



Earthquake-induced deformation structures along Trans-Yamuna active fault system: Doon Valley, NW Himalaya

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Due to continued continental convergence of Indian–Eurasian plates, the Himalayan region witnessed several high-magnitude earthquakes and is prone to major seismic events in future as well. Most of the countries with seismically active faults examine paleo seismic data in site specific as well as regional seismic hazard analyses. Hence, it is of great concern to find evidence for prehistoric earthquakes following the morphotectonic route and establish the recurrence intervals of potential earthquakes by characterising and dating large prehistoric events. The present study discusses the paleo seismicity and induced deformational features in the Trans-Yamuna region of the outer Northwest Himalaya by interpreting soft sediment deformation and paleo-liquefaction features. We targeted two sites along the Trans-Yamuna active fault system, which are located in the Sirmurital and Bharli villages; both of these locations are close to Doon Valley along the Main Boundary Thrust. Temporal distribution of paleo-liquefaction features evident major seismic events likely to occur during 16th and 19th centuries, which clearly indicates reactivation of faults in this hinterland region that could experience major rupture during the recurrence of large magnitude earthquake and therefore, constructional activities are a matter of great concern to design structures accordingly.

Keywords. Active tectonics; Trans-Yamuna active fault system; seismic hazard assessment; seismites.

1. Introduction

Himalaya is one of the most seismically active and youngest folded mountains amongst global continental collisions. It was formed by the Indian and Eurasian plate convergence during the Late Cretaceous to Early Paleogene time period. It demarcates the northern boundary of the Indian Plate and forms a barrier between the Tibetan Plateau from the north and the alluvial plains of the Indian subcontinents to the south. The convergence

continued over the time period, resulting the décollement zone beneath northwestern Himalayan part provides adequately large and coherent fault system mainly Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT) from North to South, respectively. This Himalayan south verging thrust system is attached with root thrust, which is namely Main Himalayan Thrust. The convergence rate along the Himalayan arc varies from 12 to 21 mm/a, forming a long lateral zone extending over

2500 km accommodated crustal deformation and formed numerous thrusts along the stretch (Gansser 1964; Seeber and Armbruster 1981; Tapponnier 1982; Lyon-Caen and Molnar 1985; Styron *et al.* 2010). Numerous geodetic studies published the high convergence rates across northwest Himalaya ranging from 13.6 ± 1 to 14 ± 1 mm/year (Banerjee and Burgmann 2002; Kundu *et al.* 2014) and range between 17.8 ± 0.5 and 20.5 ± 1 mm/year across Nepal Himalaya indicates high seismic activity in the region. The Eurasian plate thrusts over the Indian Plate and locked the MHT, causing varied deformation rates along the plate boundary region. The principal Himalayan thrusts MCT, MBT and HFT regulate stress accumulation and deformation process in which most of the crustal accommodation takes place along HFT (Gautam *et al.* 2017; Rawat *et al.* 2019). As a result, the HFT offer wide attention among researchers across the world and has been significantly studied in the Asian region (Wesnousky *et al.* 1999; Kumar *et al.* 2001, 2006; Lavé *et al.* 2005; Kumahara and Jayangondaperumal 2013; Sapkota *et al.* 2013; Bollinger *et al.* 2014; Hetenyi *et al.* 2016; Le Roux-Mallouf *et al.* 2016; Jayangondaperumal *et al.* 2017). However, from the limited available data previous workers suggests that the less explored hinterland region could be considered a potential segment for researchers to study and understand the slip accommodation consumed by developing small scale out-of-sequence thrusts and imbricate faults. There are only a few researchers studying potential seismic zones in the hinterland zone, especially Trans-Yamuna region (Oatney 1998; Philip and Sah 1999; Oatney *et al.* 2001).

To carry forward the previous work, our study is heading towards identifying and mapping active faults using different techniques such as analysis of satellite imageries, morphotectonic signatures, paleoseismic traces, carbon dating and geophysical surveys. Active faults are important to study as they are evidence of movement due to slip accommodation in the recent geological past and these movements are correlated with the historical seismicity of the region. An active fault can be defined as a fault that slipped during the late Quaternary and is likely to be displaced in the future, which can cause seismic and other natural hazards (Malik *et al.* 2010). Motivation to study active faults in Himalayan region is that several scientific studies suggested that generally, earthquake events have been reported with the proximity of active faults or many major earthquakes have been found close to active faults

and the most spectacular morphogenic examples of Indian earthquakes are 1505 Kumaon–Nepal ($M 8.7$), 1803 Kumaon ($M 7.5$), 1819 Kutch ($M 7.8$), 1883 Nepal ($M 7.7$), 1897 Shillong ($M 8.7$), 1905 Kangra ($M 7.8$), 1934 Bihar–Nepal ($M 8.4$), 1950 Assam ($M 8.7$), 1991 Uttarkashi ($M 6.8$); 1999 Chamoli earthquake ($M 6.7$), 2001 Kutch earthquake ($M 7.6$), 2005 Muzaffarabad ($M 7.6$), and 2015 Gorkha ($M 7.8$) events (Oldham 1897; Pande and Kayal 2003; Jayangondaperumal *et al.* 2017; Arora *et al.* 2019; Malik *et al.* 2023). The purpose of this study is to assess seismic hazard in the Trans-Yamuna region by carrying out active fault mapping to determine historical earthquake events and their proximity with the active faults by principally using paleoseismic methods incorporating Carbon-14 dating (charcoal samples) to determine the correlation with historical earthquake events which are not being recorded instrumentally. Usually, historical records of great earthquakes ($M > 6.5$) are available because small and moderate earthquakes can rarely be preserved near the surface (McCalpin and Nelson 1996).

2. Geological set-up of the study area

The study area lies between the Kangra recess in the west and the Nahan salient in the east. The soft sediment deformation structures (here interpreted as the seismites) are located in two sites. One site is along the Bharli Fault near north of the Main Boundary Thrust (MBT) and another site at the eastern extremity in west bank of the Sirmurital Fault joining the Giri River (figure 1). The area is traversed by the MBT (Krol Thrust) and the Nahan Thrust. The north-dipping MBT separates the Lesser Himalayan Pre-Cambrian Chandpur phyllites (forming the hanging wall block) from the carbonate rocks of the Krol Group and/or the Nagthat quartzite. Near the basal part of the hanging wall block, the slate-phyllite sequence with thick quartz veins (up to ~ 1 m) suffers from brittle deformation. The Nahan Thrust or the Main Boundary Fault (MBF) delimits the Paleogene Dagshai rocks from the Neogene Lower Siwalik rocks of the sub-Himalaya. Along the Nahan Thrust, the pulverized limestone and sandstone beds show outcrop-scale pinch and swell structures. The generalized stratigraphic succession with lithology is given in table 1. A number of elongated sag ponds, filled with the Quaternaries, have formed along the deeper portion of the lineament.

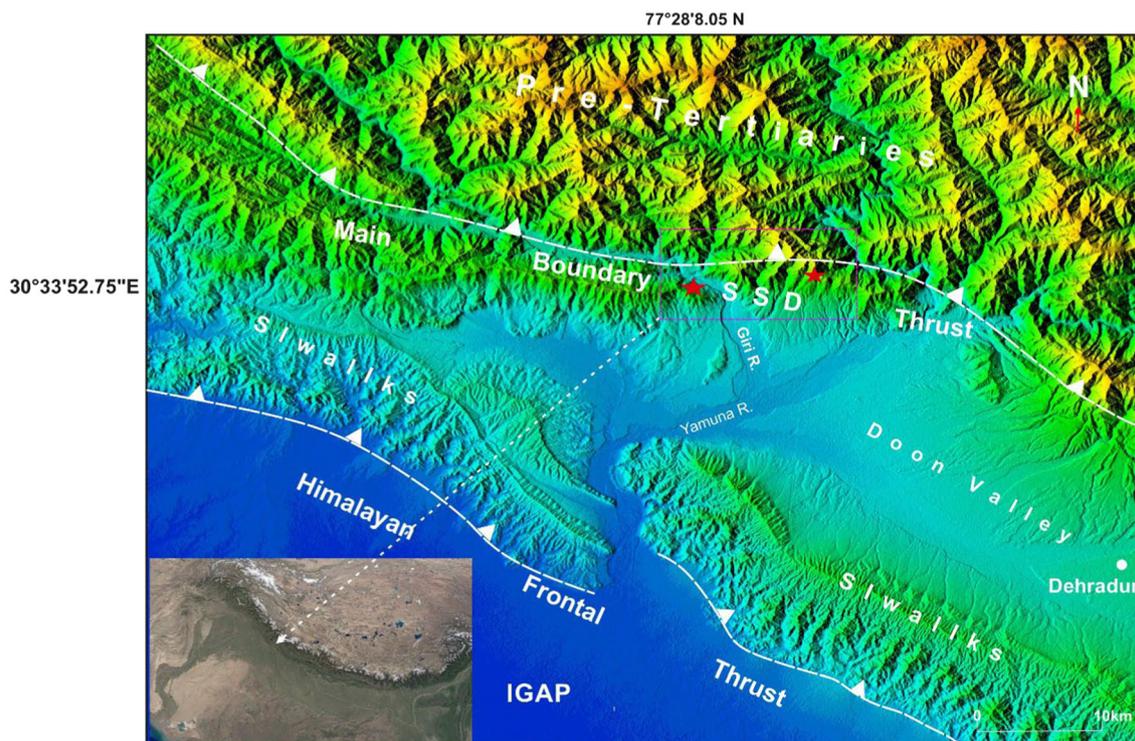


Figure 1. Regional location map of the study area (SRTM image) showing major thrusts and faults in the NW segment of Doon Valley. The area within the box is the TYAF region with highlighted STF and BAF sites.

Table 1. The generalized stratigraphic succession of the study area (Valdiya 1984; Sharma et al. 2020) and present work.

Age	Group/Formation	Lithology
Pleistocene–Holocene	Doon gravels	Alluvial fan deposits and river terraces with boulders
Pliocene	Up Siwalik Formation	Conglomerates with sandstone, clay and siltstone interbeds
Miocene	Mid Siwalik Formation	Sandstone with minor claystone, some beds of conglomerates
	Lr Siwalik Formation	Sandstone-claystone alterations with minor siltstone and pebbles
Oligocene	Kasauli Formation (Up Murree/Dharamsala)	Green and grey sandstones with minor claystones
	Dagshai Formation (Lr Murree, Dharamsala)	Purple clay and siltstone sequence with minor sandstone
	Subathu Formation	Olive green nummulitic shales, minor limestones and sandstones
Pre-Cambrian to Cambrian	Krol Group (Blaini, Infra-Krol, Krol, Tal formations)	Limestone, siltstone, shale, carbonaceous shales and conglomerates, slates, marl, rhythmites, quartzite
	Jaunsar/Shimla Goup (Nagthat, Chandpur, Mandhali formations)	Argillaceous and arenaceous rocks with quartzite, phyllite, slate, greswacke, marble
	Shali Group (Tejam/Deoban Formation)	Limestone and slate with cherty and argillaceous bands

Note. Lr: Lower, Up: Upper, Gp: Group, Mid: Middle.

The E–W trending Sirmurital–Dhamaun–Bharli (SDB) Fault, forming a part of the Trans-Yamuna Active Fault System of Oatney (1998), is an active

lineament, which is clearly seen in the satellite imagery. Along the fault, the southern side has gone up as compared to the downthrown northern

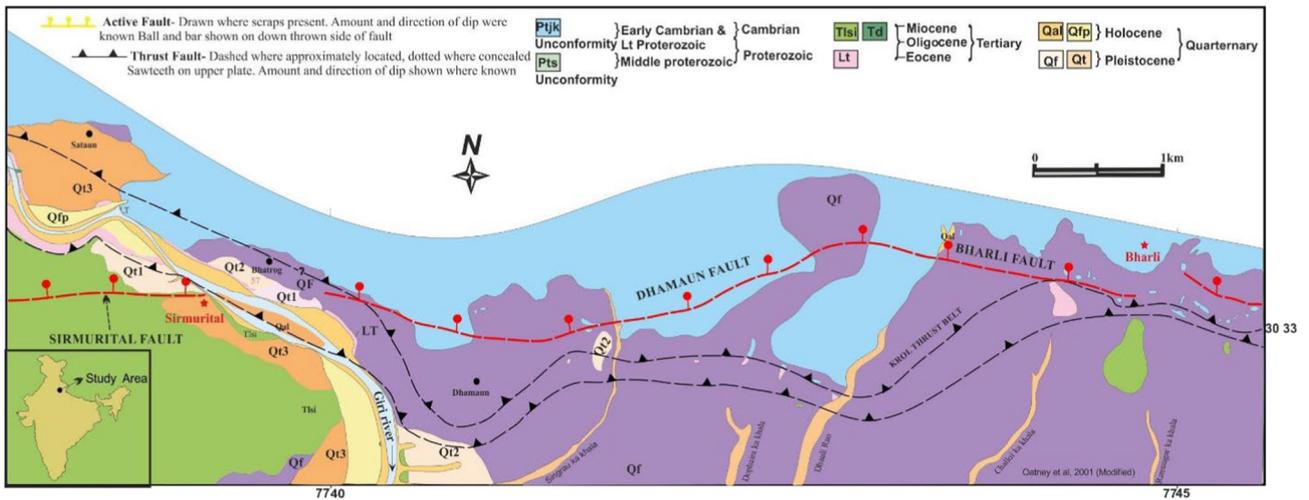


Figure 2. Geological map of the Trans-Yamuna region with SDB, fluvial terraces and litho-tectonic units. Map modified after (Oatney *et al.* 2001).



Figure 3. Satellite image showing the sag pond close to the Bharli fault. F and F' sharp lineament marks the Bharli fault, including a close-up of the sag pond field photograph.

side. The seismites have been observed in these Quaternary deposits (see the geological map, figure 2).

The Sirmurital Fault (with a 20-m high scarp, Oatney 1998) traverses through the Lower Siwalik sandstone beds, including the Quaternary alluvial terraces deposited by the Giri River. Thus, this fault is syn-to-post Pleistocene–Holocene. Developing about 3–7 m high fault scarps with left-lateral offset of a stream (Oatney 1998), the influence of strike-slip fault is interpreted along the Bharli Fault (figure 3). Along the fault, the Chandpur slate-phyllite sequence is deformed with the

development of brittle open fractures and extensional bedding-parallel shears.

3. Paleoseismic studies

Paleoseismology is the study of pre-historic seismic events through the evaluation of geological traces developed during particular past earthquakes (Solonenko 1973; Wallace 1981). Paleoseismic studies have a strong societal importance to assess the recurrence of future potential earthquakes (Kumahara and Jayangondaperumal 2013).

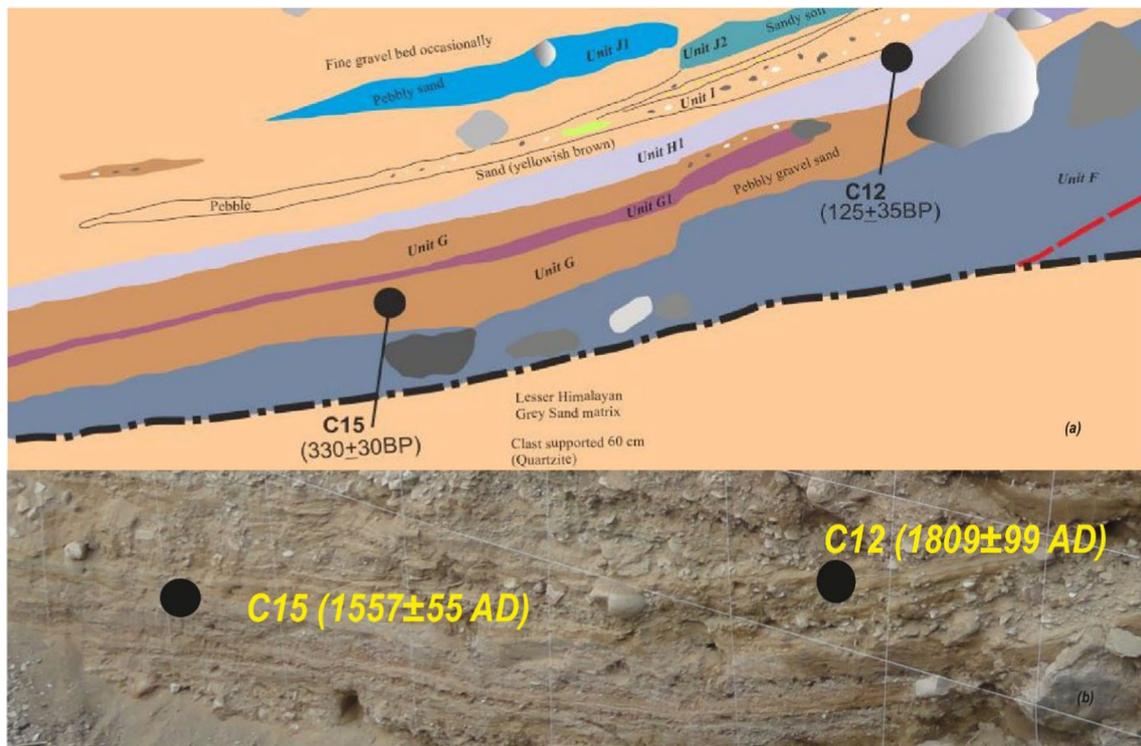


Figure 4. (a) Digitized cross-section of Sirmuri Tal site preserved SSD structures along STF, located on the west side of the Giri River. (b) The black dots on the log indicate collected organic (charcoal) sample spots, which are incorporated with analysed Carbon-14 dates.

Paleoseismologists focus on studying only those earthquakes that produce considerable surface deformation or landforms, which are termed as morphogenic earthquakes (Caputo 1993). Based on remotely analysed satellite data, the TYAF system cuts the Quaternary deposits of late Holocene epoch (Oatney *et al.* 2001; Arora *et al.* 2019). Recently, GPR surveys (Saikia 2015) were also conducted in the south of the Bharli village for confirmation of the fault, and the findings are that the dip direction of the fault is in the north, which reveals that it may be a high-angle reverse fault along with the presence of a strike-slip component. Following previous work, we attempted to study the TYAF system to assess the potential seismic hazard in the region in which we mainly emphasised the Sirmurital and Bharli sites. In the present study, deformation patterns at the sub-surface level are being observed around Sirmurital and Bharli villages. Both of these sites are part of the Trans Yamuna active fault system, which is parallel to the MBT and lies in the outer Doon valley in the northwest Himalayas. Evidence of paleo-earthquakes in the form of small-scale soft sediment deformation (SSD) features and paleo-liquefaction features have been observed in the fluvio-lacustrine deposits along the trans-Yamuna

region. We assessed the output of the study with the support of carbon-14 dating of organic (charcoal) samples from the sites (figure 4).

4. Soft sediment deformation features along Sirmuri Tal Fault

The deformation features from Sirmuri Tal village have been empirically examined from the exposed fluvio-lacustrine sediments at a depth of ~2 m from the surface. These sediments are composed of mud, sand, and variable sizes of clasts with alternating deformed and undeformed beds. Based on the characteristics of observed paleoseismic-induced features, the STF cross-section laterally extends ~4 m. It has been broadly divided into five layers such as A, B, C, D and E from top to bottom, respectively (figure 5). The topmost layer, A, is undeformed and comprises unsorted clasts with varying sizes. Layer B, composed of sandy and clayey mud, shows well-preserved deformed structures at ~3 m range. Layer B has been classified broadly into three sub-sections further for detailed analysis of the deformation structures close-ups of soft sediment deformation (SSD) structures are as flame structures (Z10), clastic dykes, fissure fills

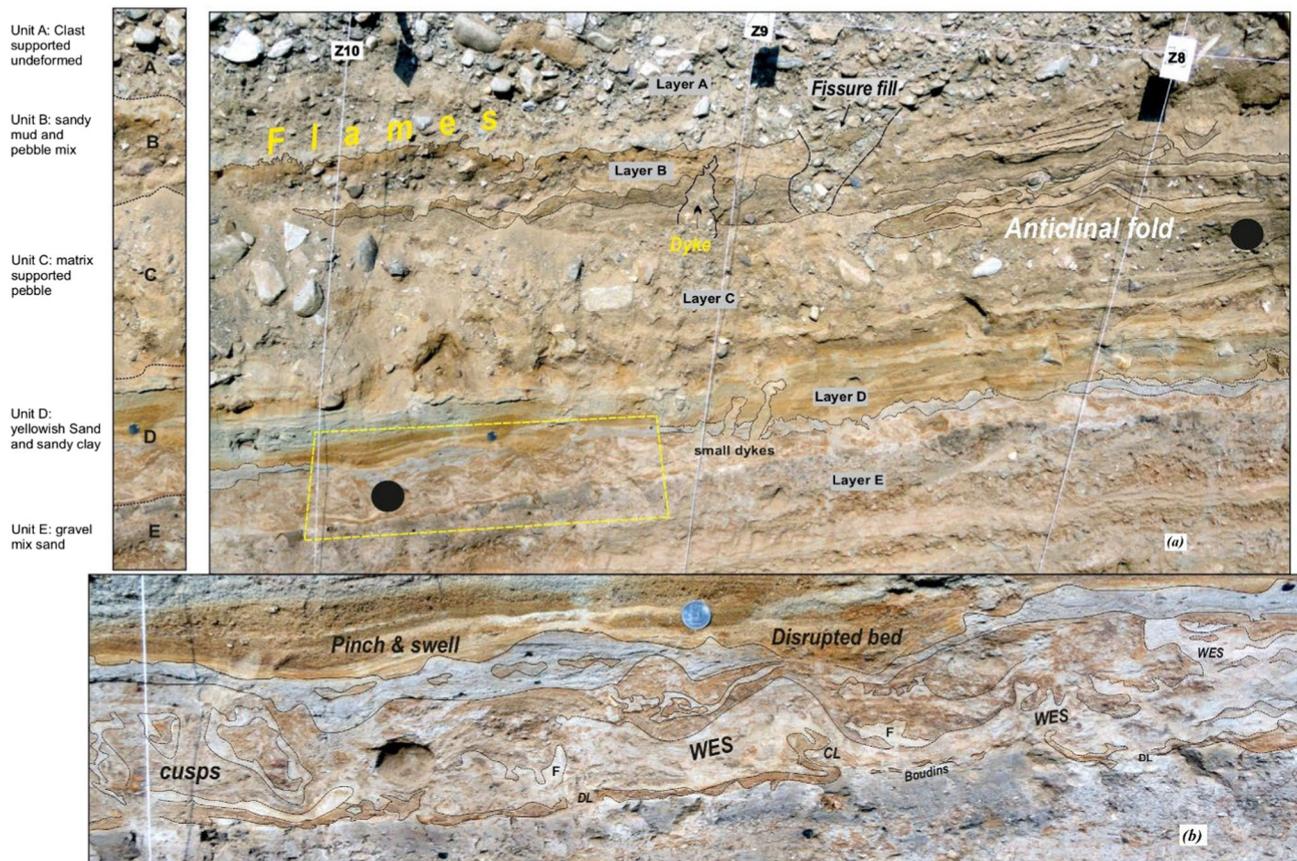


Figure 5. (a) Photograph displays identified SSD structure along Sirmuri Tal fault, including litho-section marked in layers E to A from bottom to top, layer C highlight the spot of dated charcoal sample C12 as 1809 ± 99 years AD. (b) This is a close-up of layer D displayed spectacular preserved SSD structures, including organic sample C15 spot dated as 1557 ± 55 years AD.

(Z9) and complex antiformal structures (Z8). Layer C is prominently undeformed and matrix (sand) supported. The deformed layer D has been carbon dated 1557 ± 55 AD; this layer is prominently composed of medium- to fine-grained sediments with a rare presence of boulder size clasts. The layer depicts well-preserved features in a horizontal range of ~ 1.5 m for pinch swell, sand dykes and continuous convoluted and disrupted lamination for $\sim 6-7$ m and the bottom-most undeformed layer E is composed of gravel mix sand (figure 4).

4.1 Sirmuri Tal (layer A)

In figure 5, the Sirmuri Tal cross-section in which layer A is lithologically composed of variable shapes and sizes of pebbles are shown. Pebbles are crushed at approximately 3 m in range laterally. Though it is undeformed, due to pebbly composition, no significant paleo-liquefaction structures have been observed from this layer.

4.2 Sirmuri Tal (layer B)

Layer B is composed of sandy and clayey mud. This layer includes some well-preserved deformed structures in the ~ 3 m range (figure 5).

4.2.1 Water escape structures (WES)

The deposited sediments are observed from the fluvio-lacustrine depositional settings near the Giri River at Sirmuri Tal village. In this saturated layer, trapped water in the pore spaces becomes over-pressured due to shaking, and the space created in the overlying layer allows fluid to be released at high velocity in an upward direction (Reineck and Singh 1973; Lowe 1975).

4.2.2 Flame structures

Flame structures are intense characteristics of ground-shaking phenomena during earthquakes. In this litho-section, saturated sands are squeezed out

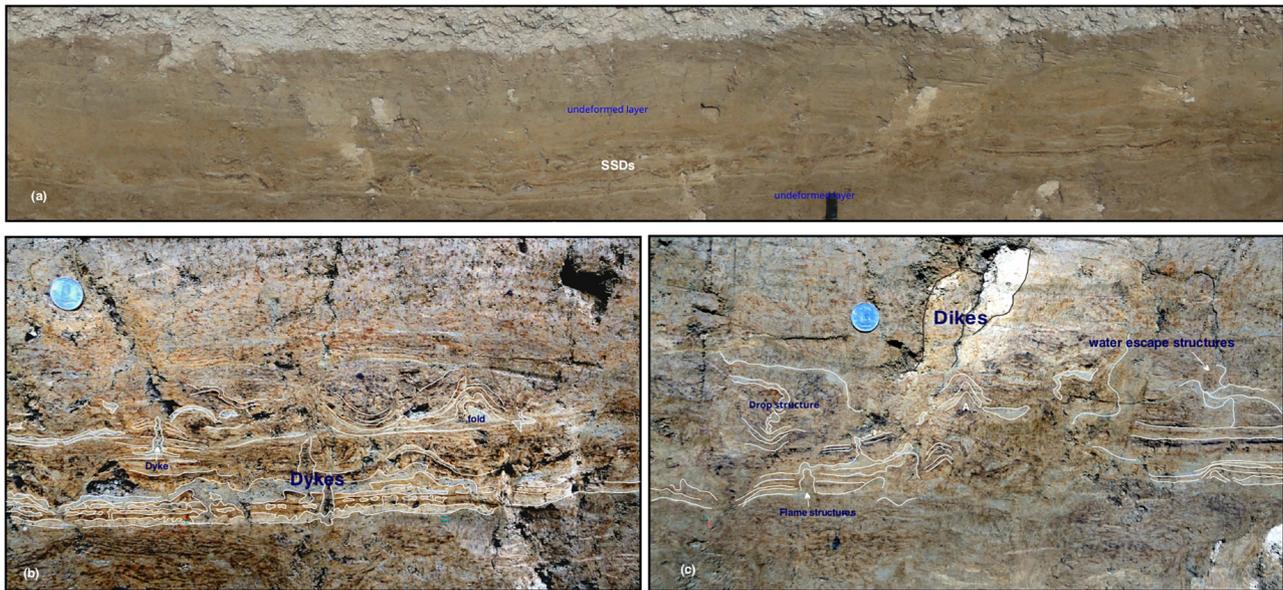


Figure 6. Photograph shows SSD features along Bharli fault site (a) captured a log section including various SSD structures, (b) displays micro SSD structures of the left side of the section, whereas (c) shows vividly visible sand dykes on the right side of the section.

in the upward direction due to the density variation of the sediments (figure 5).

4.2.3 Dyke

A prominent gravelly-filled dyke structure has been observed in layer B. This irregularly shaped dyke widens at the base and cross-cut through the sandy bed by pushing up gravel within it (figure 5).

4.2.4 Fissure fill

Fissure fill descended upper bed material rushed downward, comprised with variable sized pebbles which apparently formed in response to actively balance out associated upward rush of gravel filled dyke in layer B. In this structure pebbles are slumping downward due to cyclic shearing of the sediment (figure 5).

4.2.5 Microfolding structures

A highly deformed folded layer exposed in the profile is sandwiched between clast-supported sediment layers in a range of approximately 1.30 m. The micro-folded layers are developed in a mixture of sand and pebbles with sharp anticlinal hinge points (figure 5).

4.3 Sirmuri Tal (layer C)

Observations derived from the exposed lithological profile are being interpreted as undeformed layer C is lithologically composed with variable size of pebbly supported sediments.

4.4 Sirmuri Tal (layer D)

This layer is lithologically composed of brown sand and grey-coloured clay sediments. This layer is sandwiched by undeformed layers C from the top and E to the bottom. Some spectacular seismically induced features from 1557 ± 55 AD (C-14 dating) shocks have been observed in this section like internal foundering features, disrupted and convoluted beds and flame structures, etc. (figure 5).

4.4.1 Pinch and swell structures

A set of complex liquefaction-induced deformation structures has been observed from layer D, which is lithologically composed of comparatively fine-grained brown sand and grey clay sediments. These structures are apparently similar to pinch and swell structures where brown sandy bed enclosed cusps of grey-coloured clayey material at approximately 1 m in range laterally. The clay bed continuously extended for approximately 3 m which has been

disrupted at places by associated deformation structures (figure 5).

4.4.2 Flame structures

Flame structures developed due to density variation of the sediments; saturated cohesion less sediments become compact and act like flowing water in an upward direction at the time of shaking of the ground. In layer D, flame structures are formed where light-coloured comparatively finer saturated sediments flow upwards in response to continuous triggering by surface waves in high pore fluid conditions at the approximate entire range of layers (figure 5).

4.4.3 Convoluting and disrupted bedding

The fine-grained sediments bearing beds convoluted and disrupted, associated with earthquake-induced structures most commonly are very sharply vertical cross-cut sand dykes developed cutting across clay bedding, many complicated folded structures, boudins in the sandy lamination and water escape structures. These deformed structures occurred in fine grained sand and clay beddings in approximately 4 m (figure 5). These structures signify the intense level of ground shaking during the differential liquefaction process (Williams 1960; Reineck and Singh 1980).

4.5 Soft sediment deformational features around Bharli Fault

Bharli Fault is a subset of the Tran-Yamuna active fault system that lies parallel to the MBT in the outer part of northwest Doon Valley (Oatney *et al.* 2001). The Bharli Fault lies north of MBT and is quite close to active geomorphic features, i.e., fault scarp and two sag ponds (figure 3). These sag ponds served as a favourable environment to develop paleo-liquefaction features in the study area. The observed SSD has been exposed in the Bharli village along with TYAF, which is ~15 km distant from the previously studied site, i.e., Sirmuri Tal village.

4.5.1 Identified SSD features from the Bharli site

Bharli active fault strikes E–W for approximately 4–4.5 km; it lies on the easternmost side of the

TYAF system. Two sag ponds have been observed from high-resolution satellite images which are evidence of strike-slip formation. The Bharli fault is exposed just south of the eastern sag pond, on the west side of the road leading to Bharli Village (figure 3). The presence of sag ponds provides favour to preserve SSD features at shallow depths.

4.5.2 Dykes

From the Bharli site, multiple sand and clay dykes with different shapes and sizes were observed in litho-section. Two broad-sized sand dykes intruded into overlying beds by breaching the upper bed (figure 6). These discordant upward injected dykes are clear-cut indications of sudden abrupt hydraulic force due to intense seismic shocks.

4.5.3 Folding structures

Folds are very common ductile deformation structures. Some complex folded layers were observed from the Bharli site with various shapes and sizes. The exposed section consisted of different open anticlinal and tight synclinal forms developed within a saturated mixture of sand, silt and clay sediments (figure 6).

4.5.4 Water escape structures

Water escape structures such as dykes, pillars, flames and cusps are associated with sandy-clay sediments (figure 6a, b). These structures are developed because of high water saturation during earthquake-induced elevated hydraulic pressure; such pressures released through water contained seepage in the process of solidifying the sediments than pre-shock conditions (Seilacher 1969).

5. Correlation of SSD along TYAF fault

Exposed litho strata from the Sirmuri Tal site, Unit G has shown explicitly deformed soft-sediment features, which are likely to be induced by several high-magnitude seismic events. Therefore, this particular unit has well-preserved liquefaction features to extend ~5 m laterally and ~2 m tangentially, whereas unit H, lying above unit G, has shown deformational activities, is dated as 1809±99 AD, the layer is sandwiched with crushed gravels (figure 5). To a continuous extent, the deformation pattern Unit F has been consistent

with haphazardly larger size of pebbles mixed with sand sediments. Identified SSD features have been observed from two segments of SDB, precisely Sirmurital and Bharli (figure 1) and dated charcoal samples are being utilised as a tool to correlate with induced events.

6. Results and discussion

Our study is an attempt to evaluate the tectonic activity along the Trans-Yamuna (SDB fault) region of the Himalaya. We are motivated by the work done by previous researchers who used a combination of geomorphological mapping, analysis of satellite data and field surveys. They identified several Quaternary landforms in the form of uplifted alluvial fans, offset streams, pressure ridges, and sag ponds in the satellite imageries that represent vulnerable zones, which could have accumulated strain from major earthquakes in the late Quaternary and Holocene and could rupture in the future.

We made an approach to discuss a variety of SSD features (Seilacher 1969; Ghosh *et al.* 2011, 2012) along the STF and BAF in the Trans-Yamuna region to interpret the characteristics of the features induced by the paleoseismic events. Therefore, the observed deformation pattern from both the exposures and the correlation of the deformation layers with radiocarbon dating gave a clear-cut indication that the SSD structures have been developed by multiple moderate to high magnitude earthquake events during the 16th and 19th centuries. Some of the Paleoseismologists (Wheeler 2002; Perucca *et al.* 2009; Topal and Özkul 2014; Ali and Ali 2018; Yousuf *et al.* 2021) published fine work to define fundamental conditions to fulfil requirements to form the seismically induced SSD features are as follows:

- The deformed sediment layers carrying SSD features along the Sirmurital and Bharli faults have been observed as sandwiched between undeformed layers and produced almost similar patterns of features. Both the locations lie in the vicinity of the MBT, but apparently, the seismic energy is released along the STF and BAF rather than MBT (figure 6).
- We identified a small gravel-filled dyke and flame structures in layer B; these features are traces of sudden strong forces to bolster the upward movement of the sediments. We also

observed a sense of shearing at the right corner of layer b (Z8) and a vivid sharp hinged antiformal microfolding structure. Some small-sized sand dykes are sharply visible in the Sirmurital (figure 5), and Bharli sites are finely exemplified seismites (figure 6).

- Sirmuri Tal fault has been identified in the east of the Giri River, cutting across terraces Q1 and Q3 (figure 2), whereas sag ponds are available quite close to the Bharli Fault. Both of these sites are possibly saturated and supporting formation to preserve the signatures of deformation.
- As the authors explored two different sites in the Trans-Yamuna region precisely along the STF and BAF at a distance of approximately 13 km. Some spectacular SSD features have been preserved in the sites such as sand dikes, water escape structures, microfolding and disrupted beddings. This correlation is also verified by C-14 dating and events are a clear-cut indication of seismic energies released along the SDB fault in the recent past.

7. Conclusion

It is evident from various studies that the Himalaya is an ever-growing, seismically active mountain range. The Trans-Yamuna region lies within the central Himalayan seismic gap, which spread over the span of 700 km and is a spot of high-magnitude earthquakes such as the Kangra earthquake of 1905 and the Nepal–Bihar earthquake of 1934. Researchers analysed satellite data and performed geological mapping and geophysical surveys to identify the seismic signatures in the Trans-Yamuna Active Fault (SDB) system. The TYAF system is subparallel to and cuts the MBT, but the geomorphological expressions of this fault indicate that it does not show reactivation signatures of the MBT, which indicates dissipation of seismic energy along nearby faults. Our study is an approach to assess potential seismic hazards towards the highly populated townships located in this region. With the help of available data and literature review, we targeted the Sirmuri Tal Fault (STF) and Bharli Active Fault (BAF) along the TYAF region to find traces of missing historical seismic events by utilizing generated paleoseismic data. We observed some spectacular SSD features preserved along the fault system. The characteristics and distribution of the SSD structures in the

region provide evidence for seismically induced deformation. Also, our data (Radiocarbon dating) supports the observation that deformation persisted episodically or continuously into the recent past. Moreover, it is concluded that the seismic source should be north of the Trans-Yamuna Active fault system, with recent seismic activity recorded during the earthquakes of the 16th and 19th centuries and possibly reactivated in the future.

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Author statement

S K Ghosh: Initial discussion, supervision and final drafting. Rekha: Conceptualization, formal analysis, investigation, software, data curation, and writing original draft.

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