Field documentation and genesis of the back-structures from the Garhwal Lesser Himalaya, Uttarakhand, India

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Abstract: Collisional fold-and-thrust belts are characterized by foreland-verging thrusts. Conversely, structures with hinterland-ward vergence, known as the back-thrusts, also exist. Strain intensification, critical taper deformation and the presence of thrust ramps generate back-thrusts. This study focuses on the exposure-scale brittle and ductile structures showing hinterland-ward vergence (back-structures) from a part of the Garhwal Lesser Himalaya, NW India, mainly along the Bhagirathi river section. In our field-traverse, back-structures were found at 31 locations. Towards the north, in the Outer Lesser Himalaya, the back-structures are located on the inverted limb of the Mussoorie Syncline (Group 1). The Tons Thrust is a south-dipping thrust (i.e. back-thrust). Hence, the Tons Thrust and nearby areas show intense back-structures (Group 2). In the Inner Lesser Himalaya, back-structures have been generated by shearing related to the folded Berinag Thrust (Group 3). The back-structures at and near the Main Central Thrust Zone (MCTZ) (Group 4) can be correlated with the presence of the Delhi–Haridwar Ridge. In this way, this study establishes the back-structures to be an integral part of the Garhwal Lesser Himalaya and provides the genesis of those structures by correlating them with the (local) tectonic settings.

Supplementary material: Tables listing seismic events and the GPS coordinates of the field locations, and figures showing structures at these field locations are available at https://doi.org/10.6084/m9.figshare.c.4339784

Since the *c.* 54 Ma onwards India–Eurasia collision (Hu *et al.* 2016; Najman *et al.* 2017), the Himalaya has been an active orogen (Yin 2006; Mukherjee 2013*a*; Martin 2017*a* and references therein). Collisional orogens like the Himalaya are characterized by compressional fore-thrusts that dip towards the hinterland and verge towards the foreland. Such thrusts accommodate significant crustal shortening. But, although less numerous, thrusts with the opposite dip direction (i.e. towards the foreland) and with opposite vergence towards the hinterland also exist. Such thrusts, known as back-thrusts, generally originate along with the fore-thrusts, but reactivate during the later stages of deformation (Xu *et al.* 2015). The study of back-thrusts is of great importance since: (i) these are generally related to high-strain build-up zones and seismicity (e.g. Little 2004; Buttinelli *et al.* 2016; Zhang *et al.* 2016; Jayangondaperumal *et al.* 2017); (ii) they seem to constitute integral parts of collisional orogens (e.g. Sun *et al.* 2016; Zelilidis *et al.* 2016); and (iii) structural traps for hydrocarbons might consist of these structures (Butler *et al.* 2004; Shen *et al.* 2016).

Previous workers have reported back-structures from various Himalayan segments: for example, the Siwalik in Nepalese Himalaya (e.g. Mugnier *et al.* 1998), the Lesser Himalaya in Himachal Pradesh, India (Mukhopadhyay & Mishra 2005), and the Higher/Greater Himalaya along the Bhagirathi river section, Uttarakhand, India (Mukherjee 2013*b*). Previous workers have documented back-structures from other orogens as well (Alps: Platt *et al.* 1989; Pyrenees: Dumont *et al.* 2015: Zagros: Molinaro *et al.* 2004). Back-thrusts have been deciphered mainly from seismic studies and laboratory-based models (e.g. Namson & Davis 1988; Li *et al.* 2016; Shah & Abdullah 2017; Marshak *et al.* 2018). Analogue and analytical models of collisional orogens also simulate back-thrusts and folds (e.g. Rodgers & Rizer 1981; Dotare *et al.* 2016; Li & Mitra 2017). In the field, exposures of the foreland part of the fore-thrust mechanisms are manifested as structures showing a top-to-the-foreland shear sense or folds verging towards the foreland. Numerous discussions on such structures are present in the literature. However, field-exposure-scale evidence of structures showing top-to-the-hinterland shear was hitherto reported sparsely (e.g. Thakur *et al.* 2007; Samimi & Gholami 2017).

The aim of the current study is to postulate the back-thrust mechanisms at exposure scale, and at the same time to delineate the genesis of these exposure-scale back-thrusts in view of the local geological setting. In mesoscale, back-thrust mechanisms produce structures showing a top-to-the-hinterland shear sense. Here, the term ‘back-structures’ refers

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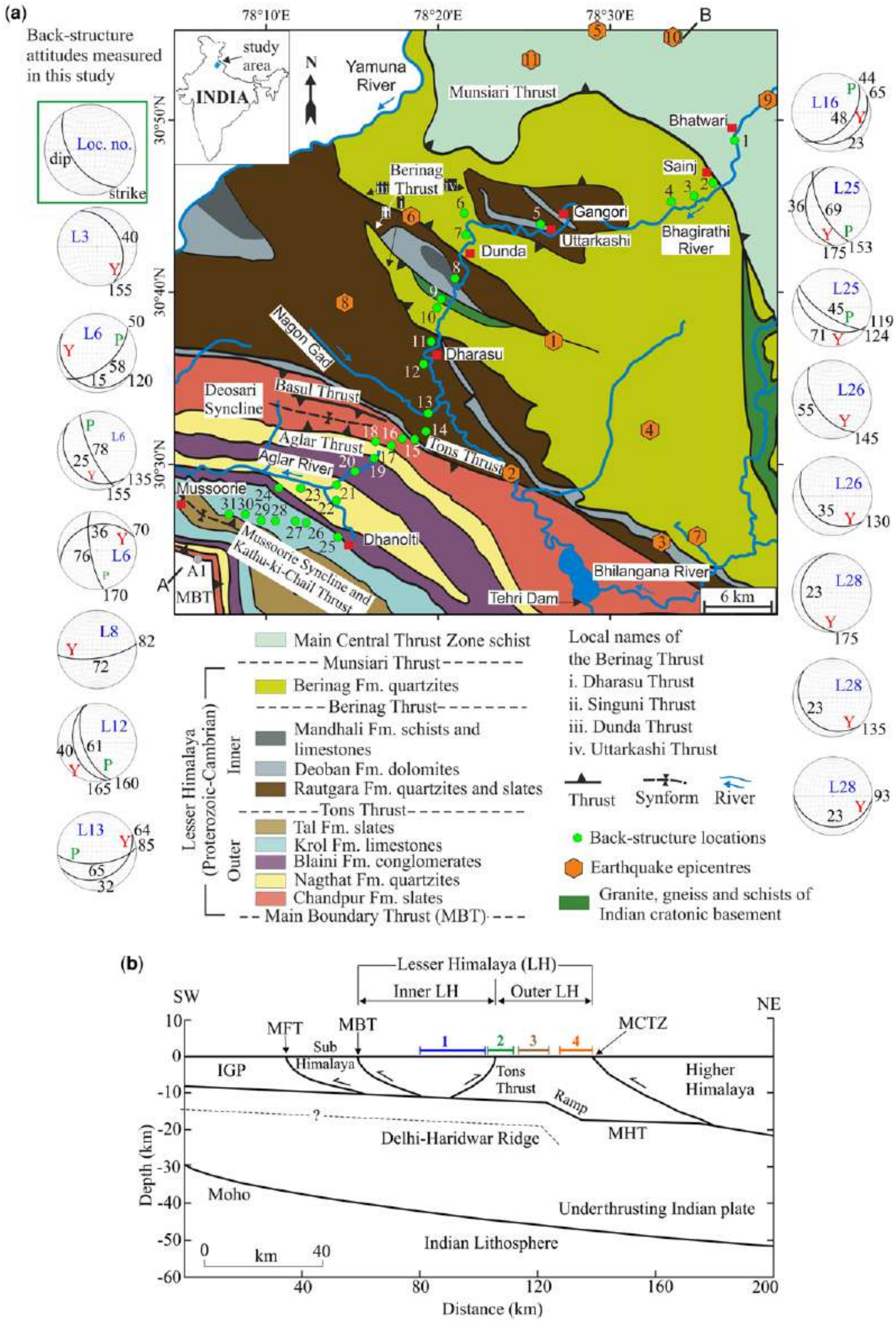
(a)
Back-structure attitudes measured in this study
Loc. no.
dip
strike
L3
L6
L8
L12
L13
L16
L25
L26
L28
78°10'E
78°20'E
78°30'E
30°50'N
30°40'N
30°30'N
B
A
study area
INDIA
N
Yamuna River
Munsiari Thrust
Bhatwari
Sainj
Berinag Thrust
Gangori
Uttarkashi
Dunda
Bhagirathi River
Nagon Gad
Dharasu
Deosari Syncline
Basul Thrust
Aglar Thrust
Aglar River
Tons Thrust
Mussoorie
Dhanolti
Mussoorie Syncline and Kathu-ki-Chail Thrust
MBT
Tehri Dam
Bhilangana River
6 km
Main Central Thrust Zone schist
Munsiari Thrust
Berinag Fm. quartzites
Berinag Thrust
Mandhali Fm. schists and limestones
Deoban Fm. dolomites
Rautgara Fm. quartzites and slates
Tons Thrust
Tal Fm. slates
Krol Fm. limestones
Blaini Fm. conglomerates
Nagthat Fm. quartzites
Chandpur Fm. slates
Main Boundary Thrust (MBT)
Lesser Himalaya (Proterozoic-Cambrian)
Inner
Outer
Local names of the Berinag Thrust
i. Dharasu Thrust
ii. Singuni Thrust
iii. Dunda Thrust
iv. Uttarkashi Thrust
Thrust
Synform
River
Back-structure locations
Earthquake epicentres
Granite, gneiss and schists of Indian cratonic basement
(b)
Lesser Himalaya (LH)
Inner LH
Outer LH
SW
NE
MFT
MBT
MCTZ
Sub Himalaya
IGP
Tons Thrust
Ramp
Higher Himalaya
Delhi-Haridwar Ridge
MHT
Moho
Underthrusting Indian plate
Indian Lithosphere
Depth (km)
Distance (km)
0 km 40

collectively to such faults and associated folds, showing a 'top-to-the-hinterland' brittle or ductile shear. This shear sense is observed in the field in terms of the angular relationship between the brittle Y- and P-planes, sheared quartz veins, etc. In the ductile domain, hinterland-verging back-folds also develop. The prerequisites for the generation of back-thrusts are strain-build-up zones, brittle rheology and low-confining pressure (review by Xu *et al.* 2015). The Lesser Himalaya is: (i) mostly made up of low-grade metasedimentary rocks of the Indian passive margin; (ii) deforming under the critical taper mechanism when a brittle rheology is presumed; and (iii) a tectonically active zone with a high strain build-up, as indicated by intense duplexing and frequent seismicity. Hence, the Lesser Himalaya is a suitable zone to host back-structures, and a traverse in the Garhwal Lesser Himalaya has been used for the current study.

Geology

Located between the Siwalik Range in the south and the Higher Himalayan Crystallines in the north, the Lesser Himalaya represents the Paleoproterozoic–Paleozoic weakly metamorphosed sedimentary successions of the north Indian continental margin (Fuchs & Sinha 1978; Geological Survey of India 1979; Thakur 1992; Kumar 2005; Dubey 2014; Mandal 2014; Mandal *et al.* 2016; Assemblage 'A' of Martin 2017*a*, *b*), with a Vindhyan affinity (rare earth element studies by McKenzie *et al.* 2011). Tectonically, the Main Boundary Thrust (MBT) in the south and the Main Central Thrust (MCT) in the north demarcates its two boundaries. The Greater/Higher Himalayan metamorphic rocks thrust for *c.* 80–125 km over these sedimentary piles. Erosion of this metamorphic thrust sheet/nappe produced several windows/klippes (Jain 1972; reviews by Bhargava 1980; Valdiya 2016) in the Lesser Himalaya. Internally, the tectonics of the Lesser Himalaya are mainly characterized by duplexing (Dahlen 1990; Srivastava & Mitra 1994), resembling the Lesser Himalaya in other parts of the Himalaya (e.g. in Sikkim: Mitra *et al.* 2010). The field locations of this chapter are in the Dehradun, New Tehri and Uttarkashi districts of Uttarakhand state in India.

Structural divisions and lithology

To the north, the major thrusts in the study area are: the Main Boundary Thrust (MBT), the Tons Thrust, the Berinag Thrust and the Main Central Thrust (MCT), occurring as a zone. The Mussoorie Syncline (Shanker & Ganesan 1973; Valdiya 1978) represents the Outer Lesser Himalaya. The major (fore-) thrusts in its southern limb are the Krol and the Garhwal thrusts, which are the basements for the Krol and the Garhwal nappes, respectively. Dubey & Jayangondaperumal (2005) referred additionally to the Kathu-ki-chail Thrust along the main synclinal axis of the Mussoorie Syncline. On the northern limb of the Mussoorie Syncline, Jain (1971) referred to an approximately north-dipping Aglar Thrust, and an approximately south-dipping Basul Thrust as the basal thrust of the Deosari Syncline. The thrust separating the Inner Lesser Himalaya in the north from the Outer Lesser Himalaya in the south has been recognized variously as the Tons Thrust, the Srinagar Thrust (Thakur & Kumar 1994; Valdiya 2016) and the North Almora Thrust (Agarwal & Kumar 1973; Kayal *et al.* 2002). The south-dipping Tons Thrust brings the Chandpur Formation over the Rautgara Formation. The Tons Thrust is an assemblage of SW-dipping shear zones displaying an overall top-to-the-NE shear (field evidence of asymmetrical drag folds are given by Célérier *et al.* 2009).

Inside the Inner Lesser Himalaya, the Berinag Thrust separates the Rautgara, Deoban and Mandhali formations from the overriding Berinag Formation thrust sheet. Yu *et al.* (2015) used the term 'Berinag Tons Thrust' to describe the two otherwise separate thrusts as a contiguous structure. Folding and subsequent erosion of the Berinag Thrust has generated window-klippe sturctures. Based on detailed field observations, various workers (e.g. Jain 1971; Agarwal & Kumar 1973) named the components of the folded Berinag Thrust towards the south as follows (Fig. 1): (i) The Uttarkashi Thrust: this antiformally folded thrust skirts the Uttarkashi window, which exposes the Kot Syncline and the Netala Anticline, both with NW axial traces. The Gangori–Jamak Fault coincides with the axial trace of the Netala Anticline. At the northern margin of the Uttarkashi

Fig. 1. (**a**) Field locations plotted on the geological map of a part of the Garhwal Lesser Himalaya (compiled from Jain 1971; Agarwal & Kumar 1973; Valdiya 1980; coloured as per Célérier *et al.* 2009). The 'Kathu-ki-chail Thrust' (KT) passes through the synformal axial trace of the Mussoorie Syncline (Jayangondaperumal & Dubey 2001). Numbers associated with the earthquake epicentres (inside hexagons) represent their corresponding serial number (Sl. no.) as given in Supplementary Table 1. The inset stereonets show the back-structure-related attitudes of the Y- and P-planes obtained in this study. The structural detail of the Gangori Shear Zone over a small area is from Bose *et al.* (2018). (**b**) Cross-section of the Garhwal Lesser Himalaya drawn along the line joining A–B in (a), and compiled after Sati & Nautiyal (1994) and Kanaujia *et al.* (2016). IGP, Indo-Gangetic Plane. The tentative extent of groups 1–4 (Section 4) are shown on the cross-section by corresponding numbers and bars.

Window, the Uttarkashi Thrust dips locally towards the north. The presence of Mata Volcanics along the thrust zone helps to identify this thrust. (ii) The Dunda Thrust: this north-dipping thrust is separated from the Uttarkashi Thrust by the NW-trending Pujaragaon Syncline of the Nagni Thak klippe. (iii) The Singuni Thrust: (=the Khattukhal Fault of Agarwal & Kumar 1973) passes through the axial trace of the Khattukhal Anticline of the Dunda window. (iv) The Dharasu Thrust: this is the same as 'the major tectonic unit', Nalupani Fault, Dharkot Dislocation and the North Almora Thrust as referred to in Agarwal & Kumar (1973 and references therein). It separates the NE-dippng Dharasu Formation from the strongly folded SW-dipping Dichli Dolomite of the Garhwal Group. This thrust dips towards the south to SW (Jain 1971; Agarwal & Kumar 1973; Valdiya 1980). Based on detrital zircon data and ε_{Nd} values, Mandal *et al.* (2014) recognized the Almora Thrust as the Main Central Thrust. However, Khanal *et al.* (2015*b*) referred to the Almora Thrust as an 'Intra-Greater Himalayan Crystalline Thrust'. Kothyari (2007) provided field evidence of the North Almora Thrust still being active, and hence it represents an out-of-sequence deformation (Mukherjee 2015).

Metamorphism

At the northern boundary of the Lesser Himalaya in the Bhagirathi river section, the metamorphic facies jumps abruptly from greenschist (the Berinag quartzites of the Inner Lesser Himalaya) to amphibolite (granite gneiss and mica schist of the MCT Zone) near Sainj village towards the north without any structural discordance (Valdiya 1978; Thakur 1992; Metcalfe 1993; Jain *et al.* 2002; further field evidence is given in Mukherjee 2013*b*). Inverted metamorphism is well documented in the MCT Zone rocks, formed under the thermal effects imparted by the uprising and far-travelling 'hotter' nappe/thrust system of the MCT sheet (e.g. Heim & Gansser 1939; Purohit *et al.* 1990; Khanal *et al.* 2015*a*). This boundary between the Lesser Himalayan sedimentaries and the medium- to high-grade metamorphics with granitic intrusions is named the Munsiari Thrust (Valdiya 1978; =Jutogh Thrust of Thakur 1992; =Budhakedar Thrust/MCT III of Saklani 1993; Srivastava & Mitra 1994; =MCT_L of Godin *et al.* 2006; =MCT_2 of Mitra *et al.* 2010; see Martin 2017*b* for a recent review of the MCT). This thrust may not mark the real MCT (i.e. the Vaikrita Thrust in this region: Valdiya 1978), but certainly indicates the initiation of the MCT Zone deformation (Choubey *et al.* 1999). The Munsiari Thrust also acts as the roof thrust for the Lesser Himalayan duplexes (Robinson & Pearson 2013).

Deformation

At least two major folding episodes have been identified in the Garhwal Lesser Himalaya by Agarwal & Kumar (1973) and Misra & Bhattacharya (1973): the regional NW–SE-trending folds were refolded producing NE-trending doubly plunging folds. In addition, Pant *et al.* (2012) reported a prior NE–SW-trending folding. Further, Saxena (1974) found another phase of folding with diverse scales and orientations; he correlated NNW-trending synclines, north- to east-trending foliations and NNW- to NE-trending folds along with this phase. From mesoscopic and macroscopic features in the Garhwal Synform, Gairola (1992) deciphered an epiorogenic and five synorogenic (Himalayan) deformation phases. The back-structures discussed in this report are the result of the Himalayan deformation. Gairola (1992) considered the synorogenic D_3 and D_5 phases to be products of approximately north–south compression in the brittle regime. The author did not specify whether back-structures could have been produced during these deformation phases. K–Ar (muscovite) and Ar/Ar (hornblende) ages indicate that the MCT in the Garhwal Himalaya activated during 19.8 ± 2.6 and 5.9 ± 0.2 Ma (Metcalfe 1993; Catlos *et al.* 2002). From Ar–Ar geochronology of biotite, Sen *et al.* (2012) reported that the deformation in the Wangtu Gneissic Complex (in Sutlej section, Himachal Pradesh, India; equivalent to MCT Zone in this study) is no older than *c.* 9 Ma. From Ar–Ar studies on biotites from mylonitic granites, Sen *et al.* (2015) predicted that the MCT in the Garhwal Himalaya activated *c.* 10 myr ago. Similarly, based on Ar–Ar geochronology of muscovite, Montemagni *et al.* (2018) report that the northern boundary of the MCT Zone (i.e. the Vaikrita Thrust) activated during 9–6 Ma. Apatite fission-track ages (Patel *et al.* 2015; Singh & Patel 2017) aided by field observation of shear senses (Agarwal *et al.* 2016) suggest that, in the Kumaun Lesser Himalaya, the North Almora Thrust and the nearby Kasun Thrust reactivated as back-thrusts during rapid exhumation (0.58 mm a^{-1}) during 11–6 Ma. The MBT activated in the western Himalaya during the Miocene Period (Meigs *et al.* 1995). Following the rapid uplift of the Tibetan Plateau, the Himalaya reached the overcritical-wedge condition that promoted rapid movement along the wedge thrusts and subsequent intense erosion during 12–10 Ma (Huyghe *et al.* 2001).

Subsurface features and seismicity

Seismicity has been well recorded in the Lesser Himalaya (e.g. Chaturvedi *et al.* 1973; Rajendran *et al.* 2017 and references therein). In the recent past, two major earthquakes have occurred in the

Garhwal Lesser Himalaya: the 6.8 M_w, 20 October 1991 Uttarkashi and the 6.5 M_w, 28 March 1999 Chamoli seismicity (Khattri *et al.* 1994; Kayal *et al.* 2002). Reporting an average convergence rate of *c.* 2 cm a^{-1}, Bilham *et al.* (2001) predicted that this study area has accumulated a 4 m slip potential, equivalent to an 8 M_w seismicity. However, this huge amount of accumulated strain is being released by continuous micro-earthquakes (<4 M_w) in the brittle upper crust (Paul 2010). A few of the previous earthquake epicentres (see Supplementary Table 1) have been plotted in Figure 1a. However, their correlation with the observed back-structures remains a matter for future study.

A basement horst, named the Delhi–Haridwar Ridge (DHR: Valdiya 1976), has been enhancing the fluid activity, exhumation rate, seismicity and orogen-parallel tectonic activities in this area (Khattri 1992; Raval 1995; Godin & Harris 2014 and references therein; see a recent review in Godin *et al.* 2018). The DHR is also believed to have had some role in the Uttarkashi and Chamoli earthquakes (e.g. Sati & Nautiyal 1994; Rajendran *et al.* 2000). From Landsat images, Barkatya & Gupta (1982) pointed out multiple regional lineaments – for example, the Tehri Lineament (trend 170°, length *c.* 180 km) and the Nagaon Lineament (trend 130°, length *c.* 110 km) – in the Garhwal Himalaya. Mithal *et al.* (1972) reported substantial slope instability near the locations of structurally weak planes (e.g. joints, shear (fault) planes, fold-axial traces). This criterion, along with the tectonoclimatic configuration, has made this highly active region prone to landslides (Mithal 1988; Mehrotra *et al.* 1993). Between the locations of Chham and Bhaldiyana, where the Bhagirathi River flows along the active Srinagar Thrust (=Tons Thrust), six river terraces indicate three deformation phases younger than Upper Pleistocene–Lower Holocene, which is the age of the other three terraces (Valdiya 2016). Based on ^{10}Be-derived catchment-averaged erosion rates from the Yamuna River valley, Scherler *et al.* (2014) deduced a *c.* 0.1–0.5 mm a^{-1} erosion rate for the Garhwal Lesser Himalaya. From continuous GPS measurements, Yadav *et al.* (2019) estimated a 18 mm a^{-1} convergence rate for the Kumaun–Garhwal region, which has become one of the most vulnerable zones in the Himalaya due to the high strain build-up over the past *c.* 500 years. Such features indicate a continuous stress build-up in this seismically active region, which has a high chance of future earthquakes (Sreejith *et al.* 2018).

Field observations

Structural fieldwork was conducted along a *c.* 174 km traverse (road distance) inside the Garhwal Lesser Himalaya, Uttarakhand, India. In the Inner Lesser Himalaya, the traverse follows the Bhagirathi River valley. In the Outer Lesser Himalaya, the traverse is across the Mussoorie Syncline. Fore-structures in terms of ductile top-to-the-south/-SW shears are abundant in both the Inner and the Outer Lesser Himalaya (Fig. 2). Here, we focus on the field observations of back-structures. Figure 1a presents the traverse and back-structure locations (GPS locations are given in Supplementary Table 2). Back-structures are mostly present as brittle shears, where the curved/sigmoid P-planes are enveloped by a pair of (sub-) parallel Y-planes (fig. 3 of Bartlett *et al.* 1981; fig. 5.50 of Passchier & Trouw 2005).

Near Bhatwari (see Fig. 1a for the location), back-shear is present in the augen-schists inside the MCTZ (Fig. 3a). Whereas, close to the Munsiari Thrust, such shears are also present in the Berinag Formation quartzites (Fig. 3a, b). Top-to-the-north/-NE (down) extensional (i.e. normal faults) back-structures exist only in this zone. Intense back-shear is present. Quartzites of the Berinag Formation are exposed along a subvertical road-cut section trending approximately south (170°). Back-structures exist here as brittle Y- and P-planes showing an approximately top-to-the-north (350°) shear (Fig. 4; for more examples see Supplementary Fig. 1a, b). Such back-structures exist in exposures on the other bank of the Bhagirathi River (Supplementary Figs 1c, d & 2a–c). This zone of intense back-structures continues *c.* 200 m towards the south along the highway as well (Supplementary Fig. 2d). Further south along the national highway, back-structures occur in the Mandhali Formation schists and limestones (Supplementary Figs 3 & 4a). In addition, back-structures are also present (Supplementary Figs 4b, c & 5a, b) at various other locations in the Inner Lesser Himalaya, where the Berinag Formation is thrust over the Rautgara, Deoban and Mandhali formations. Compressional back-structures have been documented at the footwall of the Tons Thrust (Fig. 5a, b; for more examples see Supplementary Figs 5c, d & 6a). At the Tons Thrust zone (Supplementary Fig. 6b, c), back-structures are present in the foliated quartzites of the Nagthat Formation exposed along the Bhal–Marad road. In the Outer Lesser Himalaya, back-structures are exclusively compressional (Fig. 6; for more examples see Supplementary Figs 6d & 7). These locations are on the inverted limb of the Mussoorie Syncline. While most of these observations are brittle shears, a few ductile back-folds have also been observed. However, it is to be noted that axial surfaces of minor folds can dip in various directions in a region of superimposed folding. They do not always represent back-folding (e.g. Supplementary Fig. 5a). For this reason, back-folds (e.g. Fig. 5b) have only been confirmed in those locations where brittle

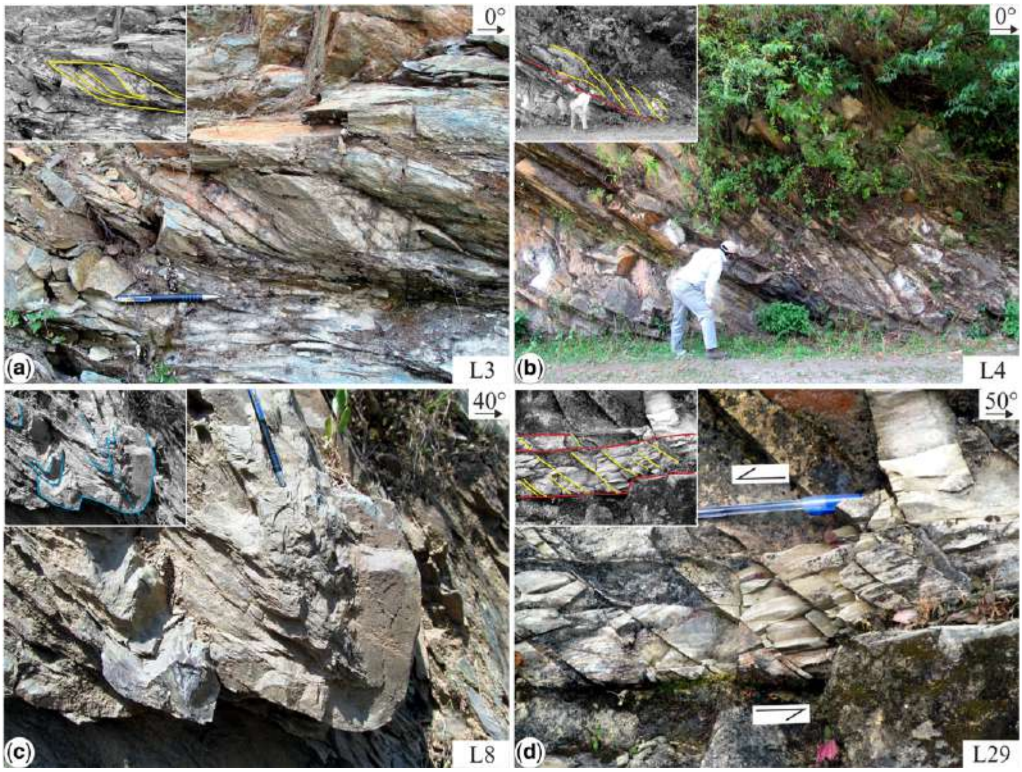

Fig. 2. A few of the fore-structures encountered in the field. Marker pen length is 12 cm for scale. (**a**) Fore-structure in Beringag Formation schists. Location 3 (L3) in the Inner Lesser Himalaya (30.76° N, 78.5811° E). (**b**) Y-planes accompanied by sigmoid P-planes indicate a top-to-the-south sense of shear. Berinag Formation quartzite. S. Mukherjee as a marker. Location 4 (L4) in the Inner Lesser Himalaya (30.7544° N, 78.5593° E). (**c**) SW-verging synformal fore-folded slates of the Rautgara Formation. The blue dashed line is the axial trace. Location 8 (L8) in the Inner Lesser Himalaya (30.6802° N, 78.3497° E). (**d**) Fore-shear in the Krol Formation limestone. Location 29 (L29) in the Outer Lesser Himalaya (30.4459° N, 78.1619° E). (a)–(c) are incorporated into Group 3, as referred to in the Discussion, and (d) is in Group 1.

back-structures (e.g. Fig. 5a) are also present. Antithetic shear inside a back-structure zone (Supplementary Fig. 8a) is not considered as a Himalayan fore-shear. Similarly, antithetic extensional top-to-the-north shear inside fore-shear zones (Supplementary Fig. 8b) are not considered as back-structures.

Discussion: genesis of back-structures

Based on their spatial concentration and local tectonic setting, back-structure locations reported in this study can be grouped as shown in Figure 7a. Group 1: a major cluster of locations on the northern limb of the Mussoorie Syncline; Group 2: near the Tons Thrust; Group 3: in the central part of the Outer Lesser Himalaya; and Group 4: close to the Munsiari Thrust, a strand of the MCT. The tectonic settings of these four groups have been correlated below with the genesis of back-structures, as summarized in Figure 7b.

Group 1

Group 1 locates on the inverted northern limb of the Mussoorie Syncline of the Outer Lesser Himalaya (Fig. 6; for more examples see Supplementary Figs 6d & 7). Structural elements like the Deosari Syncline, and the Basul and the Aglar thrusts (Jain 1971), exist in this part. In such a tectonic setting, the back-structures were generated as secondary fold-accommodation faults following the mechanisms described by Mitra (2002). From a field study of folds, Joshi & Tiwari (2005) deciphered approximately top-to-the-north shear on the northern limb of the Almora Syncline, which is tectonically equivalent to this northern limb of the Mussoorie Syncline. Jayangondaperumal & Dubey (2001)

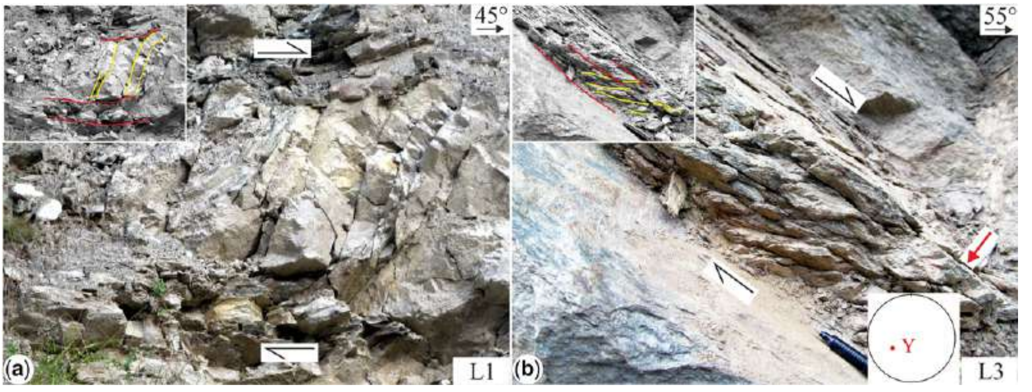

Fig. 3. Back-structures observed at various locations. (**a**) Top-to-45° brittle shear in the MCT Zone augen-schist at Location 1 (L1) (30.8136° N, 78.6205° E). Width of the photograph is *c.* 1.5 m. (**b**) Extensional back-structures in the Berinag Formation schistose quartzite, Inner Lesser Himalaya. Top-to-55° down brittle shear at Location 3 (L3). The attitude of the Y-plane is 155°/40°→65° (strike/dip→dip direction: measured at the red arrow; stereo-plot of pole in the inset). Intense deformation was found in these rocks, which are visually similar to the MCT Zone augen schists. Near a 'Yatri Nivas' and a 'Himlingeswar Temple'. (a) & (b) are incorporated into Group 4, as described in the Discussion.

reported few back-thrusts at the core of the Mussoorie syncline. These back-thrusts resolve the space problem created by the nearby, older and NW–SE-trending Kathu-ki-chail Thrust, which was earlier a normal fault, but reactivated as a reverse fault due to Himalayan compression (Dubey 2014).

Group 2

The cluster for Group 2 is close to the Tons Thrust, mainly on its footwall block (Outer Lesser Himalaya) and partly in the hanging wall (Inner Lesser Himalaya) (Fig. 5; for more examples see Supplementary

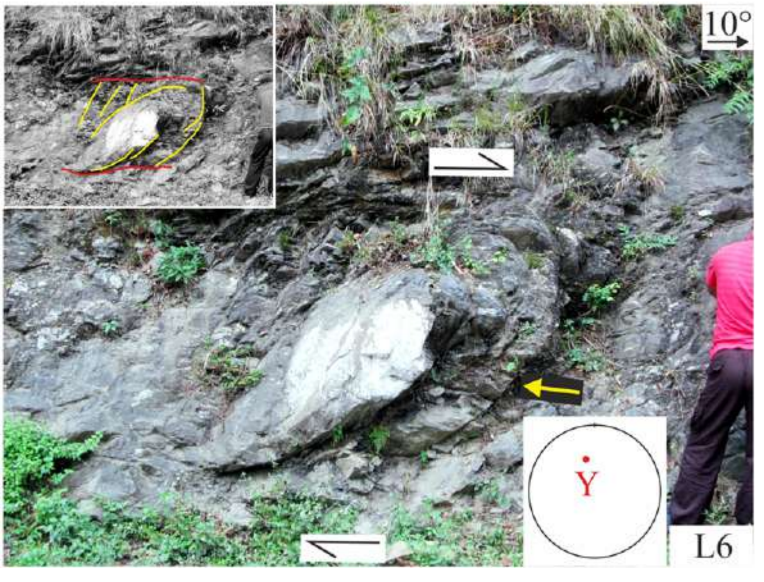

Fig. 4. Compressional brittle back-structures in the Berinag Formation quartzites were seen near the Raturi Sera Bridge on the Uttarkashi–Gangotri Road (National Highway 108). Top-to-10° compressional brittle shear at Location 6 (L6). The P-plane attitude is 120°/37°→30° (strike/dip→dip direction: measured at the red arrow; stereo-plot of pole in the inset). This location is incorporated into Group 3, as described in the Discussion.

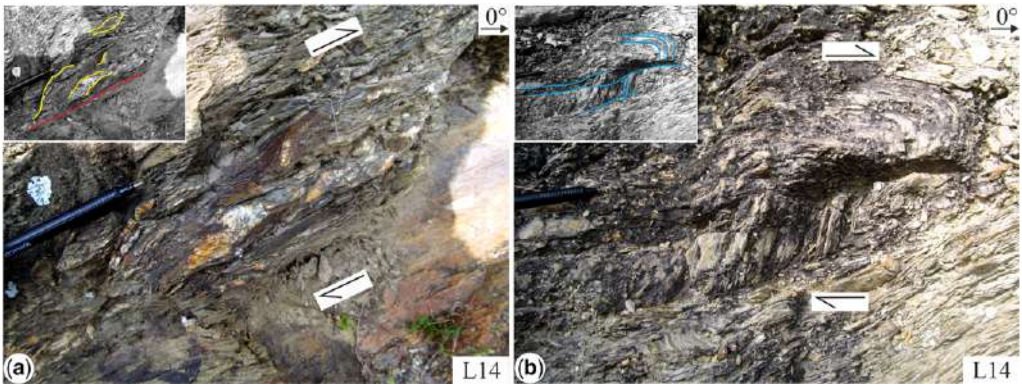

Fig. 5. (**a**) Compressional brittle back-shears (top-to-0° up) in the Rautgara Formation quartzites and schists at Location 14 (L14) (30.531917° N, 78.321317° E). Shears are shown by quartz-vein-rich schists. (**b**) A drag fold (Mukherjee 2014) with moderately rounded hinge and markedly different dip of the limbs along an approximately horizontal shear plane at Location 14. (a) & (b) are incorporated into Group 2, as described in the Discussion.

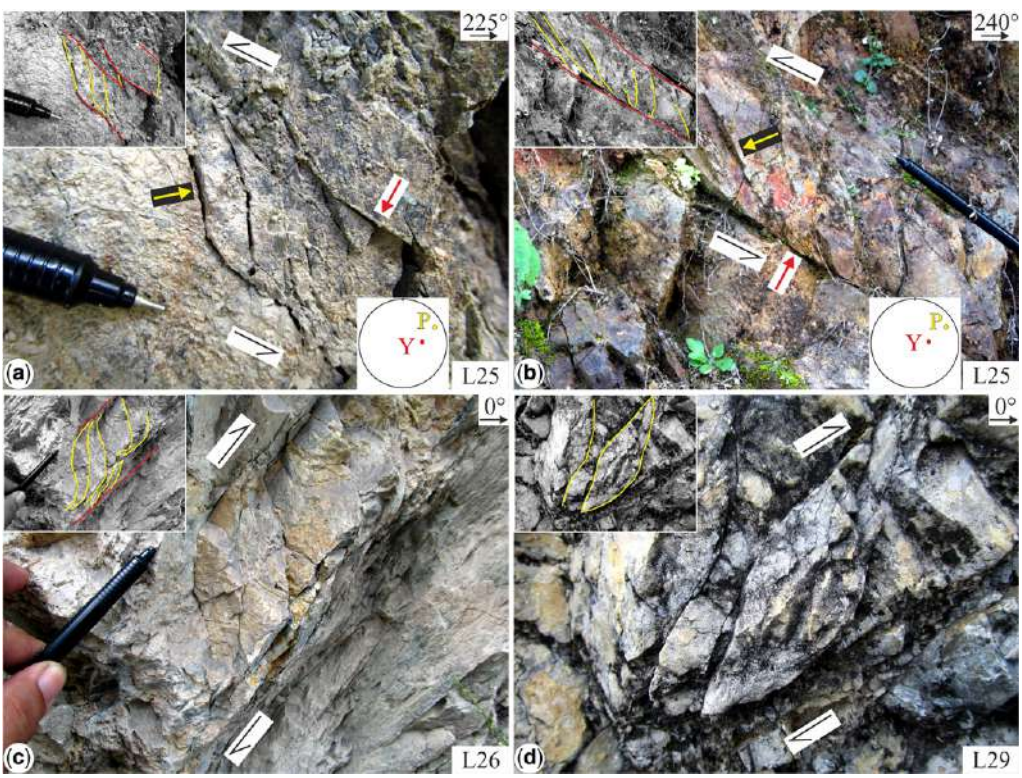

Fig. 6. (**a**) & (**b**) Compressional brittle back-structures in the Blaini Formation slates and phyllites at Location 25 (L25) (30.4297° N, 78.2362° E), near the Dhanaulti Eco Park. (a) Top-to-45° up shear. The attitudes of the Y- and P-planes are 175°/36°→265° (strike/dip→dip direction: measured at the red arrow) and 153°/69°→243° (measured at the yellow arrow), respectively. (b) Top-to-60° up shear. The attitudes of the Y- and P-planes are 172°/25°→262° and 152°/68°→242°, respectively. (**c**) Top-to-0° up shear at Location 26 (L26) (30.4435° N, 78.2053° E). (**d**) Compressional brittle back-structures in the Krol Formation limestone. Top-to-0° up shear at Location 29 (L29) (30.4459° N, 78.1619° E). (a)–(d) are incorporated into Group 1, as described in the Discussion.

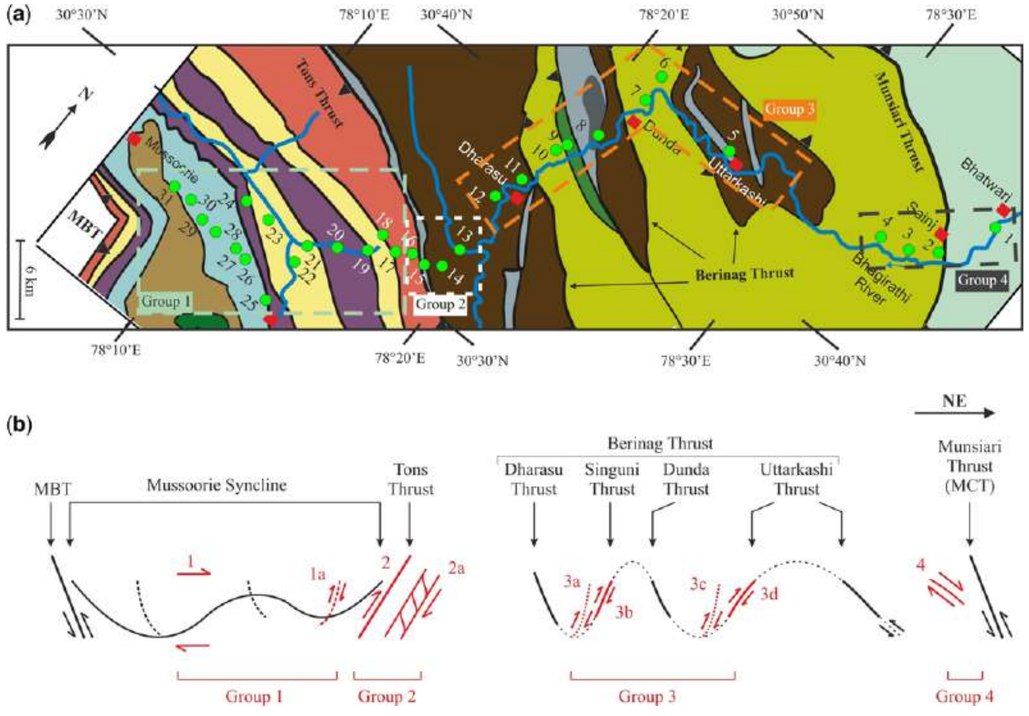

Fig. 7. (**a**) The four groups of back-structures are located on the map. (**b**) Major tectonic units as described in the earlier section on 'Geology' in this paper. On the NE–SW schematic cross-section, the back-structure-bearing portions have been marked by red and the four groups are shown. **Group 1**: 1, top-to-the-NE shear on the northern limb of the Mussoorie Syncline (this shear is produced by synclinal folding); 1a, Basul Thrust. **Group 2:** 2, Tons Thrust; 2a, footwall of the Tons Thrust. **Group 3:** 3a, 3c, locations where strain failure produces back-structures on the thrust sheet; 3b, 3d, SW-dipping segments of the Berinag Thrust, where the fore-structures are likely to be overwritten by subsequent back-structures. **Group 4:** 4, part of the Lesser Himalaya, which experiences strain intensification and extension due to the presence of the basal ramp/ridge (as discussed in the Discussion), as well as receiving a strong 'push' from the nearby 'harder' MCT Zone schistose materials.

Figs 4c, d, 5 & 6a–c). Mehdi *et al.* (1972) and Saxena (1974) reported that the Precambrian Tons Thrust nearly parallels the axial plane of the Almora Syncline and reactivated later. They also support that this is an isolated thrust and has no relationship with either the South Almora Thrust or the thrust at the base of the Almora Syncline (cf. Valdiya 1978; Yedekar & Powar 2005). In the Kumaun Lesser Himalaya, the North Almora Thrust (equivalent to Tons Thrust in this study) reactivated as a back-thrust at *c.* 14 Ma (Patel *et al.* 2015; Agarwal *et al.* 2016; Singh & Patel 2017).

Group 3

The Group 3 locations are in the Inner Lesser Himalaya (Fig. 4; for more examples see Supplementary Figs 1, 3 & 4a, b). As discussed in the 'Geology' section, the Berinag Thrust sheet sheared top-to-the-SW before it folded. This folding might have accumulated significant strain within the thrust sheet. Hence, back-structures noted in this group, produced presumably by strain release, are the manifestations of the fold-accumulation faults (Mitra 2002). Again based on the mechanisms of folding, a top-to-the-north shear is expected in the south-dipping limbs of the folded Berinag Thrust (e.g. as shown in the cross-sections of fig. 5 of Misra & Bhattacharya 1973), which matched with the observations made in this work.

Group 4

The back-structure locations in this group are inside the Inner Lesser Himalaya within the MCTZ or within the footwall rocks of the Munsiari Thrust (Fig. 3). Studying the seismicity of this region, Kanaujia *et al.* (2016) indicated the presence of a ramp (Fig. 1b) at 10–12 km depth and on the subhorizontal Main Himalayan Thrust (basal detachment) underlying the Lesser Himalaya. Based on seismic studies, Parija *et al.* (2018) has also indicated such a crustal ramp at the NW Himalaya at 12–22 km below the MCT. The presence of such a ramp was supported by Morell *et al.* (2015), while they established a physiographical transition (Uttarakhand Physiographic Transition 2) in the northern part of the Kumaun–Garhwal Himalaya. Due to the influence of such factors as the basement ramp and the Munsiari Thrust, etc., this part of the Himalaya experienced relatively higher strain, and therefore intense seismicity (e.g. Khattri 1992; SEISAT 06 of Dasgupta *et al.* 2000; Kanaujia *et al.* 2016; Kanaujia & Mitra 2018). This highly strained part is below a zone of extension (fig. 4 of Sati & Nautiyal 1994) at the surface. This strain intensification probably plays the key role for the extensional back-structures observed here. However, the influence of the Delhi–Haridwar Ridge (see the subsection on 'Subsurface features and seismicity' earlier in this chapter; see also Fig. 1b) on the genesis of back-structures is to be checked. At the same time, here the lower-grade metasediments of the Lesser Himalaya (i.e. the Berinag Formation quartzites) are pushed against the higher-grade MCTZ schists across the Munsiari Thrust. This is comparable with the strain elevation in the 'softer' wedge material present near the 'harder' backstop of the critical taper mechanism (fig. 1a of Xu *et al.* 2015). From regional observations and conceptual models related to the Sevier orogenic wedge (USA), DeCelles & Mitra (1995) proposed erosion-aided taper building stages, which can be applicable to this geologically active region in the current study. From field observations in Nepal Himalaya, Mugnier *et al.* (1994) documented normal faulting along the MBT despite remaining in an overall compressional tectonic setting. These authors also related these normal faults to deviations in the principal stress axes due to fluid activity. Whether such conditions also work in this Group 4 region, remains a matter for further study.

Previously, based on field observations, Mukherjee (2013*b*) reported brittle and ductile back-structures from the Greater Himalayan Crystalline (GHC) from the same traverse (i.e. the Bhagirathi river section). The observations were correlated to plate-scale phenomenon, such as channel-flow extrusion followed by critical taper-wedge deformations. Similar to his observations in the GHC, both compressional (e.g. Fig. 6c) and extensional (e.g. Fig. 3b) back-structures are also consistently found in this work from the Lesser Himalaya. Although, the overall Lesser Himalaya deforms mainly by the critical taper mechanism (Srivastava & Mitra 1994), the back-structures reported in this study are controlled presumably by local tectonic settings, unlike the Greater Himalayan case described by Mukherjee (2013*b*).

Conclusions

- Despite being less abundant than the fore-structures, the back-structures are well spread in the Garhwal Lesser Himalaya. Among the documented back-structures, brittle back-shears are more numerous than the ductile back-folds.
- Based on their spatial concentrations and local tectonic settings, the back-structures can be clubbed into four groups. These back-structures are mostly governed by fold-accommodation faulting (in the Inner and the Outer Lesser Himalaya), shearing related to regional back-thrusts (near the Tons Thrust) and by the presence of a basement ramp near the Munsiari Thrust.
- Fieldwork from the Lesser Himalaya shows the prominent presence of back-structures, which is linked with the local/regional geological setting. The observations related to the present study establish back-structures to be inherent in parts of the Lesser Himalaya.
- At the same time, the current study holds a very high potential to promote future investigations on back-structures. For example: (i) absolute dating of the gouge of the back-structures will provide more detailed information about the genesis of these structures, as well as the tectonic evolution of the study area; and (ii) microstructural studies, stress–strain analyses and numerical modelling can be carried out to check if the observed back-structures are related to strain-build-up zones/seismicity.

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