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## Seismically-induced soft-sediment deformational structures around Khalsar in the Shyok Valley, northern Ladakh and eastern Karakoram, India

Rajeev Upadhyay\*

Geodynamics Unit, Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore 560 064, India

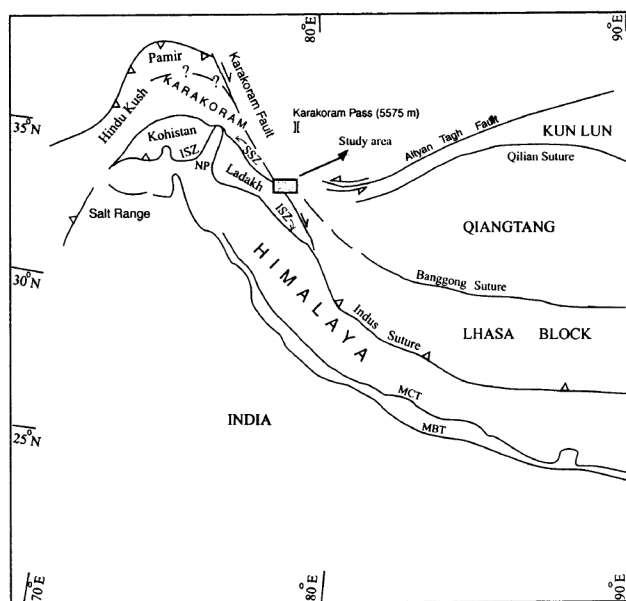
\*Present address: Birbal Sahni Institute of Palaeobotany, 53 University Road, Lucknow 226 007, India

**Soft-sediment deformation structures occur in the ~ 150 m thick Pliocene–Quaternary fluvio-lacustrine sediments exposed around Khalsar and Tirit area in the Shyok Valley, eastern Karakoram, India. Occurring at different stratigraphic horizons, these structures vary in morphology and pattern and satisfy criteria for correlating with seismic events. The deformation structures are thus interpreted as resulting from earthquake-induced liquefaction that happened at ~ 5 Ma and were associated with the tectonic activity along the Karakoram Fault.**

THE various deformation structures attributed to seismic activity include ball-and-pillow<sup>1</sup>, pseudo-nodules or cyc-

loids<sup>2</sup>, pinch-and-swell bedding and lenticular boudins, pocket and pillar structures<sup>3</sup>, flame-like structures<sup>4</sup> and sedimentary dykes. The soft-sediment deformational structures involving escape of pore fluids in fine sediments are linked to seismic shocks<sup>5,6</sup>. These structures play an important role in identifying the distribution and intensity of ancient tectonic activity<sup>7</sup>.

The continued post-collisional convergence of the Indian plate and the Asian landmass causes intense seismicity<sup>8,9</sup> and attendant topographic changes in the Himalaya and the Tibetan Plateau. The 2500-km long east-west trending Himalaya is cut by several major north dipping thrusts, such as the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT)<sup>9</sup> (Figure 1). In the extreme north-west lies the seismically active knot of the Hindukush, the Karakoram and the Pamir (Figure 1). Seismological studies in the Hindukush show that earthquakes of intermediate depth are abundant at depths between 70 and 300 km<sup>10</sup>. The usually high *P*- and *S*-wave velocities observed, indicate that the lithospheric material is being subducted beneath the Hindukush range<sup>10</sup>. While there is some palaeoseismicite-documentation of historic and pre-historic earthquakes in the Himalayan region<sup>11–13</sup>, no such records of pre-historic earthquakes are available from northern Ladakh and eastern Karakoram. Studies carried out in the belt of the Altyn Tagh Fault (Figure 1) by Molnar *et al.*<sup>8</sup>, Peltzer *et al.*<sup>14</sup> and Avouac and Tappanier<sup>15</sup> show that two earthquakes of magnitude 7.2 occurred in 1924 near the western end of the fault and one earthquake of magnitude 6 occurred near its eastern end in 1951 (ref. 16).



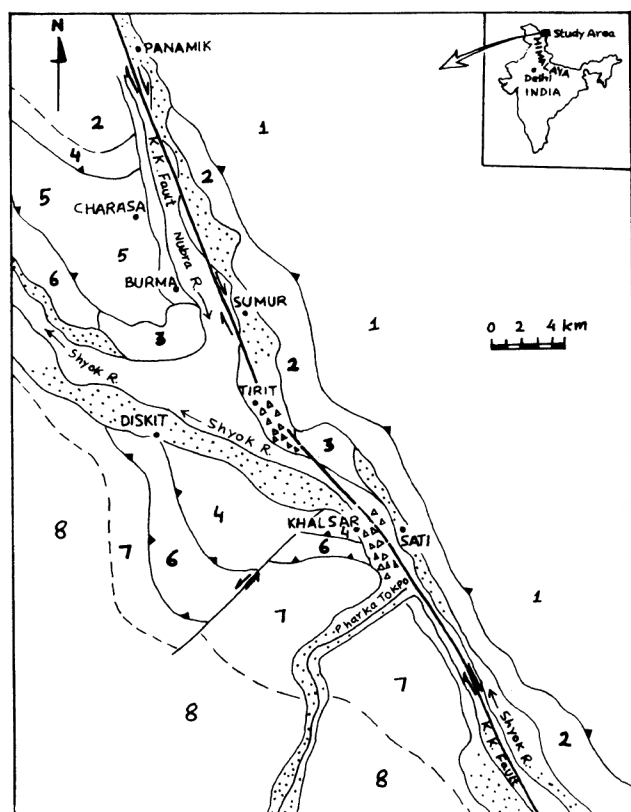
**Figure 1.** Simplified tectonic sketch map of Central Asia (modified after Searle<sup>20</sup>). Shaded box, Study area; SSZ, Shyok Suture Zone; ISZ, Indus Suture Zone; MCT, Main Central Thrust; MBT, Main Boundary Thrust; NP, Nanga Parbat.

The present study deals with soft-sediment deformational structures, identified in several horizons of ~ 150 m thick Plio-Quaternary fluvio-lacustrine sediment exposed around Khalsar and Tirit in the lower reaches of the Shyok Valley in northern Ladakh and eastern Karakoram (Figures 2 and 3 *a*). These features represent palaeoseismic events along the active Karakoram fault – that extends north-west from eastern Karakoram to Central Asian region.

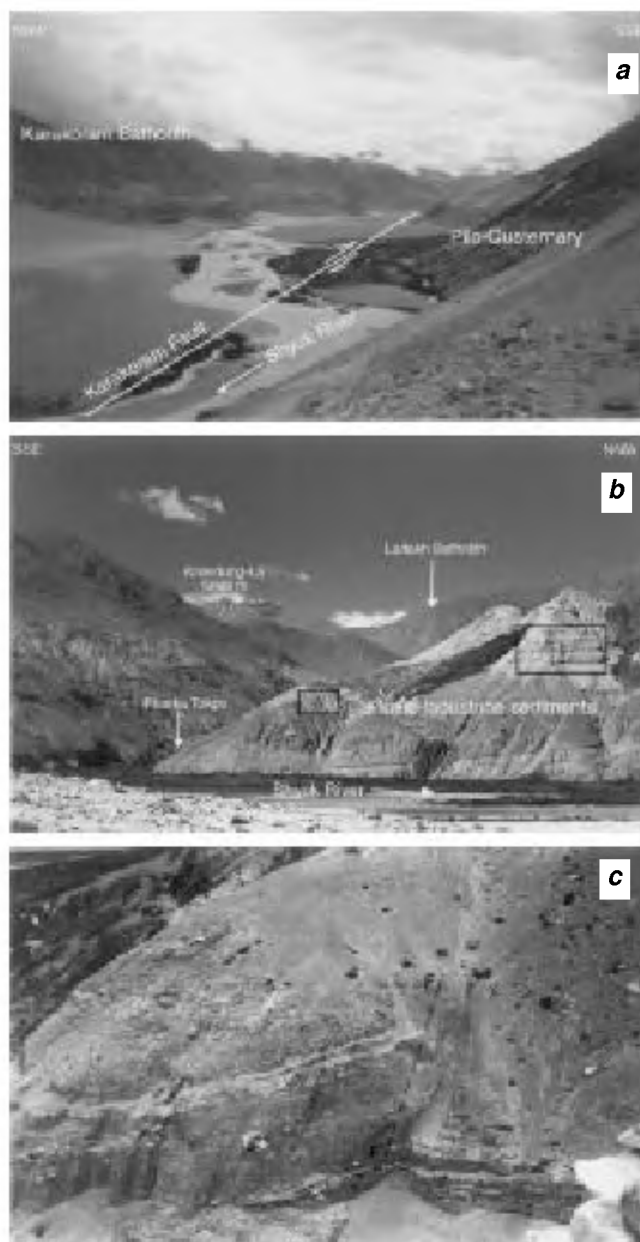
The study area in the lower Shyok Valley is located between the Ladakh Batholith in the south-west and the Karakoram Batholith in the north-east (Figures 2 and 3 *a, b*), the former lying intermediate between the Indian plate and the Asian plate. In the west, it is separated from the Kohistan Complex by the Nanga Parbat–Haramosh massif and in the east the Karakoram Fault separates it from the Lhasa Block (Figures 1 and 2). The Ladakh Block is bounded by the Indus and Shyok sutures (Figure 1).

The rocks of the NW-SE trending Shyok Suture Zone in the Nubra–Shyok valleys (Figures 1 and 2), occur as intensely-deformed tectonic slices of sedimentary, metamorphic and magmatic rocks, interpreted as the remnants of an accretionary complex<sup>17,18</sup>. Interpretation of satellite

photographs and field mapping in northern Ladakh, Pakistan, Karakoram, Nubra–Siachen area and Pamirs<sup>19</sup> showed that the Karakoram Fault that passes through the study area is extremely active (Figures 1 and 2), the right-lateral offset amounting to less than 120 km<sup>19</sup>. The Bang-gong Suture Zone, which correlated to the Shyok Suture, has a dextral offset of 85 km. The course of the Indus



**Figure 2.** Geological map of the Nubra-lower Shyok river valleys showing location of the villages of Khalsar, Tirit and Charasa, where soft-sediment deformation structures have been recorded. 1. Karakoram Batholith; 2. Ophiolitic Melange; 3. Tirit Granitoids; 4. Shyok Volcanics; 5. Saltoro Molasse; 6. Saltoro Formation; 7. Khardung Formation; 8. Ladakh Batholith; Small dots, Alluvium; Small triangles, Plio-Quaternary (modified after Upadhyay *et al*<sup>17</sup>).



**Figure 3.** *a*, Panoramic view of lower Shyok Valley near Khalsar showing the location of Plio-Quaternary fluvio-lacustrine sediments, Karakoram Batholith and Karakoram Fault. Near Khalsar (location in Figure 2) the Shyok follows Karakoram Fault; *b*, Plio-Quaternary fluvio-lacustrine sediments that show the seismically-induced soft-sediment deformational structures at Khalsar. Box (a) is the location of Figure 3 *c*. Structures depicted in Figures 4 and 5 *a* occur in box (b); *c*, Medium-to coarse-grained sand and conglomerate layers showing ~ 4 m dislocation of a layer by faulting, along the Karakoram Fault. Photograph represents enlarged view of box (a) in Figure 3 *b*.

river, has been dextrally offset by 120 km south of Pangong lake<sup>19</sup>, along the Karakoram Fault.

The soft-sediment deformation structures are seen at Khalsar and Tirit in the lower Shyok Valley (Figures 2 and 3 *a, b*), where the ~150 m thick Plio-Quaternary sedimentary succession includes fluvio-lacustrine deposits.

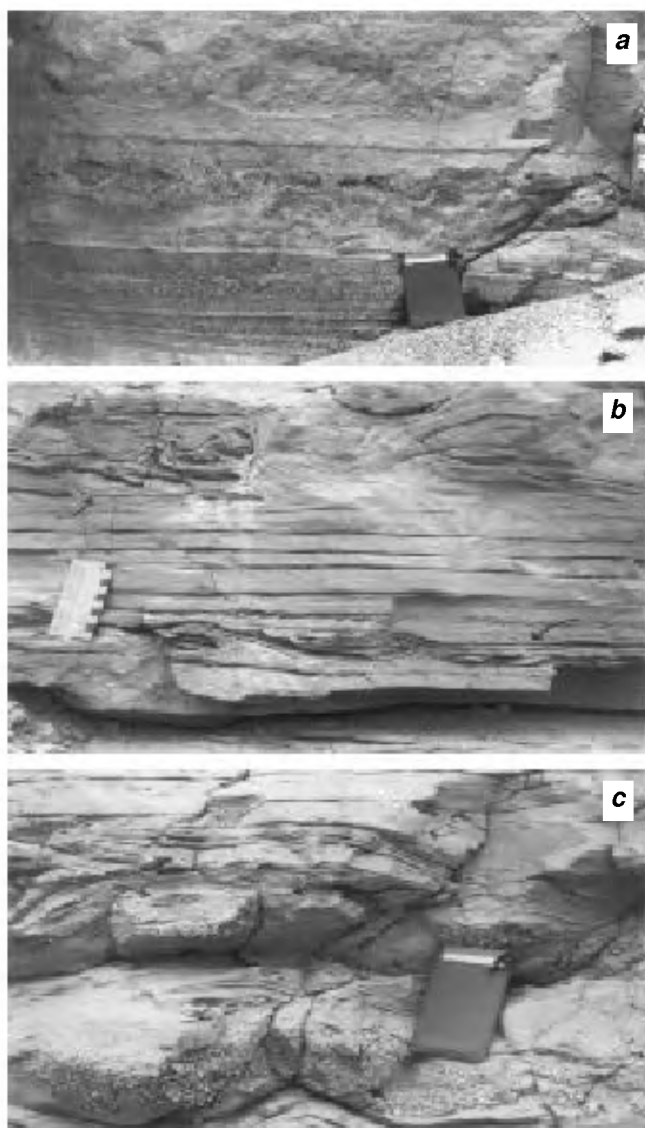
Near the village of Khalsar, ~150 m thick Pliocene-Quaternary fluvio-lacustrine sediments are exposed along the left bank of the Shyok river (Figures 2–4). Similarly, near the village of Tirit, ~20 m thick sediments are exposed along the right bank of the Shyok river (Figures 2 and 5 *b*). They are composed of thinly-bedded clay and silt and fine-to medium-grained sand, conglomerates and breccias (Figures 3 *b* and 5). Soft-sediment deformation

structures are found in several well-defined horizons that are laterally continuous for several tens of metres (Figures 3 *b*, 4 and 5). The horizons are flat-lying, separated by undeformed sediments, and vary in thickness from 5 to 100 cm; they show sharp and planar top and bottom contacts (Figure 3 *b*, 4 and 5).

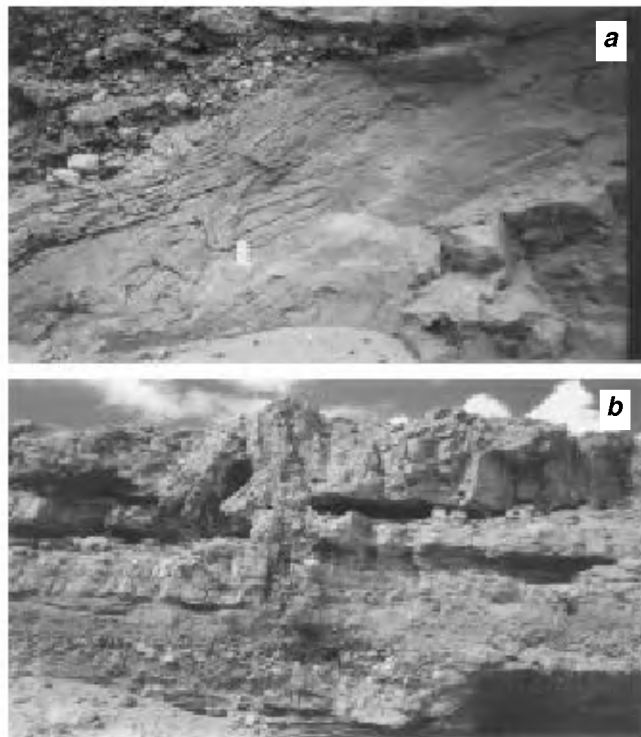
Many types of deformation are seen, including both discrete and chaotic units that contain ‘cycloids’ (pseudonodules), flame-like structures, flame convolutions, sand dyke injections, bed dislocation/faulting, flowage folds and other complicated soft-sediment deformational structures (Figures 3 *b, c*, 4 and 5).

Figure 3 *c* is an enlarged view of the inset (box (a)) in Figure 3 *b*. Here one can observe that the partially lithified sediments are made up of medium-to coarse-grained sand and conglomerate layers. We observed ~4 m vertical displacement of medium grained sandy layers along a fault (Figure 3 *c*). We do not know the sense of movement, but we suspect a neotectonically active transversal movement because the fault is very steep.

In fine- and medium-grained siliciclastic sediments, we find bedding parallel deformed layers (Figure 4 *a–c*). In Figure 4 *a* and *b*, it can be seen that in the fine, medium- and coarse-grained sandstone the laminae are unbroken above and below of the deformed horizon. In Figure 4 *a*, the deformation structures are similar to flamed convolu-



**Figure 4.** *a*, Convolution flame structure in a horizon shown in box (b) in Figure 3 *b*. Scale: 10 cm; *b*, Intrusion of mud-silt material forming flame-like structures and pseudo-nodules (cycloids). Location: box (b) in Figure 3 *b*. Note two deformed horizons lying between undeformed layers at an interval of ~20 cm. Scale: 10 cm; *c*, Recumbent fold and pseudo-nodules. Location: box (b) in Figure 3 *b*. Scale: 10 cm.



**Figure 5.** *a*, Plastically-folded layer and associated soft-sediment deformation near Khalsar. Location: box (b) in Figure 3 *b*. Scale: 10 cm; *b*, Clastic dyke intrudes into a 20 m thick horizon of mudstone, sandstone and conglomerate. Right bank of Shyok river, near Tirit (Figure 2).

tion. Similarly, the deformation of the strata into complex flame-like recumbent folds with pseudo-nodules (cycloids) are clearly observed in Figure 4 *b*. The depositional laminae in Figure 4 *c* are deformed locally into recumbent folds and disappear laterally, whereas above and below the deformed horizon, the laminae are unbroken (Figure 4). In a fine-to medium-grained sandstone horizon, we also observed plastically-folded layers and associated soft-sediment deformation structures (Figure 5 *a*). The flame structures and recumbent folds in Figures 4 *a*, *b* and 5 *a* do not show same vergence. Similarly, the deformation horizons are flat-lying and separated by undeformed layers (Figures 3 *b*, 4 and 5 *b*); therefore the possibility of a palaeoslope for the formation of these structures is ruled out. This indicates that the resultant force for producing such structures must be a high magnitude seismic shock.

Near the village of Tirit we observed ~ 20 m flat-lying horizon of mudstone, sandstone, conglomerate and breccia. This horizon is cut by a clastic dyke which is also composed of mud, sand and conglomerate (Figure 5 *b*). The dyke is emplaced upward as seen in Figure 5 *b*, which suggests earthquake-induced liquefaction. The presence of this clastic dyke, therefore, is a strong evidence for seismically-induced soft-sediment deformation structures.

Interestingly, near the village of Charasa (Figure 2), there exists severely ruptured ground in the vicinity of Karakoram Fault. The NNW-SSE trending rupturing is parallel to the regional trend of the Karakoram Fault, which indicates the active nature of this fault. Additionally, along the floodplains of the Indus and the Gar rivers in eastern Ladakh and western Tibet, the NW striking, steeply NE dipping Karakoram Fault follows the foot of the Ladakh Range Front<sup>21</sup>. Cumulative height of the scarps, tens of metres in the Late Pleistocene moraines, the 2 km high triangular facets, and the perched of the order of glacial valleys attest to rapid vertical throw on the fault<sup>21</sup>. Dextral offsets of 300–400 m of post-glacial fans and channels imply a Holocene, the slip rate being of the order of 3 cm/yr<sup>22</sup>.

There are several trigger mechanisms which may be considered for deformation in soft sediments. These are rapid deposition of sand<sup>23</sup>, earthquakes<sup>6</sup>, gravity-driven density currents and storm currents<sup>24</sup>. It is generally believed that deformation horizons can form by the liquefaction of underlying clayey silt and its subsequent loss of load-bearing capacity in response to the passage of a seismic wave<sup>3,5</sup>; or as a result of loading consolidation which leads to increased pore fluid pressures that exceed shear strength, especially after the rapid deposition of sand onto mud of high water content<sup>24,25</sup>; or from pressure changes or pore fluid pressure changes caused by the passage of storm waves/currents or the arrival of gravity-driven density currents<sup>24,26</sup>.

In Figure 3 *b* it is clearly seen that the deformed horizons are lying higher up in the section; therefore the phenomenon of loading is ruled out. The debris-flow

deposition is restricted in parts as seen in Figure 5 *b* around the village of Tirit which is otherwise dominated by a thick succession of sand, silt and mud deposited in relatively still-water conditions.

Since the deformation horizons are flat lying and separated by undeformed layers (Figures 3 *b*, 4 and 5 *b*), therefore the possibility of slumping, as a result of slope failure, on a palaeoslope is ruled out. Therefore the soft-sediment deformational structures around Khalsar and Tirit in the lower Shyok Valley satisfy the notion spelled out by Sims<sup>6</sup> for correlating them with seismic events because: (1) they occur in seismically-active Karakoram strike-slip fault zone (Figures 1–3); (2) they are restricted to individual stratigraphical layers separated by undeformed beds, but extend over a large area (Figures 3 *b*, 4 and 5); (3) the layers are flat-lying (Figures 3 *b*, 4 and 5).

It is therefore concluded that the deformational features at Khalsar and Tirit were formed by the effects of the passage of seismic waves. This interpretation is further supported by the existence of severely ruptured ground in and around Charasa (Figure 2). According to Sims<sup>6</sup>, each deformation horizon records an earthquake intensity of magnitude 6 or greater. According to Searle<sup>19</sup>, the initiation of movement along the Karakoram Fault is ~ 5 or 4 Ma and is related to the Pliocene–Quaternary northward indentation of the Pamir. We may therefore relate the soft-sediment deformation along the Karakoram Fault to pre-historic seismic events occurring during this time interval. A detailed chronology of the seismically-induced structures would provide additional information on the seismic events in the tectonically-active Karakoram area.

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