Structures of Lesser/Greater Himalaya in and Around an Out-of-Sequence Thrust in the Chaura-Sarahan Area (Himachal Pradesh, India)

Rajkumar Ghosh and Soumyajit Mukherjee

Abstract Field and thin-section documentation of structures in detail have been scarce from the out-of-sequence thrust (OOST) areas in the Himalaya. In this field guide, we present meso- and micro-scale structures in and around the OOST from the Chaura-Sarahan area (Himachal Pradesh, India).

1 Introduction

Several review papers present Himalayan tectonics as review (Yin 2006; Mukherjee 2013b). The southern portion of the Greater Himalayan Crystalline rocks of Himachal Pradesh can be encountered from the south of Jhakri up to the north of Wangtu along the Sutlej river section, Himachal Pradesh, India, along the National Highway 22A (Fig. 1). The southern boundary of this study is the Jhakri Thrust (JT) where brittle deformation and brecciated zones exist (Pandey et al. 2004; Miller et al. 2000; Misra and Gururajan 1994). The JT can be considered as the Main Central Thrust-Lower (MCT_L). The active JT plays a key role in the neotectonics of this area. Chambers et al. (2008) recognized the Sarahan Thrust (ST) around the Sarahan village, in between the Vaikrita Thrust (VT) at north and the JT at south. Singh (1979) reported a dislocation zone in the Jeori area. These thrusts JT, Jeori dislocation and ST could be a part of single larger-scale thrust. Singh (1980) described in great detail fold morphologies from Sarahan and surrounding regions, but the tectonic interpretation of these folds was not presented.

The Greater Himalayan Crystallines (GHC) lies between the Main Central Thrust Zone (MCTZ) in the south and the South Tibetan Detachment System (STDS) in the north. It comprises medium to high grade metamorphic rocks ranging from kyanite/staurolite/garnet bearing schist to quartz rich mica schist.

The Jhakri Thrust, active since <4.5 Ma, is also locally named as the Jutogh Thrust (Misra and Gururajan 1994). The Jakhri Thrust (Zone) dips 50° towards

R. Ghosh · S. Mukherjee (✉)
Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400076, Maharashtra, India
e-mail: soumyajitm@gmail.com; smukherjee@iitb.ac.in

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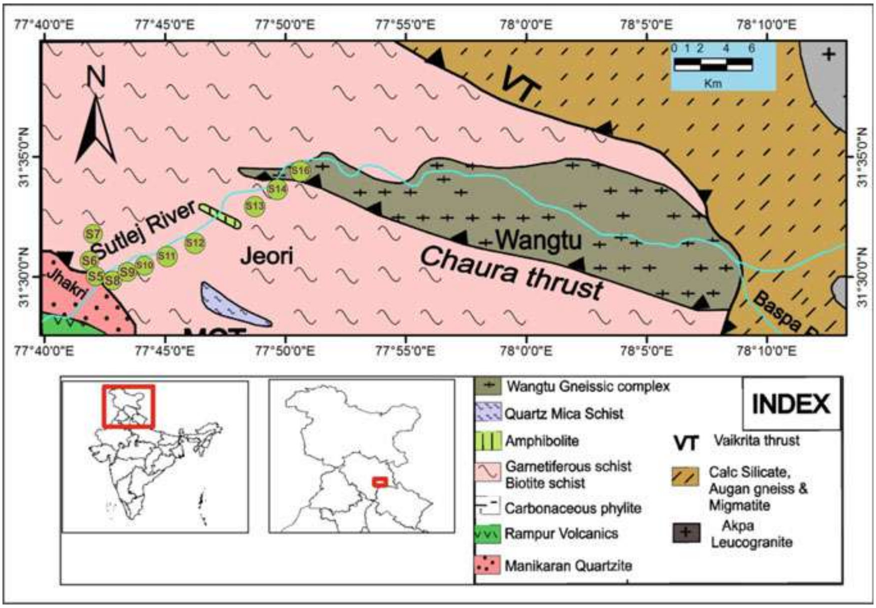

Fig. 1 Lithological map of Chaura area, Himachal Pradesh (Higher Himalaya). Reproduced from Jain et al. (2000). MCT: Main Central Thrust; VT: Vaikrita Thrust; KT: Kulu Thrust. S7, etc.: sample locations

NE and is presumably 15–17 km deep (Pandey and Virdi 2003). The MCT, or the MCTU (Mukherjee and Koyi 2010), or the 'True MCT' based on difference in εNd signature (Ahmad et al. 2010; Chambers et al. 2009) are the alternate designations of the Vaikrita Thrust. The Chaura Thrust, an out-of-sequence thrust (OOST; Jain et al. 2000; Mukherjee 2015a), is located near the 'Kinnaur Dwar' in the Kinnaur district. The Chaura area lies within the MCTZ. Singh and Jain (1993) reported ductile shear based on N/NE-dipping C-planes and associated S-planes. They also reported a flattening type of finite stain from their study area. Main foliations near the Chaura Thrust dip steeper (65–75°, at places even sub-vertical) than those further south (45–50°).

Below we present structures from the transect as shown in Fig. 1. The transect will be quite effective in demonstrating student Himalayan structures and explaining their significance, such as fore-thrusting and fore folding. Mukherjee et al. (2019) performed analogue models for out-of-sequence deformation (OOST). Using crustal channel flow mechanism in dynamically scaled models in the lab, they explained the genesis of the Greater/Lesser Himalayan OOST such as the Chaura Thrust. Recently, Dutta and Mukherjee (2019) reported opposite ductile shear senses based on thin-section study of rocks from this transect and explain it in terms of a general shear mechanism.

2 Structures

Y- and P-planes: These planes are curved. The brittle deformations are very prominent in the Rampur Quartzite/Manikaran Quartzite. Y-planes in Jhakri dip towards NE (Fig. 2). The Jhakri Thrust is located in between the quartzite and the mica schist. This is indicated by highly fractured and crushed nature of the quartzites.

Veins: Quartz veins of various regular and irregular shapes are noted. Thickness of the vein varies along their length although few cases also exist for uniformly thick veins. Veins can be (i) parallel C-plane, (ii) fold and cut across C-plane, and they are not bound by a pair of C-planes, (iii) isolated sigmoid veins show ductile top-to-S/SW shear. Veins can be faulted or warped (Fig. 3). Sometimes across the vein as cross-cutting elements, the gneissic foliation of the host rock is locally curved. Thus, a flanking structure (Mukherjee 2014a) is defined (Fig. 4).

S-C fabric and other structures

Ductile sheared rocks are usually mylonitized. Oriented thin sections were prepared such that those are perpendicular to main foliation and parallel to lineation. Where lineations are absent sections were prepared perpendicular to main foliation and parallel to the dip direction of the foliation planes. The C-planes can be wavy (Figs. 5, 6 and 7). The S- and the C-planes make <45° angles and usually range 20–30°.

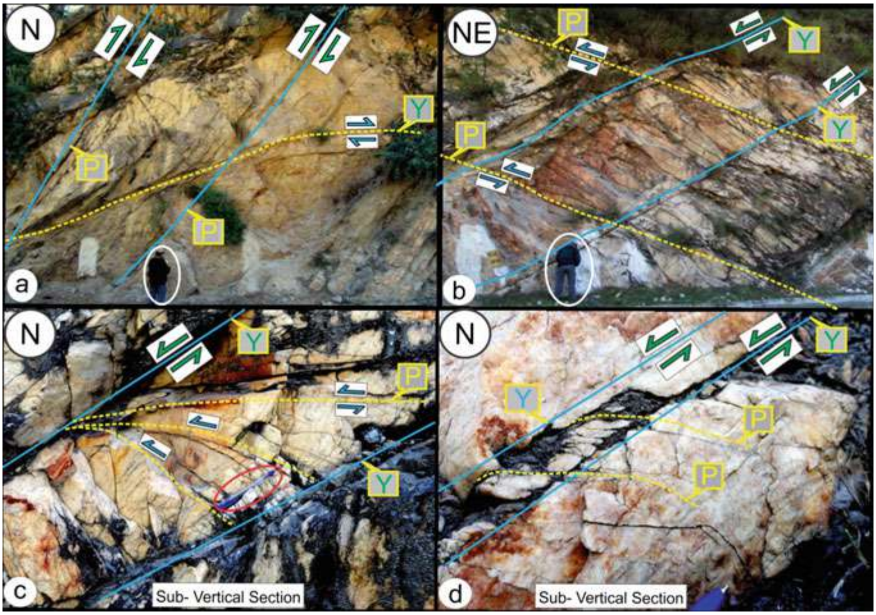

Fig. 2 Brittle shear planes in Jhakri area (location: S5 in Fig. 1). **a** Sense of brittle shearing: primary shear Y-plane dips towards NE, in quartzite

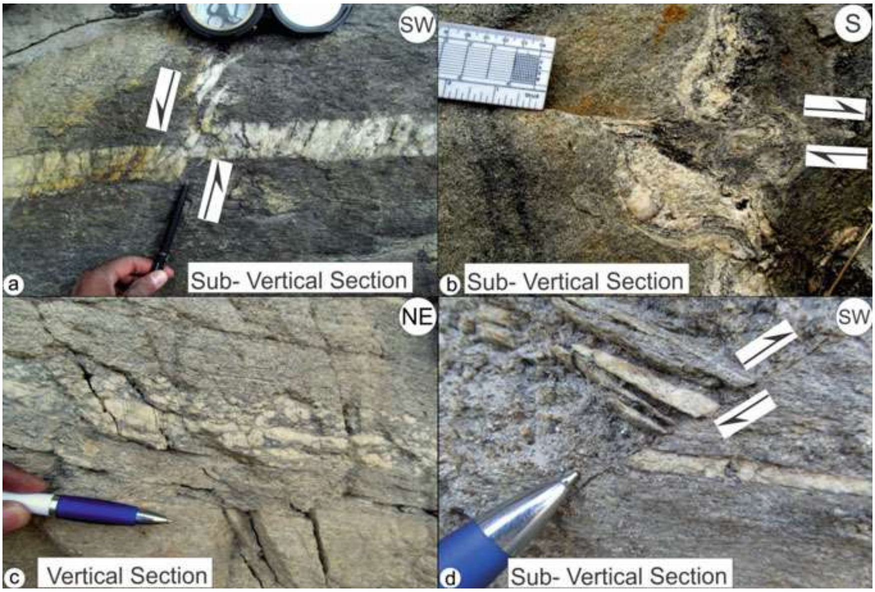

Fig. 3 Top-to-S/SW brittle faulted quatz veins. **a** near Ponda, **b** near Taranda Devi temple, **c, d** Nichar village

Curved and elongated mica grain represents prolonged deformation parallel to C-plane. One needs to be cautious in interpreting structures in micro-scale as numerous other features not necessarily related to ductile shear are also documented (Fig. 8). Symmetric structures (Mukherjee 2017) are also documented that do not indicate any shear sense. Interestingly, close to the Chaura Thrust, shear sense indicators in thin section are extremely prominent (Fig. 9). Consult Passchier and Trouw (2005), Mukherjee (2011, 2013b, 2014b, 2015b, 2020, 2021) and Misra and Mukherje (2018) as easy texts to study shear senses. Refer to Finch et al. (2020) for recent understandings on secondary ductile shear C/-planes.

Asymmetric and symmetric boudins and pods (Figs. 10, 11, 12, 13, 14, 15, 16 and 17)

Boudins and pinch-and-swell structures indicate layer-parallel local brittle/ductile extension. These are found in quartzofeldspathic schistose rock with variation in thickness and shape. Scar folds associated with boudins develop inside the inter-boudin space. Boudin trend locally parallel the C-plane. Sometimes, fractures are found restricted within the boudinaged clasts that do not continue within the host rocks. Asymmetric boudins indicate ductile shear sense: mostly top-to-SW/SSW. Symmetric clasts of boudins do not show shear sense. Intra-boudins morphological variations were encountered: (i) internal foliation parallels to boudins boundary, (ii) internal foliation at high-angle to the boudins boundary and (iii) curved internal foliations inside the boudinaged clast.

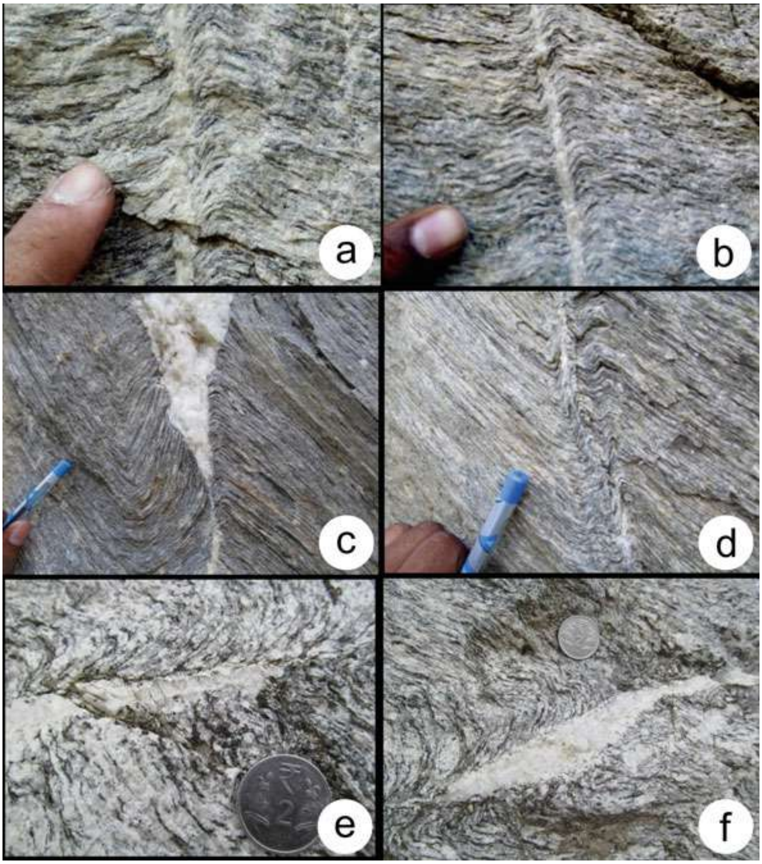

Fig. 4 Quartz veins of diverse shapes defining cross-cutting elements that sometimes locally swerve the host fabric elements defined by gneissic foliation. Here, **c** is the only case where a locally folded hinge region seems to be intruded by a vein. Near Manglad

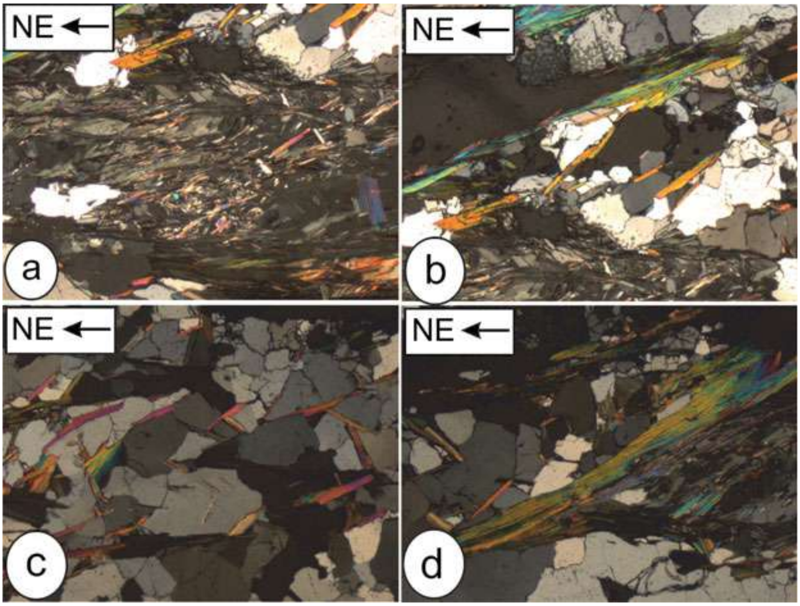

Fig. 5 **a**, **b**, **d** S-C fabric: top-to ~ S ductile shear (in images top-to-right). **c** Crenulation cleavage, not to be confused with S-C fabric! No shear sense indicated. Location: S10 (see Fig. 1)

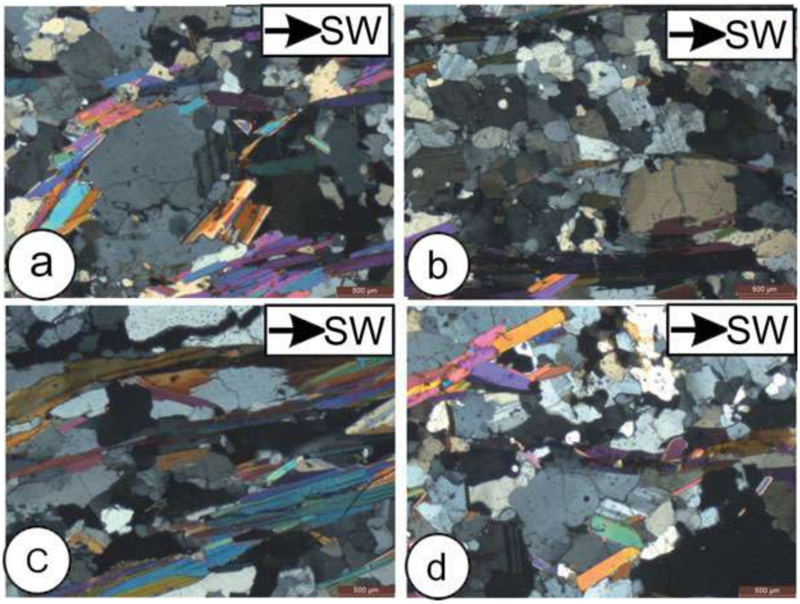

Fig. 6 Mica grains in quartzofeldspathic matrix. Out of the four examples, only **a** defines S-C fabric with top-to-SW shear. Location: S10 (see Fig. 1)

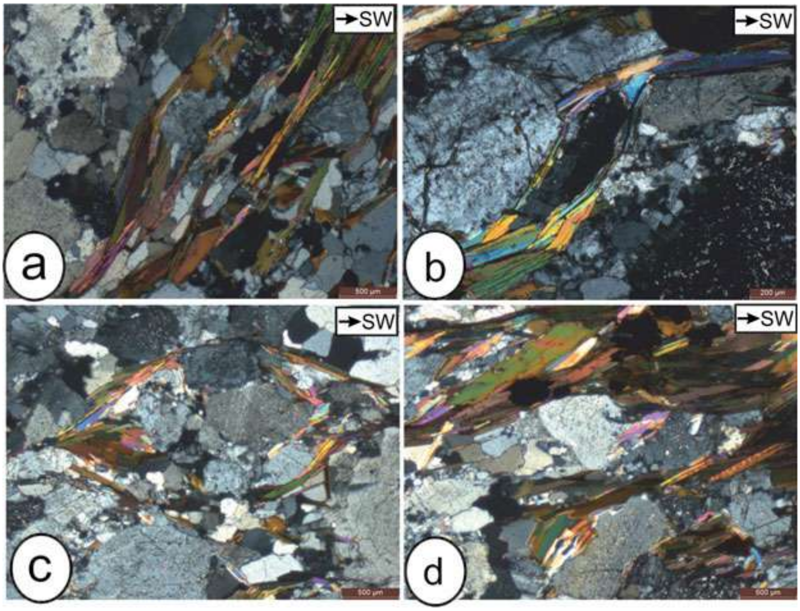

Fig. 7 Mica grains in quartzofeldspathic matrix. **a, b, d** gives ductile shear top-to-S/SW sense. **c** micas wrap few quatzofeldspathic grains: overall symmetric shape, no shear sense indicated. Location: S9 (see Fig. 1)

Deformed asymmetric clasts (Figs. 18 and 19)

Sigma-like structures of quartz and feldspar grains are common in field and under thin sections. These reveal a top-to-S/SW shear. Few clasts are fractured, but still then in some cases, the sigmoid shape of the clast can be easy deciphered.

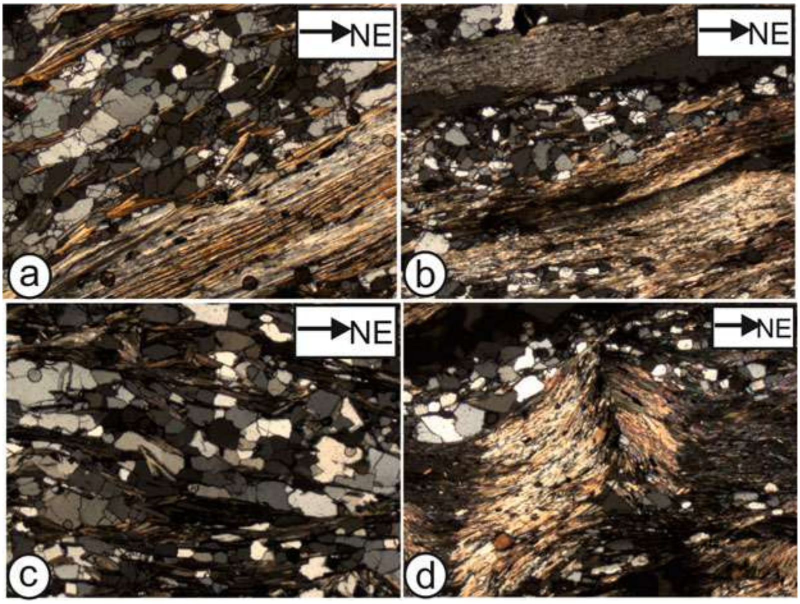

Fig. 8 Mica grains in quartzofeldspathic matrix. None of them are convincing shear sense indicators. These are not S-C fabrics. Here, **d** shows strong folding restricted inside mica aggregates. Location: S8 (see Fig. 1)

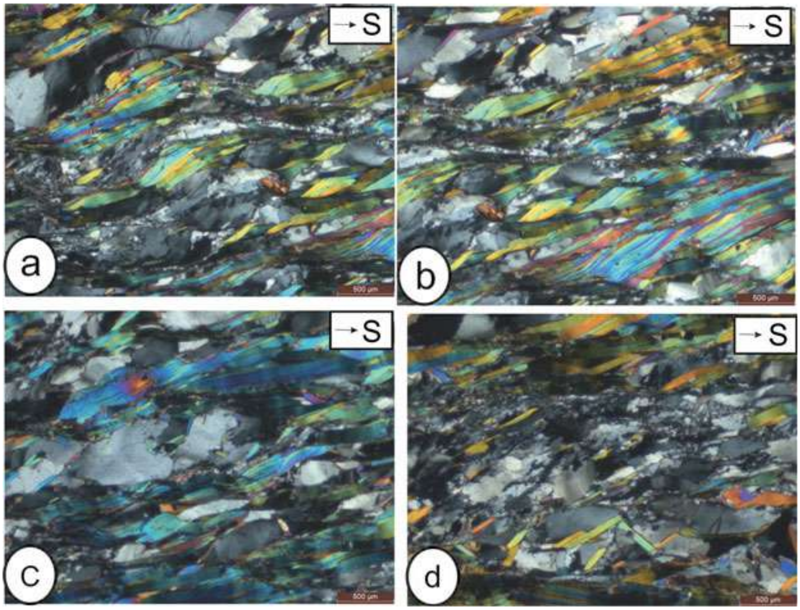

Fig. 9 Strong top-to-S shear sense indicated by sigmoid moca fish and curved recrystallized matrix materials. Location: S8, Chaura Thrust area (see Fig. 1)

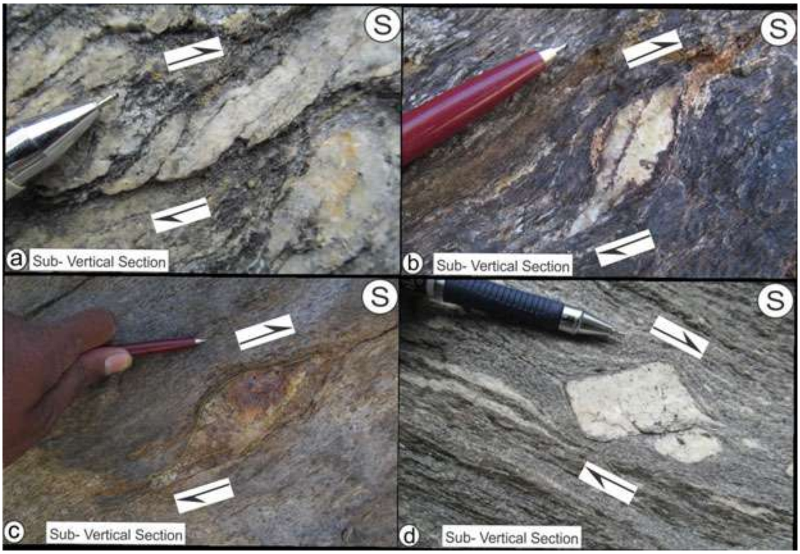

Fig. 10 **a**–**c** Top-to-SW compressional shear revealed by asymmetric quartz veins, **d** top-to-SW extensional shear revealed by a clast

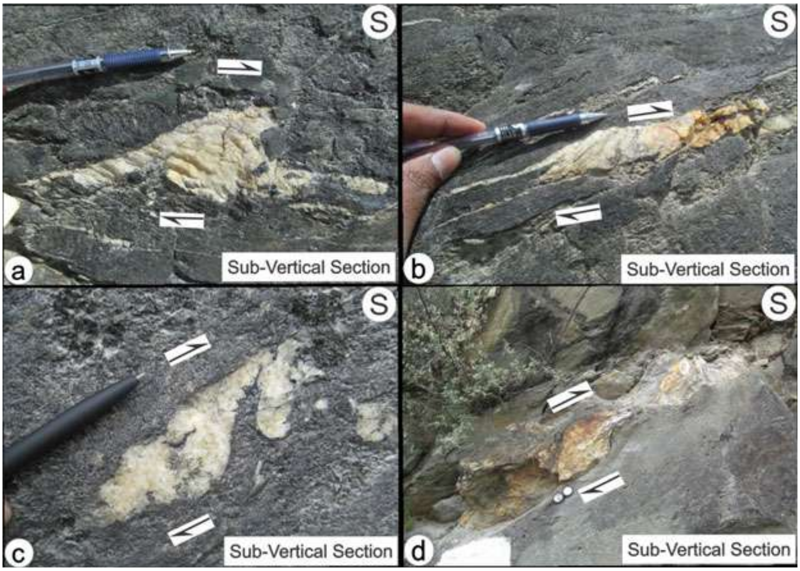

Fig. 11 Top-to-S ductile shear revealed by quartz veins of various geometries

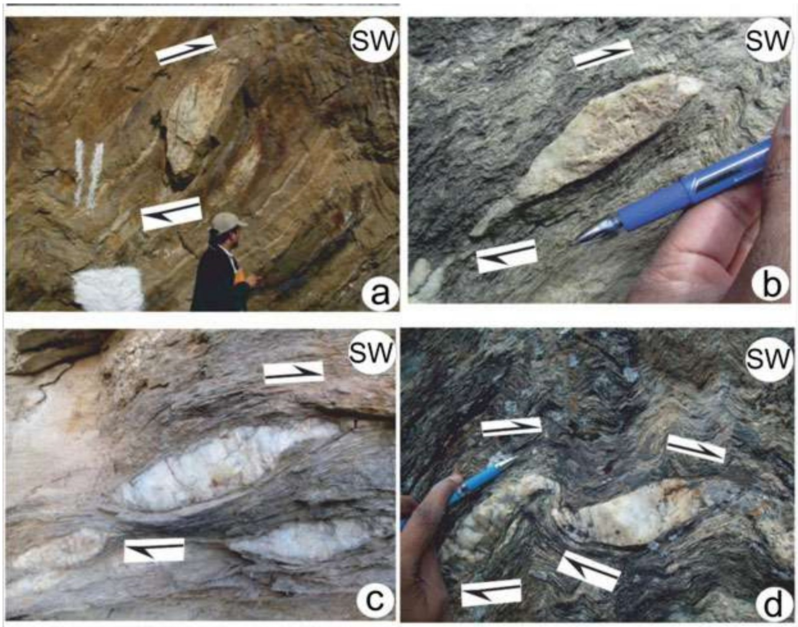

Fig. 12 Quartz pods/boudinaged clasts of various sizes display top-to-S shear sense. **b, d** intensely folded mylonitized rock

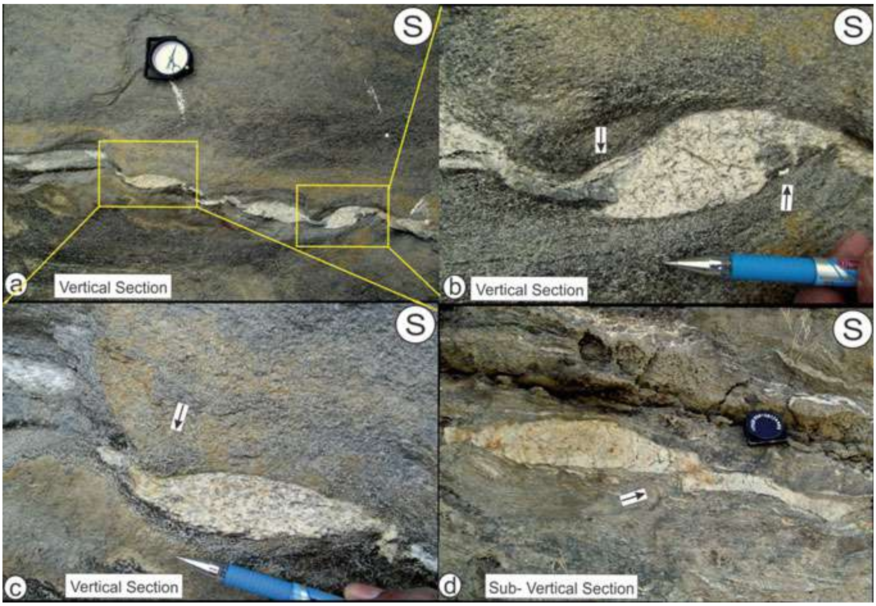

Fig. 13 **a** Boudin train, **b, c** zooed parts of the previous sub-figure, **d** slipped boudin of irregular geometry. Black full arrows: scar folds

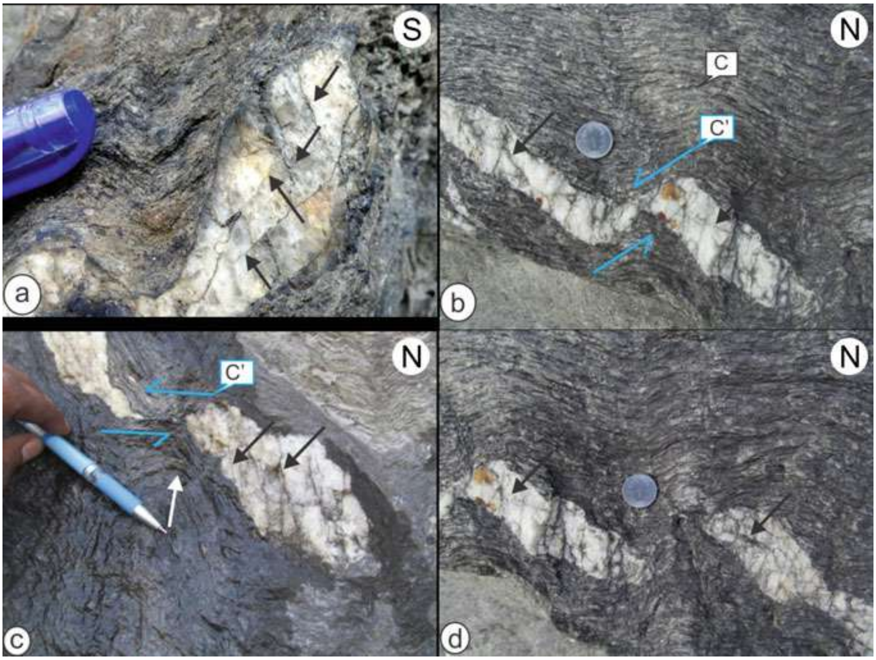

Fig. 14 Fractures quartz veins show overall a top-to-S ductile shear. South of Wangtu

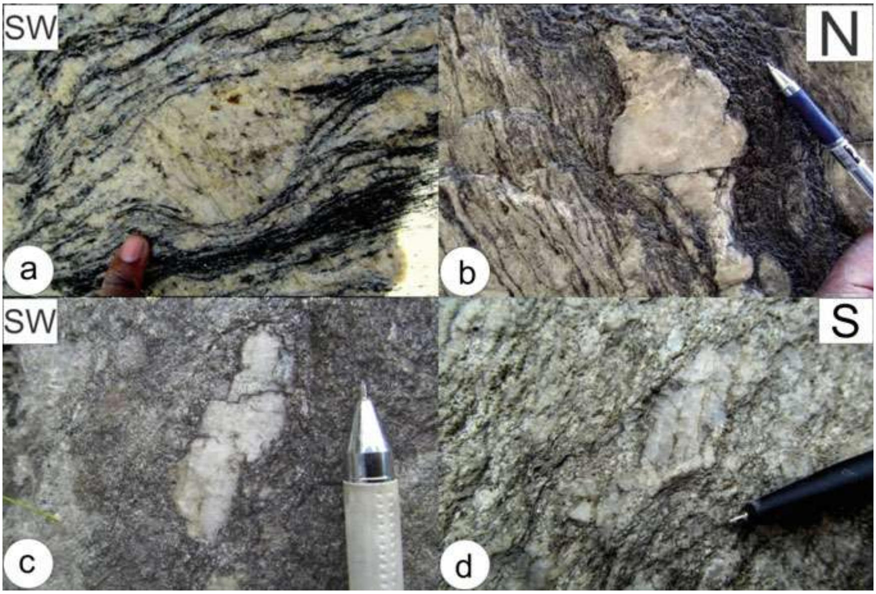

Fig. 15 Fractured quartz clasts, **b, d**: convincing top-to-S shear

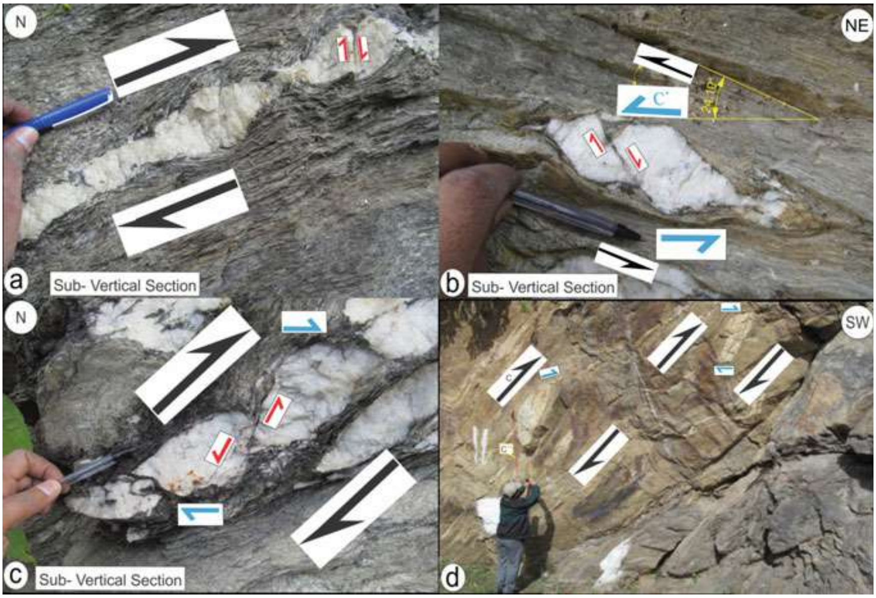

Fig. 16 Top-to-S ductile sheared quartz vein. Towards Majgaon

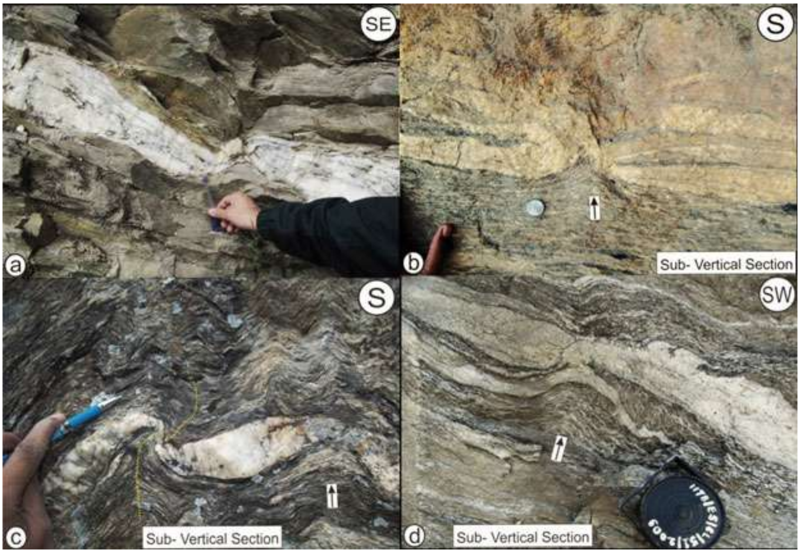

Fig. 17 Quartz veins showing clear cut boudinaging of various geometries. Black full arrows: scar folds. Near Sarahan village

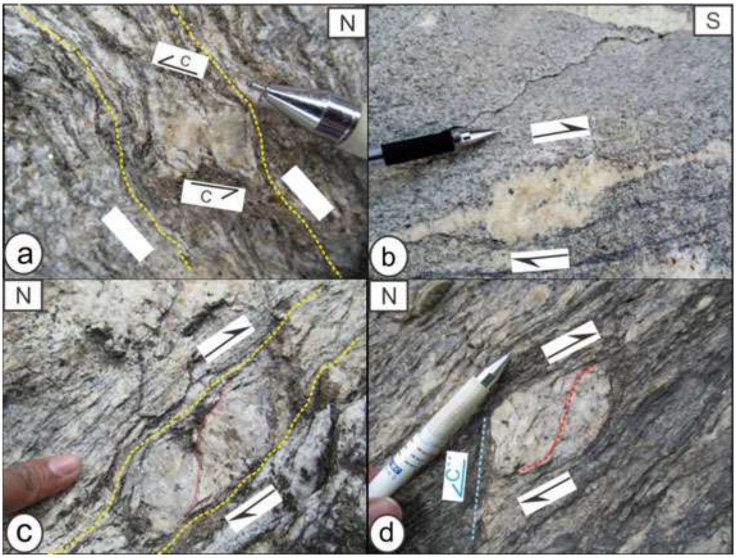

Fig. 18 Clasts **a, c, d** and vein **b** showing shear sense. For **b–d**: internal foliation (S_i) defines the shear sense. Near Chaura. In **a**, we kept two white boxes. Note the photograph and try to put half arrows there

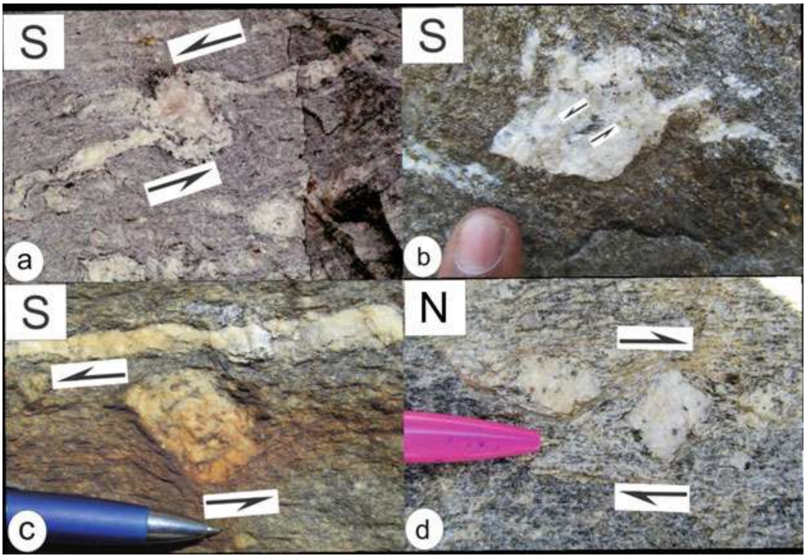

Fig. 19 Ductile shear sense deduced from clasts. **a** Looks like a delta structure (also see Mulchrone and Mukherjee 2019, 2020). **b** Biotite inclusion inside quartz body gives a shear sense. See Mukherjee (2014b) for inclusion of minerals giving shear sense

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