fine silty clay, at times mimicking flame type of intrusion (in Swit Nala and Badiyargarh road sections). We attribute these small-scale features to water-escape activity that occurred during seismic shaking[20].

Estimation regarding the antiquity of these lakes was obtained using the optical dating method. It was observed that initiation of lake formation event occurred around 14 ka (BLD) and continued till <5 ka. Based on these estimates it can be inferred that slope activation occurred around 14 ka after the Last Glacial Maximum (LGM). This period also coincides with the initiation of the southwest monsoon[22] and continued intermittently till the Mid-Holocene (~5 ka). Increasing CIA values in Badiayargarh road and Dhobhighat sections indicate wetter conditions prior to ~13 ka and at ~5 ka respectively. Following this, the termination of lacustrine environment probably occurred with the onset of Mid-Holocene aridity[23]. This is reasonable considering that an independent age estimate[24] based on the incision rate and beryllium-10 exposure ages assigned 17 ka for the oldest terrace T_6 and <10 ka for the youngest terraces T_1. Considering that the period of lake initiation corresponds to the gradual reestablishment of the southwest monsoon[23] and that its termination occurred during the initiation of Mid-Holocene aridity, it is suggested that widespread slope activation was caused with the availability of moisture during climatic transition, a condition that favours large-scale sediment mobilization as well[25]. In the Himalaya, evidences suggest that sediment mobilization was limited prior to 10 ka due to decreased fluvial transport capacity and was later enhanced with the onset of monsoon[26]. In the present case, sediment supply was not limited due to the presence of fractured and fissile phyllite rocks. However, sediment mobilization was restricted due to weak monsoon. At the onset of the southwest monsoon (after the LGM), landslides were triggered in the region during the transitional climatic condition, thus blocking the seasonal stream courses from forming lakes[27]. Duration of the lakes depended on the magnitude of the landslide and the palaeohydrological condition. We speculate that slope stability was routed through the growth of vegetation that was achieved with the full establishment of the monsoon between 14 and 5 ka. The sediment flux was well regulated as indicated by the deposition of medium-to-fine sand and clay. Large-scale landslides (slope activation) that led to the termination of lakes during Mid-Holocene were either triggered by short-lived storm surge events or the reactivation of lineaments in the study area. At this stage, it is difficult to isolate either of the two. Nonetheless, presence of soft sedimentary deformation structure in the lake sediments suggests episodic seismic activity during the existence of these lakes.

Considering the above we suggest that the role of tectonics in the present case appears to have been limited to generating sediments by episodic activity along NAT and its sympathetic splays (lineaments), whereas slope activation was initiated with the reestablishment of the southwest monsoon.

The present study allows us to draw a few preliminary inferences.

(i) Lakes were formed due to activation of slopes during the transitional climatic condition after the LGM.
(ii) Lacustrine environment persisted intermittently till the Mid-Holocene, during which the terrain witnessed episodic seismic activity between 14 and >5 ka.
(iii) Large-scale slope instability after 5 ka caused the termination of lakes in the study area, due to the combination of climate and tectonics.
(iv) CIA values of clayey silt units are helpful in deciphering the palaeoclimatic conditions that persisted during lake sedimentation.

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