Documentation of Brittle Structures (Back Shear and Arc-Parallel Shear) from Sategal and Dhanaulti Regions of the Garhwal Lesser Himalaya (Uttarakhand, India)

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1 Introduction

We study the brittle shear tectonics from the Lesser Himalayan terrain in the Mussoorie, Dhanaulti and Satengal regions, Uttarakhand, India. The Lesser Himalaya is bound by the Main Boundary Thrust (MBT) in the south and the Main Central Thrust Zone (MCTZ) in the north. The Lesser Himalayan sequence is divided in this region as the Inner Lesser Himalaya and the Outer Lesser Himalaya (Célérier et al. 2009a, b). The Mussoorie- and the Garhwal synclines are the two major structures of the Outer Lesser Himalaya. The area around Dhanaulti (Fig. 1) constitutes a part of the northern limb of the Mussoorie syncline. The Satengal region (Fig. 1) lies at the core of the Mussoorie syncline. Several workers (e.g., Srivastava et al. 2011; Bose et al. submitted-1, 2; Bose et al. 2018) discuss major structural features and the deformation phases from the Garhwal Himalaya. However, a detail study remained due on its brittle deformations. This work describes brittle shear sense indicators from the terrain.

2 Previous Works

The first-hand rock description and regional mapping in this area have been done by Middlemiss (1887), Auden (1937), Jain (1972), Shankar and Ganesan (1973), Valdiya (1975), Saklani (1978). The Mussoorie Syncline mainly consists of sedimentary rocks and low-grade metamorphic rocks of Tal-, Krol-, Blaini-, Nagthat-, Chandpur-, and Mandhali Formation. Out of all these, the Mandhani, the Chandpur

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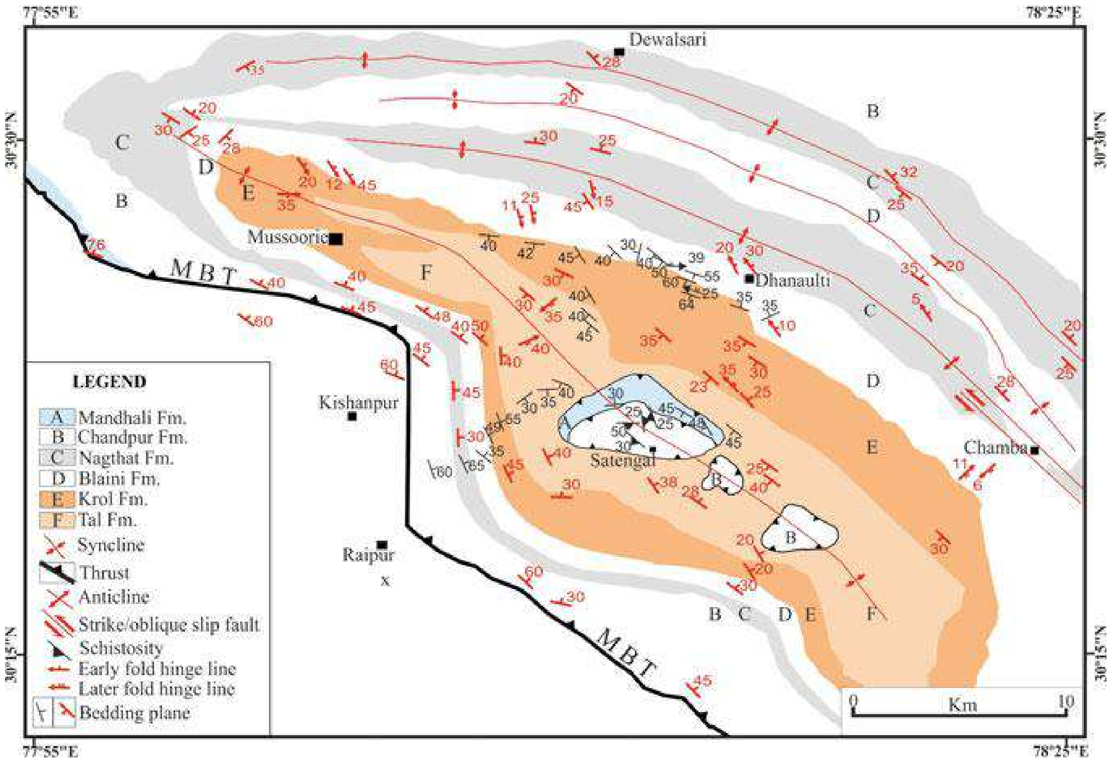

Fig. 1 Structural map of the central portion of Mussoorie syncline is showing different structural data. Structural data in red colour are taken from previous works, and those in black colour indicates those collected in the present study. The map is reproduced from Dubey and Jayangondaperumal (2005)

and the Nagthat Formation belong to the Jaunsar Group and the remainder to the Mussoorie Group (Fig. 1).

Raman Spectroscopic study of carbonaceous material of samples collected across the axis of Mussoorie Syncline yields a deformation temperature <300 °C (Célérier et al. 2009a, b). This is overlain by less metamorphosed rocks of the Simur Group and constitutes partly the Garhwal nappe. The southern limb of the Mussoorie Syncline overrides the Siwalik zone along the MBT (Fuchs and Sinha 1978). Intense-sheared black Proterozoic Chandpur phyllites along the MBT near the Sahenshahi temple has been studied in detail by Bose and Mukherjee (submitted-a). The authors use Raman Spectroscopy on carbonaceous materials and obtain a deformation temperature <550 °C (Bose and Mukherjee, submitted-a). Further, ~6–49 MPa of flow stress and ~10^{-15}–10^{-16} s^{-1} of strain rate has been obtained from the MBT zone rocks from this region that reveals a top-to-S/SW fore-shear in field and under an optical microscope (Bose et al. submitted-a).

According to Srivastava et al. (2011), the Sategal area deformed four times. The first three deformation phases are attributed to ductile deformations and the last one a brittle deformation. The Mussoorie Syncline, a structural part of the Krol Nappe, consists of Tal-, Krol-, Blaini-, Nagthat-, Chandpur-, and Subathu Formation. In Dhanaulti and nearby areas, mainly Blaini-, Tal-, and Krol Formation crop out. The main meso-scale structures in this area are primary bedding planes, slaty cleavages, axial planes of different generations of folds (Srivastava et al. 2011), and thrusts/faults (Dubey 2005). The pop-up klippen structure is indicated by the rocks of Chandpur, Mandhali and Subathu Formation at the Satengal area (Dubey and Jayangondaperumal 2005).

The Baliana Formation (/Chandpur Formation) and the Mandhani Formation (/Saklana Formation) are separated by the Ringalgarh Thrust. The pop-up klippen developed since the MBT bifurcates at south into an oblique ramp and into a blind thrust that generated two low-angle backthrusts (Dubey and Jayangondaperumal 2005).

At Satengal and in the adjoining areas, folding happened thrice. The main schistosity trends NW and NE. The NW trending earlier tight to isoclinal F_1 folds are characterized by deformed quartz veins and quartzo-feldspathic layers. The usually NE trending F_2 folds developed on the limbs of the F_1 folds with open to isoclinal geometries. F_3 chevron folds occur in phyllites of Chandpur Formation near Satengal and trends E-W (Srivastava et al. 2011).

3 Present Work

This section addresses details of S_0 and S_1 planes. Brittle shear detail is also presented from the following three traverses: (i) Mussoorie up to Kathu Khal (Surkunda Devi temple) along the Mussourie-Chamba road; (ii) Kathu-Khal to Satengal; and (iii) ~NE-SW traverse was taken from Raipur to Silla.

3.1 S_0-Plane (Fig. 2)

Primary sedimentary bedding planes (S_0) are commonly observed in the study area. These S_0 planes can be identified based on lithology change and color variation. From L-1 to L-6, dip of S_0 ranges 40°–42° with ~SW dip direction. The dip direction changes from SW to NW in and around L-7. Dip ranges 25°–65° with a ~SW dip direction between L-8 and L-11. S_0 dips oppositely towards NE and N with 30° dip at L-12 and L-13, south of Dhanaulti.

The S_0-planes near the Satengal region between L-15 to 18 show 40°–45° dip, and dip direction towards SW. At L-24 grey coloured quartzites dip N, from L-28 to 31 the dip of the S_0 varies 35°–60° with dip direction NW to E, in between L-32 and 33 dip direction varies from SE to S. S_0 dips toward SW direction in locations 33–37.

Slaty Cleavage (S_1) (Fig. 2):

The exposed rocks in and around Dhanaulti are slaty. Phyllites are observed in the Satengal region. A pervasive, parallel foliation (S_1) of fine-grained platy minerals occurs in these rocks, which generally develop perpendicular to the direction of

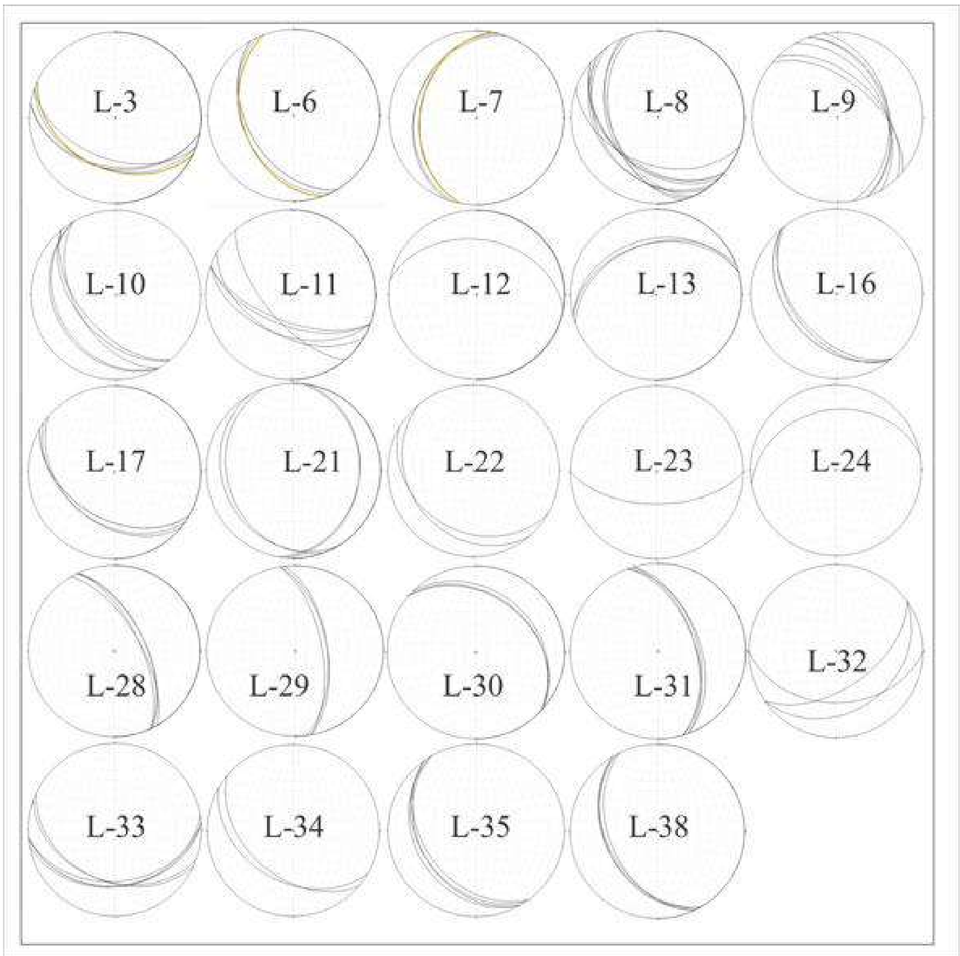

Fig. 2 Stereo-plots of planer features S_0 and S_1 on equal area net. L-21 to L-24 shows S_1-plots, and the rest represents S_0-plots

maximum stress. Usually this S_1 plane parallels the S_0 planes if not folded or sheared. In Dhanaulti region, the S_1 planes dip 30°–40° towards SW. In Satengal region, S_1 dips 25°–50° and the dip direction varies widely from SW to S to SE to N.

3.2 Shear Fractures

Shear fractures (Fig. 3) are very common structural features observed in the study area. The P-planes at L-28 and 36 generally dip in opposite direction and with the M/Y shear fracture this makes a low-angle. Kinematically, such shear planes can usually be correlated with low-angle thrusts. Within the same setting, the Riedel fractures can be represented as low-angle normal faults. The R'-planes/antithetic faults make a high-angle with the Y plane. The angles between the P, R and $R'$with the Y-plane can depend on the rock's physical properties and the stress regime.

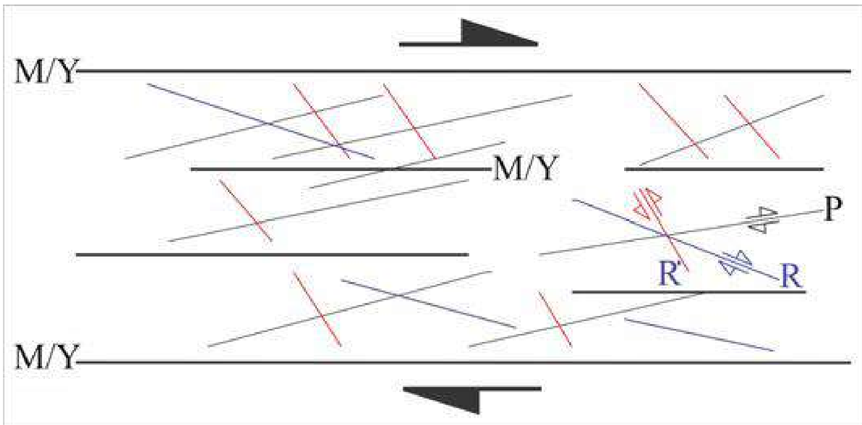

Fig. 3 Nomenclatures for shear fractures developed in a top-to-right shear zone. M/Y, Main shear plane; P: shear fractures; R: Riedel shears; R': fracture. From Petit (1987)

3.3 *Traverse-Wise Description*

The first ∼E-W traverse was taken along the Mussoorie-Chamba road from Mussoorie up to Kathu Khal (Surkunda Devi temple). A vertical shear zone (Fig. 4) exists at L-2 on a N140°S striking road cut section. Around 13 km east of L-3, top-to-SE brittle shear (Fig. 5a) was observed at L-7. Top-to-NW down shear (Fig. 6a) was observed ∼650 m SE from L-6. At L-7, top-to-NE up brittle shear (Fig. 6c), i.e., back deformation, occurs in slates. About 600 m east from L-7, the same top-to-NE up brittle shear (Fig. 6d) occurs in slates at L-8. A top-to-NE sub-horizontal brittle shear (Fig. 6b) exists in slate close to L-9. Around 300 m south of L-9, a top-to-SW up shear, also can be called a fore shear that is common in Himalayan orogen in its various units (e.g., Mukherjee 2010a, b, 2012, 2013, 2014; Mukherjee and Koyi 2010a, b) exists in slate. Top-to-NW shear (Fig. 5b) also exists.

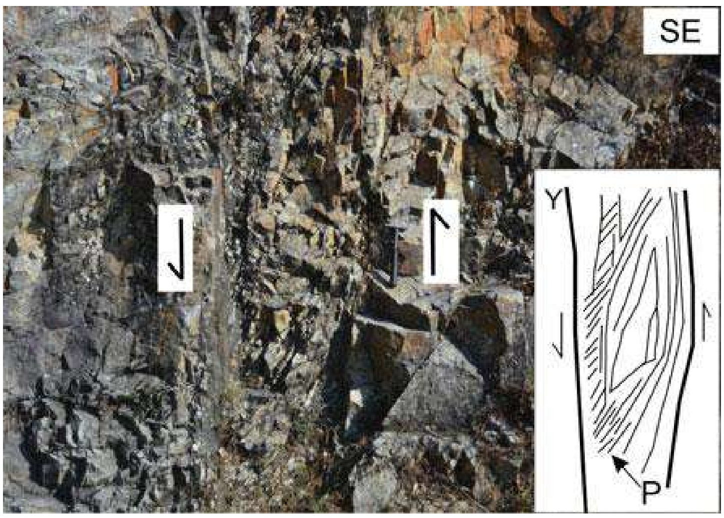

Fig. 4 Brittle vertical fault zone. Y- and P-planes well developed

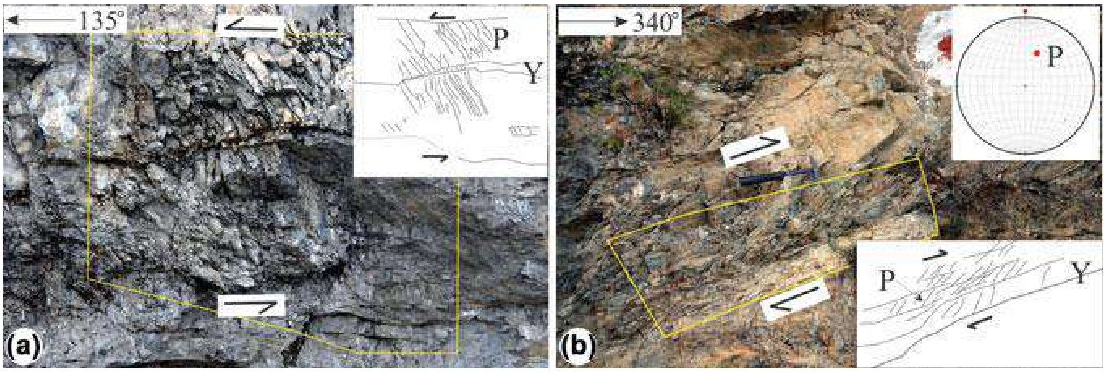

Fig. 5 **a** Field photograph of vertical exposure of quartzite showing top-to-SE shear. Y- and P-planes are stereo-plotted in inset. **b** Top-to-SW up brittle shear. Pole of P-plane (25° dip towards 10°) is plotted in inset

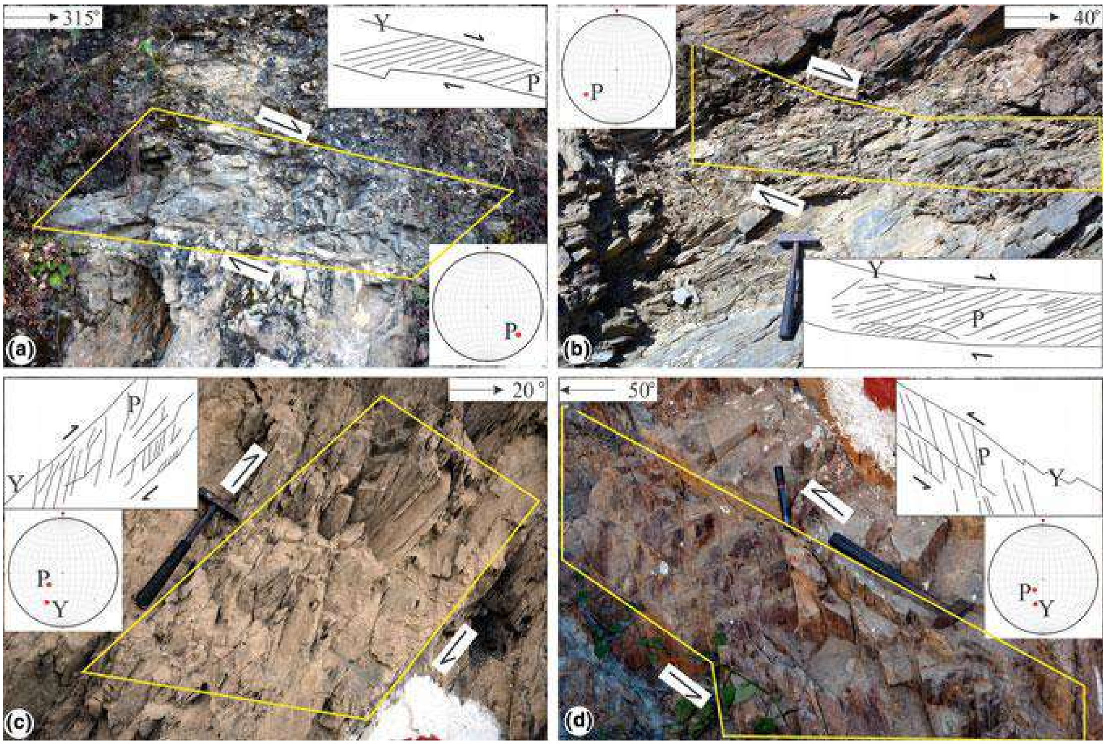

Fig. 6 Brittle shear Y- and P-planes observed in a vertical rock section. Poles of brittle planes are plotted inside insets. **a** Note a sharp contact between slate at top and quartzite at bottom. Top-to-NW brittle shear localized in slate due to high accumulation of shear strain. P-plane attitude: 10° dip towards 140°. **b** Shear fractures developed on slate. Top-to-NE brittle shear sense. The P-plane dips 14° and towards 225°. **c** Y- (dip 34° towards 200°) and P-planes (dip 65° towards 240°) developed on slate. Top-to-NE up shear. **d** Top-to-NE up shear. Y-plane: dip 35° towards 190°, P-plane: dip 70° towards 230°

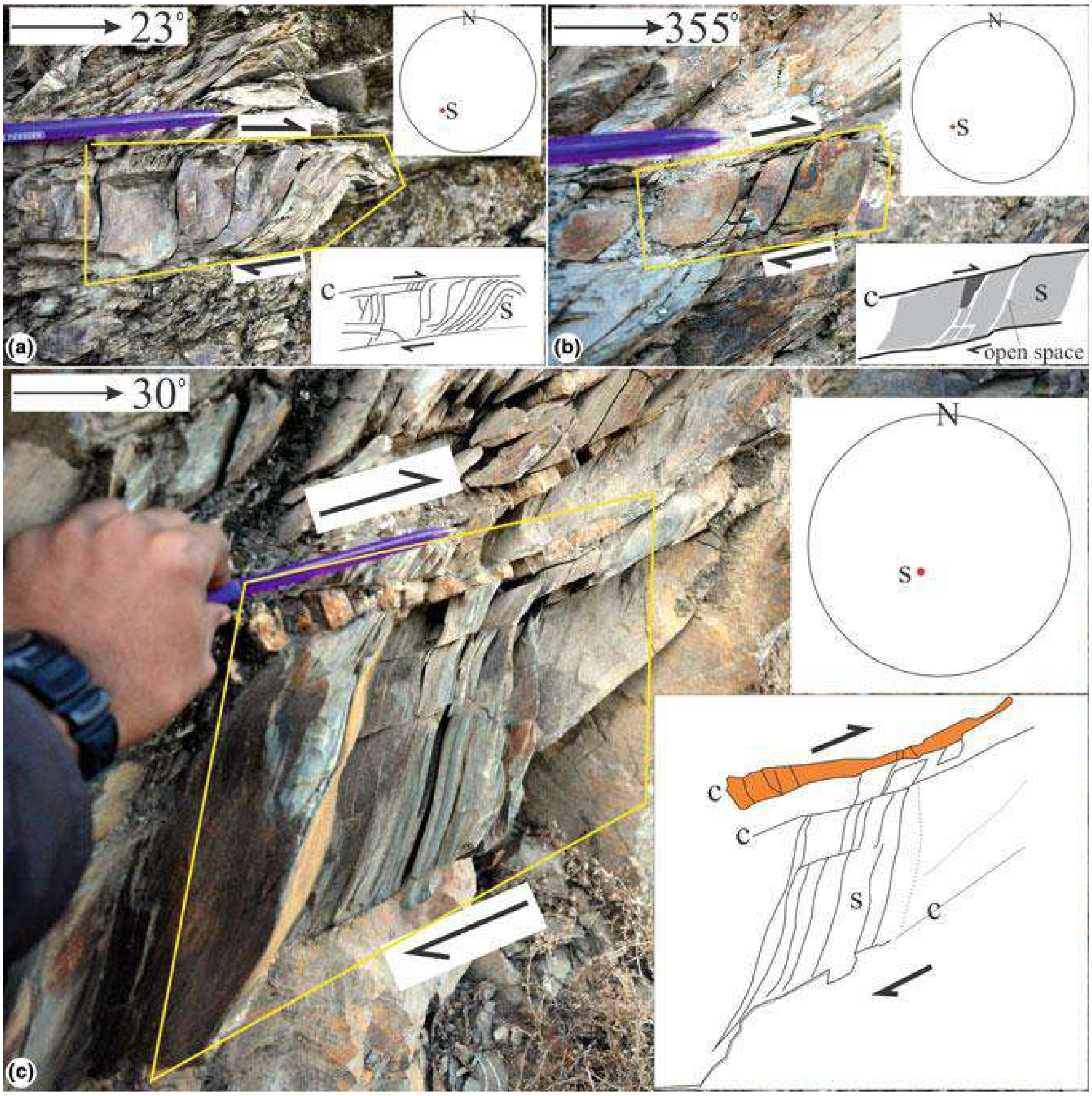

Fig. 7 **a, b** Sub-vertical sections at L-12 showing S- and C-fabrics developed in slates. top-to-NE up ductile shear. Stereo-plot of S planes in inset. Fractures developed along the S-planes in slates. In particular, in **c** the C-planes are occupied by secondary quartz mineralization. Here the pen length is 13 cm

Slate is the dominant rock type at L-12 which is ~2 km SW to Dhanaulti. Here the rocks deformed in a ductile-brittle regime. In response to ductile deformation, S- and C-fabric developed prominently in slates. Secondary mineralization of quartz is noted at few places along the shear planes that connote back-shear (Fig. 7a–c). The dip and dip-direction of S-fabric indicates a top-to-NE up shear (back-structure). Brittle shear fractures (Fig. 8c, d) also develop at L-13 showing both top-to-NE up and horizontal shear senses.

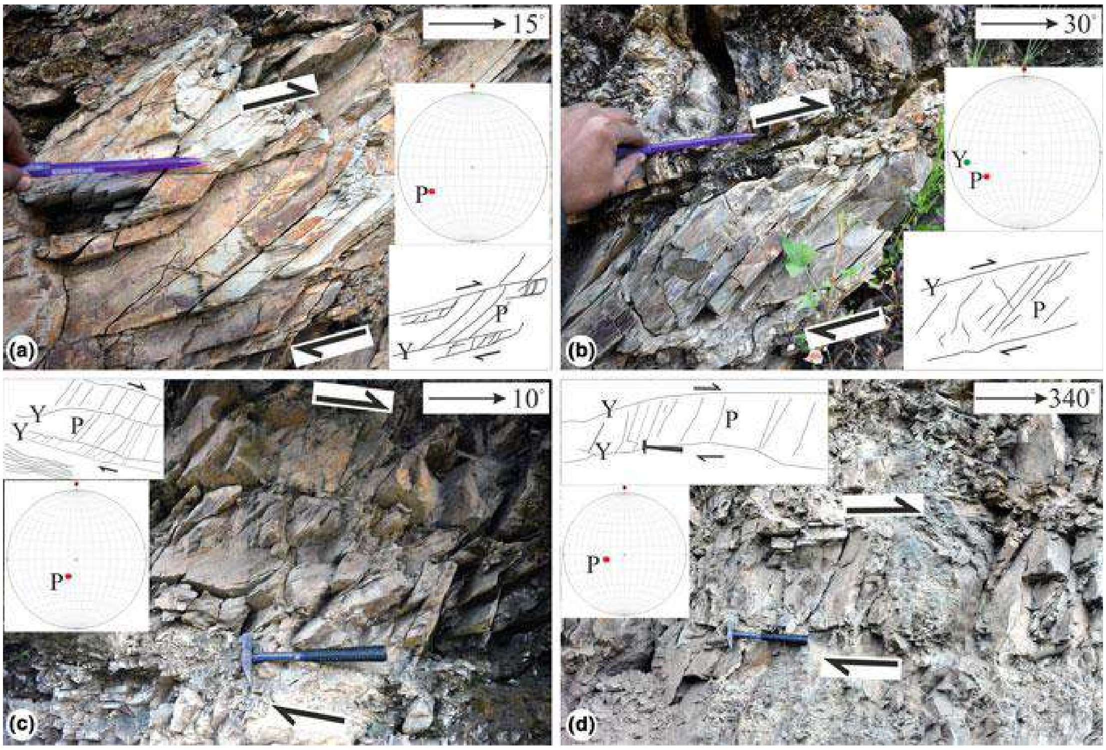

Fig. 8 Brittle shear planes in vertical sections close to L-12. **a** P-plane dips 30° towards 248°, top-to-NNE shear. **b** P-plane dips 40° towards 238°, top-to-NE shear. **c** P-plane dips 70° towards 190°, top-to-NNE shear. **d** P plane dips 65° towards 255°, at L-13. Top-to-NNW horizontal shear

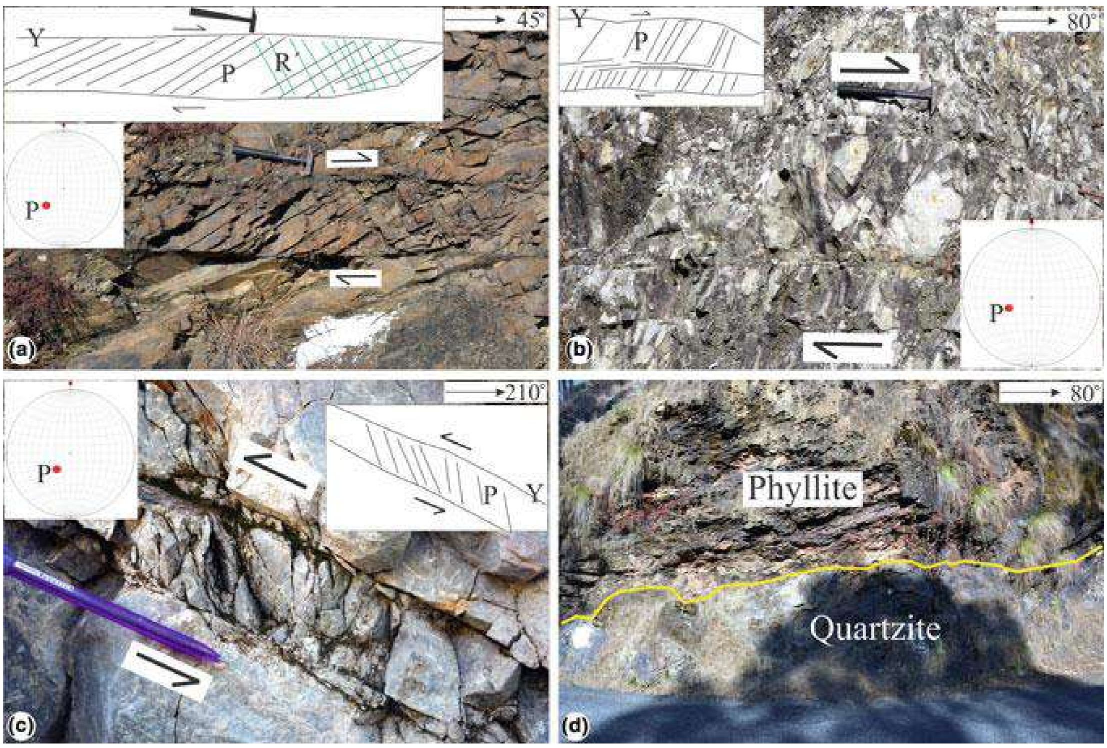

Fig. 9 **a** Clear-cut top-to-NE brittle shear observed in vertical section of slates. P-plane dips 46° towards 230°. **b** Top-to-NEE shear developed in white Ringalgarh quartzite. P-plane dips 58° towards 252°. **c** Top-to-NE up shear prominent in white quartzite. P-plane dips 65° towards 232°. **d** Sharp contact between quartzite and phyllite noted at L-19

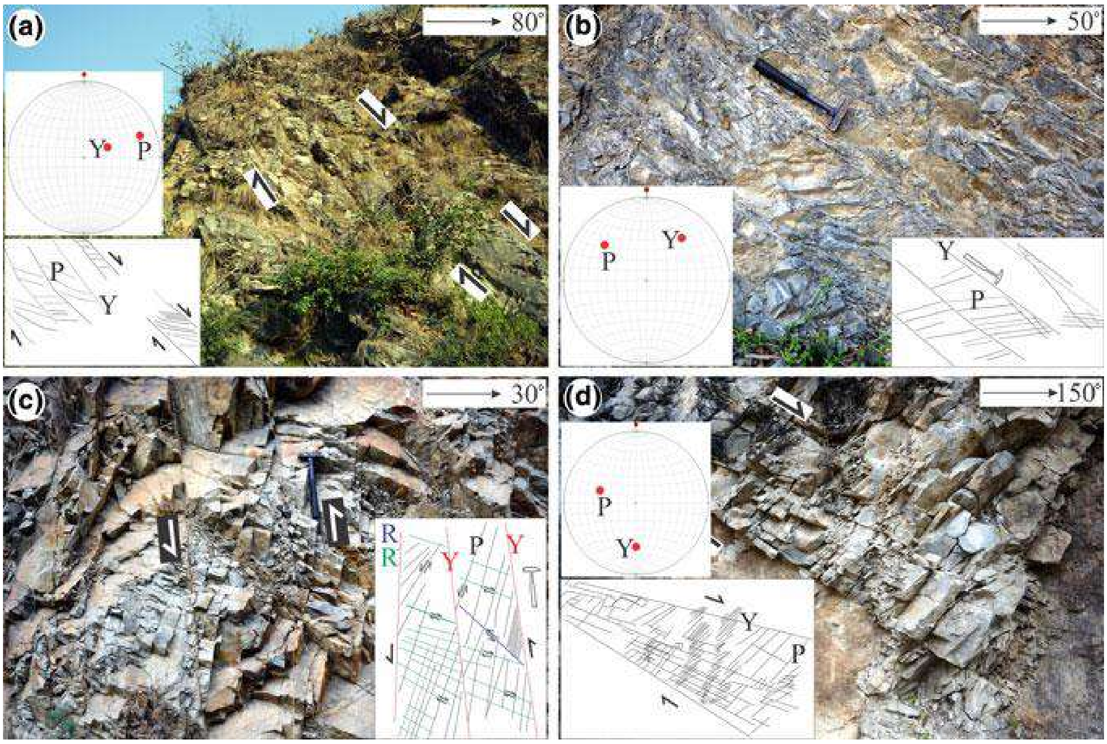

Fig. 10 **a** Top-to-NE down shear in quartzite. Y-plane dips 70° towards 78°, P-planes dips 15° towards 80°. **b** Top-to-SE down shear in shale. Y-plane dips 22° towards 38°, P-plane dips 28° towards 320°. **c** Field photograph showing vertical sensed of shear Y-, P-, R-, and R$'$-planes are marked. **d** Top-to-SE down shear in bedded quartzite. Y-plane dips 22° towards 180°; P-plane dips 36° towards 286°. **a**, **b**: sub-vertical sections; **c**, **d**: inclined sections

The second traverse was taken from Kathu-Khal to Satengal. At L-14, top-to-NE horizontal shear (Fig. 9a) was observed in slates. Near Satengal, at L-17 top-to-NE shear exists in quartzites. Top-to-NE up shear (Fig. 9b, c) occur at L-17 and 18 in white quartzites.

The third ~NE-SW traverse was taken from Raipur to Silla. At L-28 shear fractures are quite prominent in the quartzites showing top-to-NE down slip (Fig. 10a). About 1.5 km NE of L-28, top-to-SE down shear (Fig. 10b) occurs in black shale. Vertical slip (Fig. 10c) exists at L-31. Top-to-SE down shear sense (Fig. 10d) was observed at L-32. At L-33, top-to-SW down shear sense (Fig. 11a) was observed on quartzite. At L-34, top-to-NW up shear (Fig. 11b) was observed in quartzites, Near L-34, a top-to-NE up shear (Fig. 11c) was observed in white quartzite. Top-to-SW down shear (Fig. 11d) was observed at L-36 in black shale. All the observed shear senses are shown along the field traverses presented in Fig. 12.

Cross-sections (Figs. 13 and 14) were prepared along lines a–b close to Dhanaulti and along the line X–Y. The lines a–b and X–Y can be found in Fig. 12. The conventional method is used to draw the cross section. As we do not know the actual curvature at the limbs therefore straight lines are drawn to construct the fold. As sharp hinge bearing chevron folds were noted in the smaller scale (Figure with authors), a large fold of such geometry looks plausible (Fig. 14).

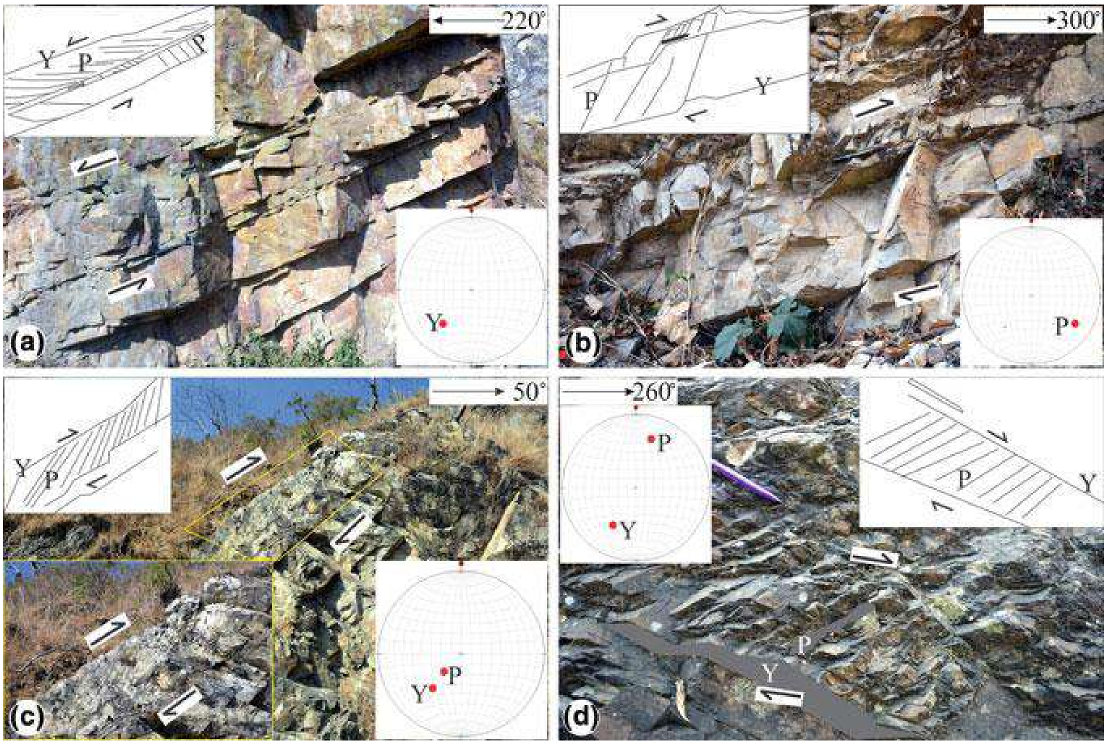

Fig. 11 **a** Shear fractures developed on quartzite showing top-to-SW down brittle shear sense. Y plane attitude dips 22° towards 223°; **b** top-to-NW up shear. P-plane dips 23° towards 218°. The rock type is quartzite. **c** Top-to-NE up shear. Y-plane dips 33° towards 226°, P-plane dips 62° towards 226°. Shear fractures developed quartzite. **d** Shear fractures developed on shale showing top- to-SW down shear sense. Y-plane dips 31° towards 222°, P-plane dips 15° towards 18°

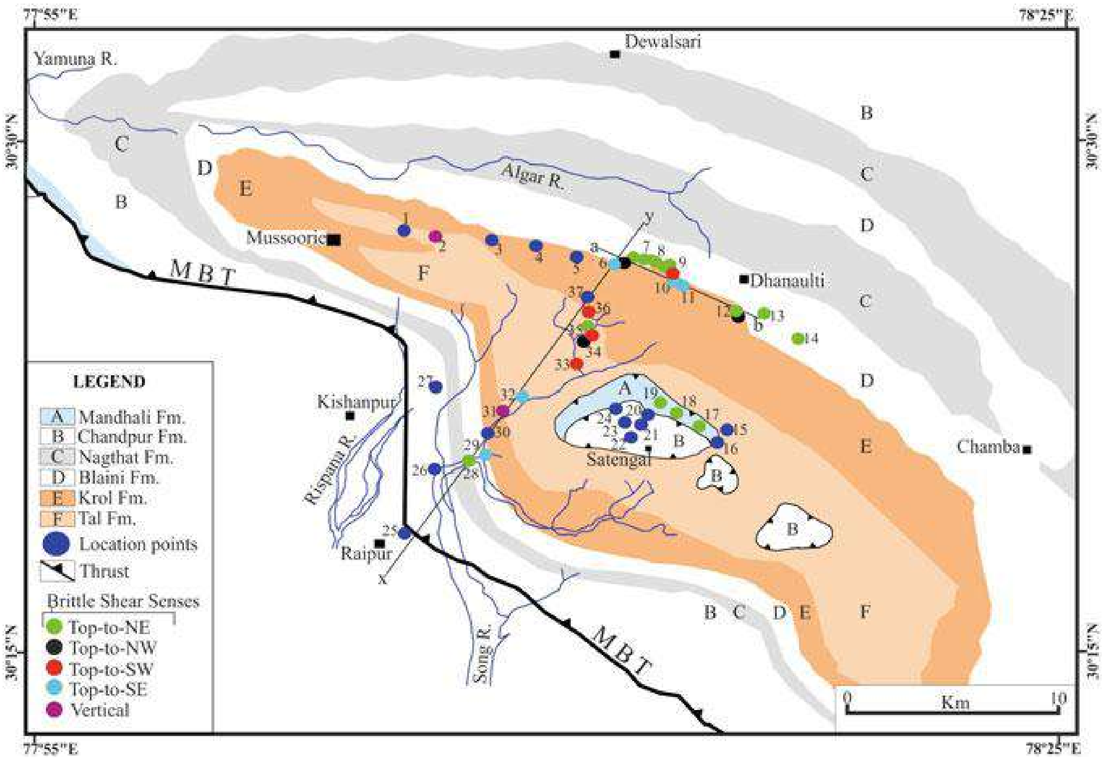

Fig. 12 Distributions of different brittle shear senses are shown in the map. The map is reproduced from Dubey and Jayangondaperumal (2005)

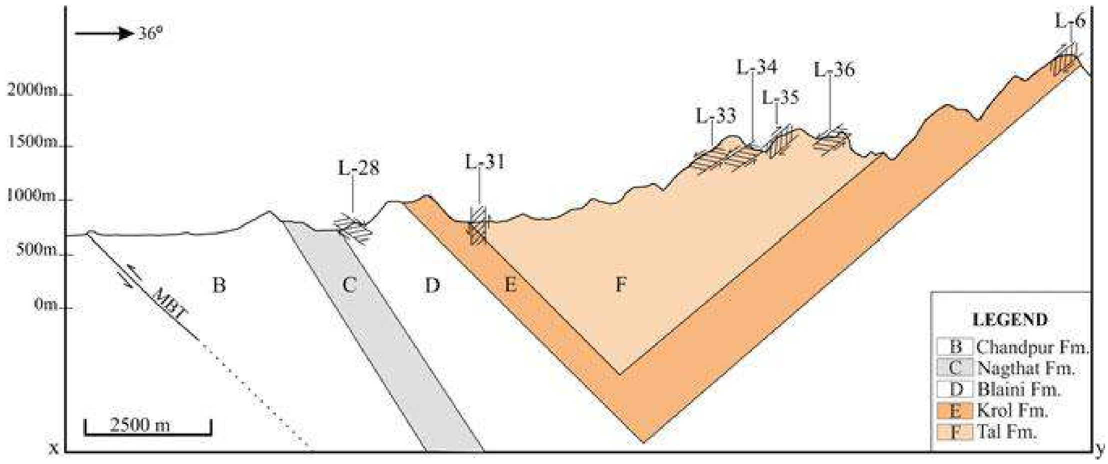

Fig. 13 Cross-section of the Mussoorie syncline is drawn along the X–Y line of Fig. 12. The X–Y line trends N36°E. B: Chandpur Fm, C: Nagthat Fm, D: Blaini Fm, E: Krol Fm, F: Tal Fm

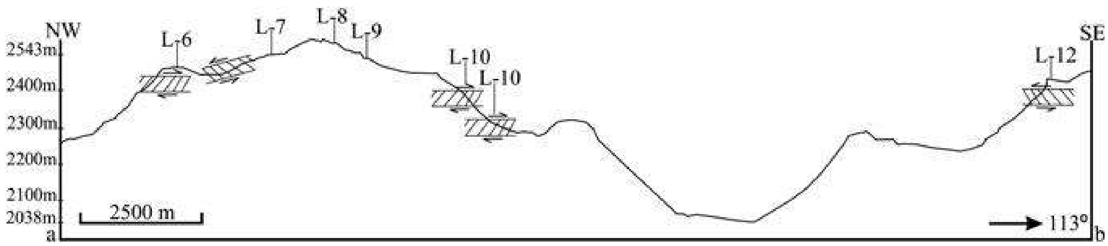

Fig. 14 A NW-SE profile along the line a–b of Fig. 13

This preliminary study reports Himalayan back-shear (top-to-NE) and arc-parallel shear (top-to-NW) for the first time in terms of meso-scale structures. We have been presently working on these issues in detail.

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