A record of lake outburst in the Indus valley of Ladakh Himalaya, India

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We report here a paleolake record of outburst discovered at ~3245 m asl in the Spituk–Leh valley of the Indus river, Ladakh Himalaya. The >55 m thick sediment package is displayed by megascopic (metre scale) and intense injective liquefactions, slumping and gliding of the lake beds, and mega-scouring by gravelly outflow with enclaves of dry lake beds. The combination of liquefaction, scouring and slumping is elaborated here as a consequence of increased hydrostatic compression producing liquefaction followed by instantaneous release of stresses due to breaching resulting into scouring, gravity sliding, collapse and more liquefaction. The episode ended with re-adjustment faults (normal faulting) and gliding of dry lake beds towards the valley floor. The unusually larger magnitudes of liquefaction structures indicate greater time available to develop them relative to that of seismites in this region. The unique geomorphic setting for the lake site in the river valley further infers the susceptibility of the Indus river to damming and outbursts in the Spituk–Leh valley that is possible during climatic oscillations.

Keywords: Liquefaction, outburst, paleolake, seismites.

INTERDEPENDENCE of glacial fluctuations to hydrometeorology and sediment transfer in the connected river basins is well recognized in the Himalayan region[1–5]. Considering the increased rates of glacial recession during past few decades[6–8], possibility of creating new lake basins by glacial melt and damming of rivers followed by lake outbursts and related flash floods is likely to increase[9]. Several reports have rated the outburst floods as one of the major hazards in the mountainous regions of the Himalaya[9,10]. Investigation of past records of damming and outbursts therefore makes one of the significant aspects of studying the potential disasters that can occur by climatic changes in the Himalaya.

The late Quaternary geomorphic set-up of the Himalaya is greatly articulated by glacial processes acting over pre-existing tectonic grains that are further modified by the interaction of fluvial and colluvial processes during recent and modern times. Variation in response times of the climate change over geomorphic landscaping can result into several dynamic conditions such as misfit valleys, damming of rivers and formation/breaching of lakes, and landslide activities. The trans-Himalayan region has historically reported several paleolake deposits related to river damming (and impoundment) during late Pleistocene[11–16]. However, majority of these are located in the modern river valleys and so records of outburst are either wiped out by later erosional processes (probably during Holocene) or are under cover by younger alluvium. We report here such a rare record inferred as lake outburst in the Spituk–Leh valley of the Indus river in Ladakh Himalaya (Figure 1).

The Spituk–Leh valley is oriented NW–SE along lithotectonic contacts of the Ladakh Batholith and Indus Formation[17]. In the downstream, the Spituk–Leh valley connects to another broad, open valley of Nimmu by a sharply dissected mountainous ridge producing narrow, sinuous gorge between the two valleys where the present site of lake outburst is located (MP, Figure 1). Since there is a trekking entry into the adjacent west-bound Markha valley, we have denoted this deposit as Markha Paleolake (MP), and also to distinguish it from the previously reported paleolake deposits near Spituk[16]. The junction of the Spituk–Leh valley with the Nimmu valley is also marked by the confluence of the Indus river with the Zanskar river. Both these valleys (Spituk–Leh and Nimmu) display 50 to >150 m thick sequence of Quaternary sedimentation characteristic of a variety of glacial moraines and glacial outwash deposits, alluvial/colluvial fans, fluvial, fluvio-lacustrine, lacustrine, varved lake and aeolian deposits. The Spituk–Leh valley becomes exceptionally narrow at MP site and is uniquely marked by a dam-like ramping ridge producing hairpin bends in the valley (H1 and H2, Figure 1). In the upstream near Spituk, thick fluvio-lacustrine deposits and their interaction with lateral moraines are prominent. The GPS recorded levels of the onset of lacustrine facies at Spituk (~3213 m), Army Check Post deposit (ACP, ~3225 m) and MP site (~3245 m; Figure 1) suggest Spituk as the deeper and older part of the lake system in the Spituk–Leh valley.

The left bank of the Indus river in the Spituk–Leh valley shows large dimension (few kilometres) and high gradient (5–15°) coalescing fans. These conglomeratic and gravelly fan complexes show glacial outwash and sometimes debris flow deposits with sharp toe cutting due to the Indus river. Further northwards in the valley, the left bank shows fluvially modified moraine complexes interfingering with moraine deposits from the left as well as the right banks.

The right bank further in the upstream valley typically exposes paleo-Indus gravels in complex interfingering with moraine deposits arising from the Ladakh batholithic range. In the central part, the valley becomes exceptionally broad and shows gravelly, braided fluvial deposits of the modern Indus river joined by the melt water-fed seasonal streams from the mountain glaciers. Although modified by anthropogenic activity, the remnant lake deposits are well exposed near the Leh town, airport and Spituk monastery area (Figure 2). Further for over a

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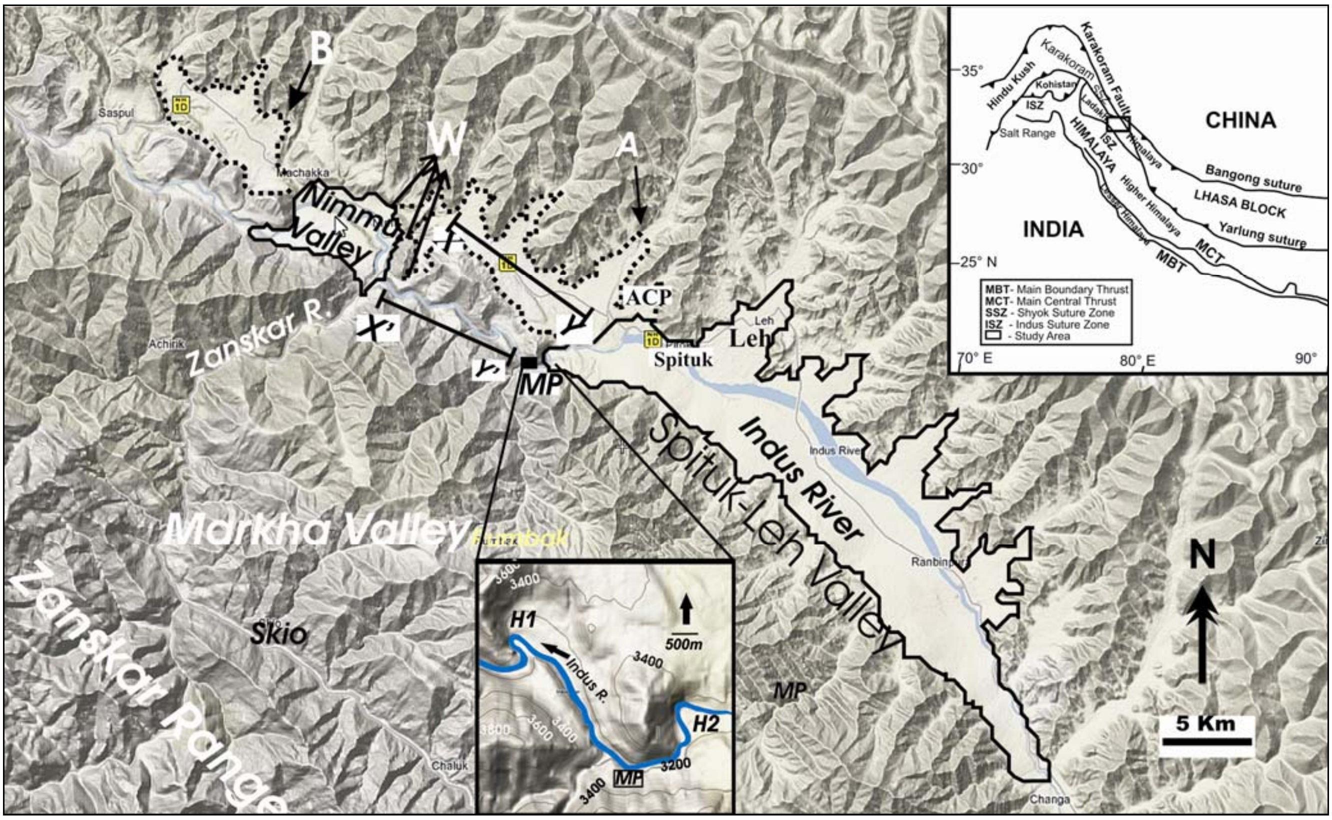

Figure 1. An overview of the study area marked by modern Spituk–Leh and Nimmu valleys (solid traces). Inset top right corner showing the location of study area (Google Earth Image). The dotted lines (A and B) indicate their probable Late Pleistocene interconnections through the wind gaps marked by W. H1 and H2 (also shown in inset bottom) mark the two hairpin bends of the present connection between the two valleys (i.e., *X′–Y′*). MP, Site of the lake outburst reported here; ACP, Deposit near Army Check Post on the Leh–Kargil highway.

stretch of 2 km downstream from Spituk, there are no lacustrine deposits preserved either in the right or left banks. After a sharp arm-like ridge, extensive fluvio-lacustrine deposition (ACP; Figure 1) occurs over the right bank till it is truncated by the large glacial moraines from the Phyang valley in the downstream terminal part of the Spituk–Leh valley.

The paleolake record at Spituk is dominated by lacustrine facies in the lower part, with lowermost horizons showing penecontemporaneous deformations (PCD). The stratigraphically middle part of this deposit shows a prominent fluvial incursion with clasts of the Indus Formation. The upper part shows varved lacustrine facies followed by typical aeolian sedimentation towards the top. The ACP deposit shows widespread fluvio-lacustrine sedimentation, with the topmost part showing aeolian facies. The lacustrine facies at ACP are mostly massive, with a majority of siltstones (devoid of varvites). They also show channel incursions at various levels with pebbles imbricating towards the average flow direction of the modern Indus. These fluvial incursions at various stratigraphic levels suggest several events of dynamic fluvio-lacustrine interactions within the valley, favourable for damming and outburst phenomena. The northern part of the valley shows entrenched moraines that may have attempted to block the river several times. As a result of this close interaction of moraines with the Indus river, the river took a sharp turn towards the left bank in this northernmost part of the Spituk–Leh valley (approaching H2 in Figure 1).

The Spituk–Leh to Nimmu valley geomorphic connection (marked *X–Y* in Figure 1) is filled by extensive lateral moraine deposits from the Ladakh batholithic ranges from east. The moraine activity from the Phyang valley (marked *A* in Figure 1) appears to have dislodged the Indus river to its present position to take the sinuous course in the deep gorges along *X′–Y′* shown in Figure 1. Phartiyal *et al.*[16] had mentioned that debris-flow deposits were responsible for the damming of the Indus river; this, however, was later correctly explained as moraine deposits[18–20]. We suggest three wind gaps (marked by *W* in Figure 1) as the possible paleo-exits of the Indus river in the Nimmu valley, that existed prior to the extensive morainic activity in the region. At the interconnection, the modern Indus river traverses into a deep gorgeous valley passage marked *X′–Y′* in Figure 1.

The left bank in the northernmost part of the valley displays enormous moraines due to Late Pleistocene glaciations in the Markha valley region to the west[19]. The ramp-like ridge comprising Ladakh Batholith and its lithotectonic contact with the Indus Formation (at H2 in Figure 1) provide a suitable geomorphic setting for damming and outburst phenomena at the site. Whereas the extensive moraine activity, especially from the Phyang valley (right bank) across the Ladakh batholithic ranges, appears to have dislodged the Indus river to its present position producing the initial damming conditions near H2 (Figures 1 and 2).

Out of the total ~55 m of the exposed thickness of lacustrine facies at the MP site, for detailed documentation we selected lower ~53 m due to better lithologic continuity. The reconstructed litholog (Figure 3) has been divided into several units based on distinct lithofacies, grain size and colour variations. The base of the section comprises ~8 m thick cliff of conglomeratic debris hanging over the valley floor at ~17 m (above the valley base). It comprises matrix-supported conglomerate of fining upward nature and angular clasts of Indus Formation in sharp contact with the basal unit (*U*/1) of the 2.5 m thick varved lake sediment facies (Figure 4 *a*). This is followed by another unit of ~2.5 m thickness of variegated, varved and interbedded lacustrine mudstone (*U*/2, Figures 3 and 4 *b*). Units 3 and 4 are packages of variegated and massive mudstones. Units 8 and 9 show dislocated blocks that contain within them the slumped boulders and related PCDs (Figure 4 *c*). Such features are also visible in some of the overlying units up to U/14 (top of level III in Figure 2 *b*). Unit 15 shows lacustrine facies with slumping features; whereas the overlying unit 16 shows a channel mega-scour (seen in Figure 2 *b*) that also includes enclaves of varved lacustrine blocks (e.g. Figure 4 *d*). This unique mega-scouring is a 7–8 m thick matrix-supported (at places clast-supported) gravelly outflow showing well-imbricated pebbles. This unit does pinch-out both the sides with a sharp crescent shape. The same unit laterally shows a normal/dislocation fault towards the upper side (Figure 5 *a*). The major lacustrine unit that has been scoured by the above unit shows deformation features like thrusting (Figure 5 *b*). The overlying units (18–20)

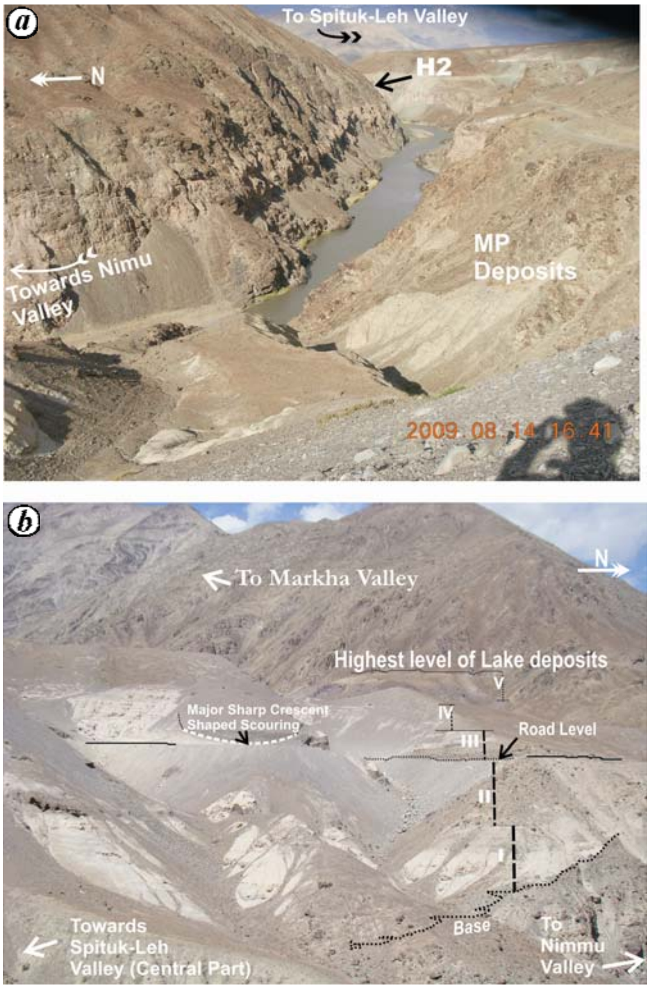

Figure 2. ***a***, Panoramic view from the paleolake site overlooking the Spituk–Leh valley. The location is characteristic of the sharp hairpin bend (H2) with the mountain cliff supposedly acting as natural dam to the Indus in the downstream. Here the valley becomes remarkably narrow from its notably broad appearance in the main valley. ***b***, Panoramic view of the remnant lacustrine basin with the Indus Formation bedrock. The vertical profile lines (marked I–V) are the studied sections separated by the horizontal lines of benchmark levels of the profile exposures. Most conspicuous amongst the features visible from long distance is the sharp crescent-shaped channel scour (described as mega scour in the text).

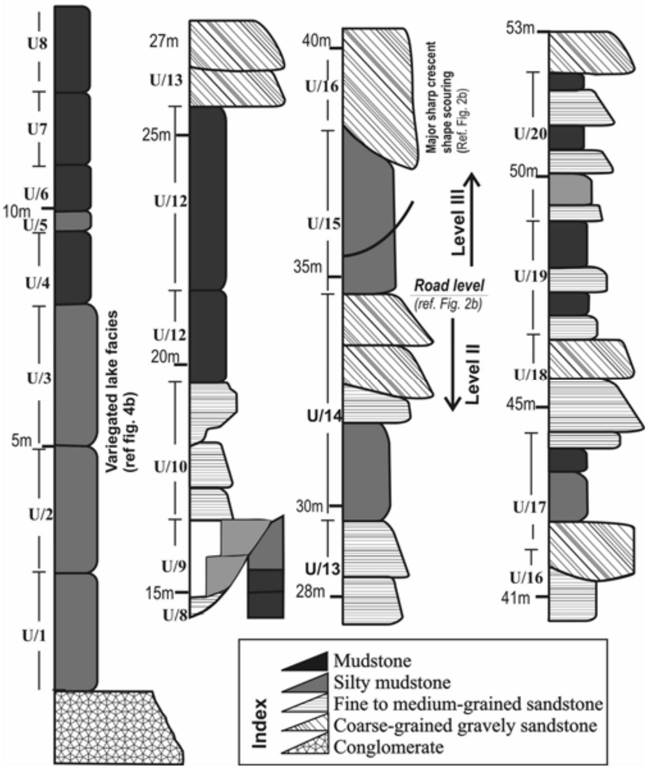

Figure 3. Litholog reconstruction for the studied profiles shown as levels I to IV in Figure 2 *b* (details discussed in text).

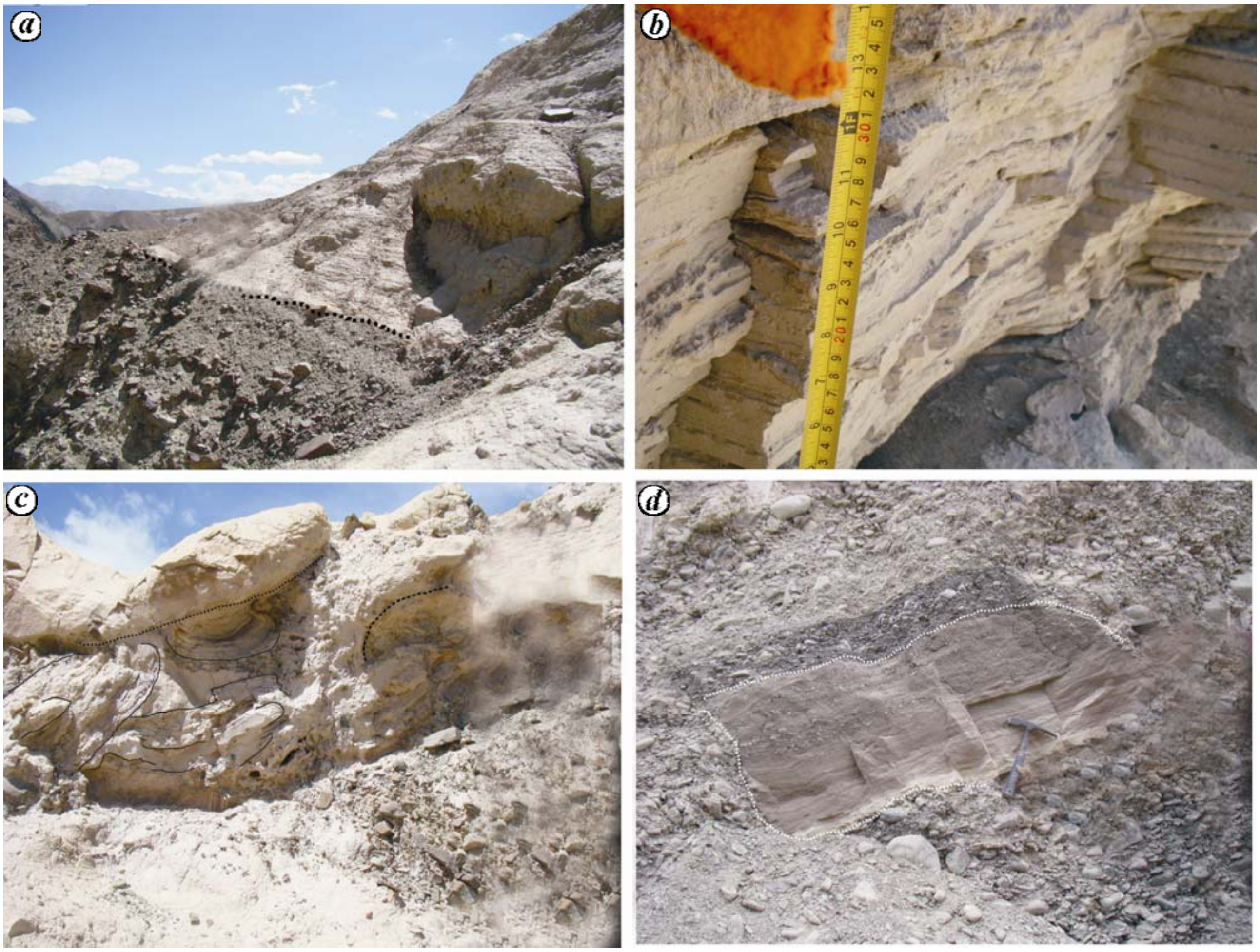

Figure 4. ***a***, Base of the paleolake with angular clasts of unstratified conglomerate with sharp contact to overlying lake facies, ***b***, Variegated lacustrine facies in level I. ***c***, Dynamic gliding and related ductile disruptions occurring in level II. It incorporates slided blocks of the varvites and pebbly layers in a complex setting (described in text). ***d***, An enclaved lacustrine block comprising varvite to pebbly mudstone measuring ~0.6×1.5 m occurring in level III.

show a complex cannibalization and lateral injection of mudstone into the coarse, sandy, gravelly facies (Figure 5 *c* and *d*). Most notable amongst these are the sliding mud blocks and the dikes shown in Figure 6 *a* and *b*.

If restored, broadly the lithofacies indicate varved lake facies in the lower part of level I, followed by massive lacustrine facies in the upper part of level II. Further, there are varved and variegated lacustrine facies with liquefaction in the lower part of level III and thick, gravely phase in the upper part of level III. Overall, level III shows a combination of PCD and its deformation (e.g., Figures 5 *b* and 6 *c*), injection (Figure 5 *c* and *d*), dykes (Figure 6 *b*) and gliding (Figure 6 *a*). Whereas level IV shows majority of the blocks of dry lake beds encased in the gravelly outflow, level V shows interbedded lacustrine and gravelly facies.

The above observations document extra-dynamic interactions between the lacustrine and gravelly facies that is more prominent in level III of the studied profile. If we extend this level southward within the Spituk–Leh valley, it corresponds to major fluvial excursions observed at Spituk and ACP sites. Furthermore, there is a notable onlap of glacial facies over typical fluvial sediments in the left bank located between ACP and MP deposits (Figure 6 *d*). The diamictite with sheet geometry indicates extensive glacial melting in the area more prominently from the western part of the valley. However, the present inference stands to detailed studies on lateral correlation with chronologic order amongst all these events.

The base of the MP deposit shows matrix-supported, unstratified conglomerate in sharp contact with the overlying varved and interbedded lacustrine units (Figure 4 *a*). This suggests a major landslide/debris fall to initiate the lake conditions at the site that might have been triggered either by tectonic or by climatic reasons. Level III shows gravelly outflow with scour base (called here as mega-scour) showing pebble imbrications towards the valley floor (Figure 4 *d*). It also includes enclaved varvite blocks; the one in Figure 4 *d* seems to be part of a dry lake bed collapsed from the upper reaches (lake periphery) producing a rigidity to be transported by the gravely mass flow. Figure 5 *a* further shows a normal faulting in level III

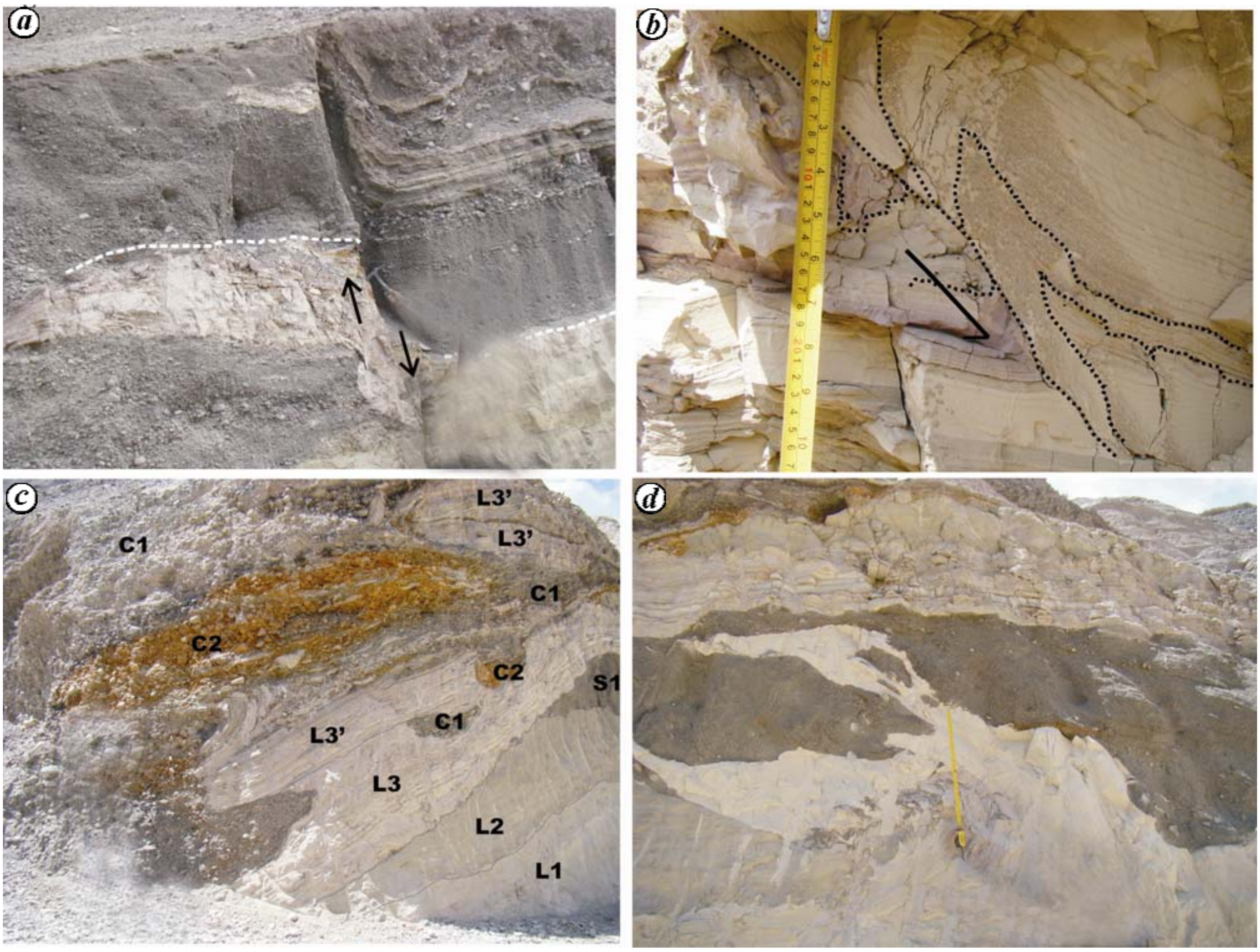

Figure 5. ***a***, A normal fault in level III with a fault slip/throw measuring ~55 cm. ***b***, A thrust fault in level III showing some characters of ductile deformation. ***c***, Dynamic disruption of the lacustrine facies (L1, L2, L3 and L3′) by coarse-grained conglomeratic facies (C1 and C2) related to the breaching event. Note the conglomerate (with rounded clasts) and yellow (limonitic/hematitic) matrix showing its deposition in warm-oxidative conditions. ***d***, Forceful injection of the lacustrine material into the overlying sandy unit.

with fault slip/throw measuring ~55 cm. This probably indicates the readjustment after a major dynamic event. In this level (III), therefore, two stages of deformation can be distinguished as ductile (d1 = PCD, Figures 5 *b*, *d* and 6 *c*) and brittle (d2 = faulting, Figures 5 *b* and 6 *c*) with d1 being the earlier stage.

Figure 5 *c* shows a complex, dynamic disruption of lacustrine facies (L1, L2, L3 and L3′) by the coarse-grained conglomerate facies (C1 and C2). This probably resulted due to the breaching of lake accompanied by scouring and gravity sliding. A conglomerate with rounded clasts and yellow matrix (limonitic/hematitic) marked as C2 suggests its deposition under oxidative environments and could not be explained here. A lacustrine block gliding into coarse-grained, stratified, gravelly outwash material can be seen in Figure 6 *a*. Sharp boundaries and softer sediments cross-cutting the gravelly beds further indicate its derivation from a dry lake bed in the upper reaches, apart from the extra-dynamic nature of the activity. Thus we infer that the upper part of the lake basin was already exposed (and hence dry/indurated) during the event. This is possible due to any of the following reasons: changes in the lake basin hydrologic conditions due to upliftment/tilting, a prevailing dry climate reducing the lake levels, or a detached dried lake. Figure 5 *d* shows a unique liquefaction due to viscous injection as a result of complex lateral compression along with gravity loading and sliding. Figure 6 *c* shows pene-contemporaneous deformation structures confined to the ~1 m unit below the mega-scour showing predominance of lateral compressive forces followed by brittle deformations. Further, Figure 6 *b* shows dyke-like injections disrupting the overlying inter-bedded mud, sand and gravelly bedded sequence in level III. These records thus show a combination of ductile and brittle deformations. The ductile deformations are related to liquefaction both by lateral compression mainly due to the collapse of the lake periphery and gravity sliding towards the valley floor, and by increased overburden (due to gravity loading). The brittle deformations (thrusting and cross-cutting) are mainly related to the dry lake beds and their interaction with the mass flow. The normal faulting

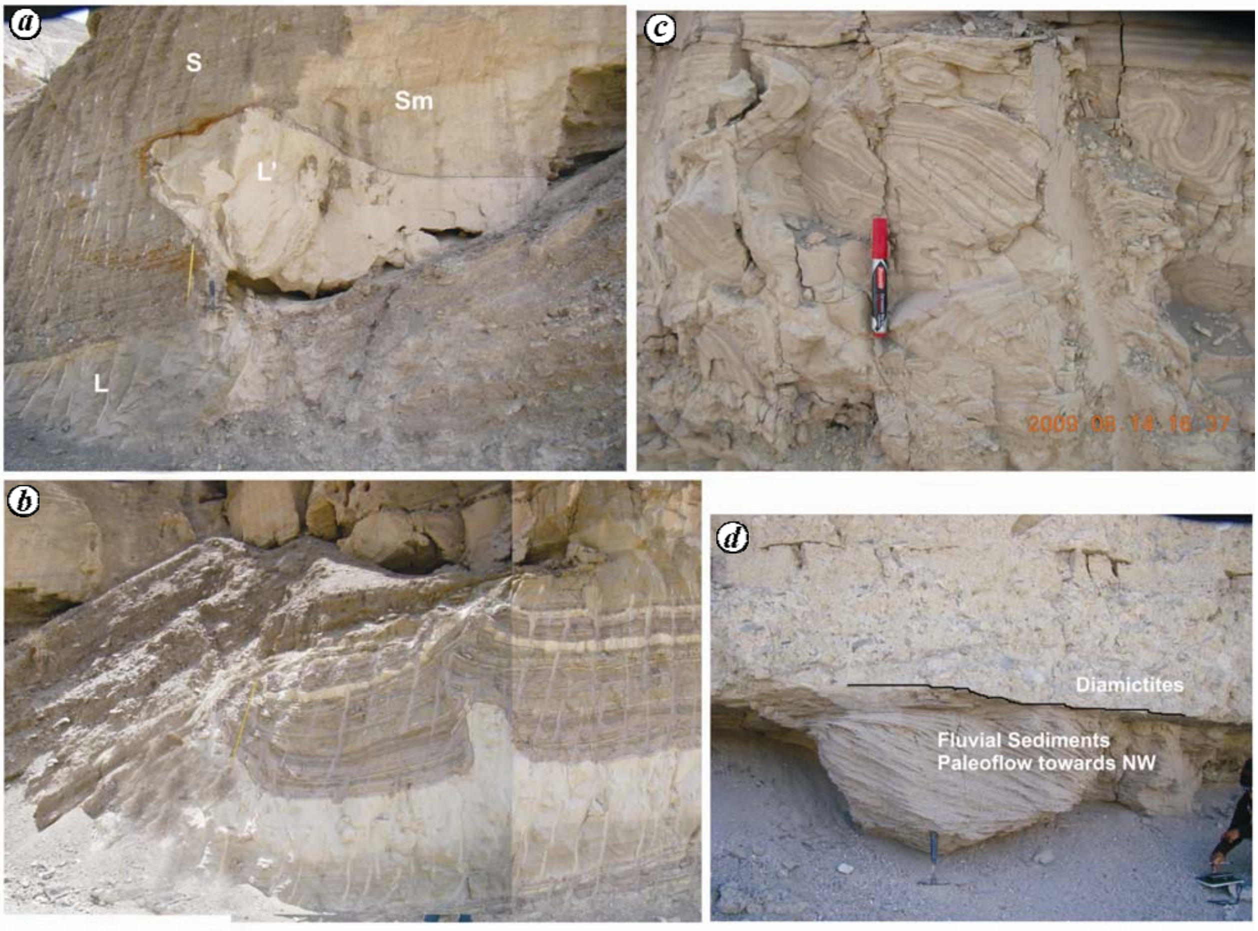

Figure 6. ***a***, Cross-cut relationship of lacustrine facies with coarse-grained stratified glacial outwash material. The sharp boundary and soft sediments cutting the gravelly beds indicate the extra dynamic nature of the activity and presence of dry lake bed (discussed in text). L and L′, Lacustrine facies; S, Sandy (gravelly) facies; Sm, Sandy or gravelly material similar to S but thin (2–3 cm) eroded mud. ***b***, Penecontemporaneous deformations showing lateral compressive nature of the forces. ***c***, Dyke injections into overlying inter-bedded mud disrupting the sand and gravelly bedded sequence at the margin of levels III and IV. ***d***, Trough cross-stratified deposits of Indus river overlain by glacial diamictites indicating dynamic depositional changes recorder at about the same elevation of level III of the MP site (lying immediate upstream).

indicates readjustments (or release of stresses) after the release of major dynamic compression.

The nature of deformation, including majority of slumping, sliding and gliding, mega-scouring, cross-cutting and large-dimension liquefied injections appears unique amongst the liquefactions generally reported as seismites in the Himalayan region[16,21–25]. The present observations therefore suggest that the larger magnitudes and higher intensities of these structures may be related to a larger lake system extensively covering the Spituk–Leh valley, including the Spituk and ACP deposits. Whereas the relatively larger magnitudes of the liquefactions compared to commonly reported seismites (op. cit.) indicate greater time available for the outburst-related deformation structures relative to an earthquake event. We finally attribute these deformation features to be a response to a combination of processes developed by the building up of hydrostatic compression followed by its sudden release and the lateral compression accompanied with sliding due to peripheral collapse. The gravity sliding is accompanied by scouring due to massive outflow and is further followed by readjustments to the available geomorphic conditions (shown by normal faulting) along the valley slopes after the release of the stresses. A more detailed work on the comparison of these structures with seismites is warranted, as also to explain the dynamic processes occurring during such lake-outburst events.

Glacial moraine advancement during Late Pleistocene[19] appears to be the most visible reason for the creation of a lake system by blockade downstream in the Spituk–Leh valley. High lake levels anticipated during the Holocene can result into critical hydrostatic pressures susceptible for breaching of the lake that may occur due to any of the envisaged reasons: (i) seismic activity, (ii) climatic oscillations and (iii) critical hydrostatic conditions resulting from geomorphic inequillibria.

Several paleolake deposits are reported from the Himalayan region, with majority of them supposedly originating from river damming (and impoundment), but no records of breaching/outburst are documented so far from this region. The present record is therefore unique because of prominent and characteristic signatures of the lake outburst with a fairly complete record (in time) that enabled the description of the deformational process and hence the outburst event. Based on field documentation, we have inferred that the characteristic structures developed by a combination of processes amongst build-up and release of stresses due to hydrostatic compression, overburden increase due to gravitational loading accompanied with slide by breaching, and finally the readjustments occurred to achieve the slope stability. These processes have developed the sediment characters that are distinct in magnitude and morphology than 'seismite-like' features described in this region. Furthermore, the present record is a witness to the susceptibility of the Indus river to damming (and outburst) due to distinctive geomorphic conditions available at the present outlet of the Spituk–Leh valley. The unique morphometric setting and the mechanism produced by 'across the valley' moraines makes the site prone to such damming under rapid climatic changes and is probably applicable to majority of the river profile of Indus in the Himalaya.

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