FLANKING MICROSTRUCTURES OF THE ZANSKAR SHEAR ZONE, WESTERN INDIAN HIMALAYA

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Abstract - Rocks of the Zanskar Shear Zone in micro-scale reveal flanking microstructures (FM). Mineral grains defining the cross-cutting elements (CE) of the type 1 FM demonstrate a wider range of aspect ratios and inclinations, crystal-plastic deformation, either rotation or strain partitioning under a top-to-SW sense of ductile shearing of ~ 22-16 Ma, and the presence of hazy zones at one of their margins despite any rheologic softening. Another variety of the type 1 FM is defined by northeasterly steeply dipping fault planes as the CE that brittle-ductilely affected the incompetent minerals. The CE of the type 2 FM post-tectonically grew in almost opposite directions, presumably as a < 16 Ma event, but does not indicate any deformation in the meso-scale.

Keywords: Flanking Microstructures, Flanking Structures, Ductile shearing, Himalaya, Microstructures, Shear sense indicator, Zanskar Shear Zone

Abbreviated title: Flanking microstructures

1. INTRODUCTION

Passchier (2001) defined ‘flanking structures’ as ‘deflection of planar or linear fabric elements in a rock alongside a cross-cutting object’. The deflected rock fabric and those which cut them are defined as the internal host fabric- and the cross-cutting elements (the internal HE and the CE), respectively (Fig. 1a). The undeflected fabric away from the CE is called the external host fabric element (external HE). Depending on the relative senses of drag and slip of the internal HE along the CE, flanking structures are classified into the s- and the a-types (Fig. 1b and caption) (Grasemann et al. 2003). Flanking structures were documented mainly from field-scale. Recently, Mukherjee & Koyi (2009) extensively reported these structures under an optical microscope in XZ-oriented thin-sections of sheared rocks of the western Indian Higher Himalaya and designate them as ‘flanking microstructures’ (FM) (also see Jain & Mukherjee 2009). Nucleated minerals are defined as the CE and deflected cleavages and margins of the host grains as the HE. The zone within which the internal HE are confined is called the ‘internal HE zone’. A wide morphological variation of the HE and the CE of the FM have been reported (see Mukherjee & Koyi, 2009).

Mukherjee and Koyi (2009) classified the FM into the type 1 and the type 2 varieties. The CE of the type 1 FM are ductile sheared into either parallelogram- or sigmoid shapes (Figs. 2a-c). The sense of drag of the internal HE across the CE are opposite in such types of FM. On the other hand, the CE of the type 2 FM grew post-tectonically at high angle to the external HEs. The senses of drag of their internal HE at the opposite margins of the CE are the same (Fig. 2d). Thus, these types of the CE are the products of grain growth, are unrelated to ductile shearing, and are indicative of micro-scale event that are not related to tectonics. That such senses of the HEs, restricted only at their contacts with the CE, cannot be due to folding of the mylonitic foliation (as shown in fig. 7.34e of Passchier and Trouw, 2005) is confirmed by nearly straight foliation planes away from the host mineral grains in the studied thin-sections. Further, had the growth of the CE been pre-tectonic, the internal HEs should not have cut across by the former grains and bowing up of the HEs around the CE would be expected (as in fig. 17.13a in Philpotts and Ague, 2009). The fact that these CE are themselves not ductile sheared into sigmoid, parallelogram of lenticle shapes are clear indication that the former are certainly not syntectonic (to the ductile shearing).

In this work, I present morphological variation and kinematics of the type 1 and the type 2 FM from the Zanskar Shear Zone (ZSZ). Some of these FM possess more pronounced drag and slip of the internal HE than what were reported in Mukherjee & Koyi (2009).
Fig. 1: (a) Diagrammatic representation of flanking structure. Reproduced from Fig. 1 of Passchier (2001) and (Mukherjee & Koyi, 2009). (b) Different senses of slip and drag of the HE in flanking structures. Reproduced from Fig. 1 of Grasemann et al. (2003).

Fig. 2: Types of flanking microstructures (FM) from their natural examples in Mukherjee & Koyi (2009); (a-c) are type 1 FM with parallelogram or sigmoid-shaped cross-cutting elements (CE) with opposite senses of drag of the internal host fabric elements (HE) across the CE, (d) is a type 2 FM with the same sense of drag (concave-up) of the internal HE along both sides of the CE.

2. GEOLOGY

The ZSZ (Fig. 3) is the northern boundary of the western Indian Higher Himalaya and comprises dominantly of mylonitized gneisses, leucogranites and migmatites (Jain et al. 2005; Yin 2006 and their references). The structural geology of this area has been discussed in detail by previous workers, e.g. Herren (1987), Patel et al. (1993), Dèzes (1999), Dèzes et al. (1999), Walker et al. (1999) and recently compiled by Mukherjee and Koyi (2010) and Mukherjee (2010). The ZSZ reveals
dominantly a top-to-NE sense of ductile shearing (e.g. Patel et al. 1993) that was a result of a channel flow mode of extrusion of the Higher Himalaya concomitant to the generation of granitic melt during 18-16 Ma (Inger 1998; Godin et al. 2006 and their review; Mukherjee & Koyi 2009b). Recently the channel flow model (Beaumont et al., 2001) has evolved as an almost unanimously accepted extrusion mechanism of the ZSZ (e.g. Mukherjee, 2005). Patel et al. (1993) first identified from field-studies a relict top-to-SW sense of ductile shearing along the same shear planes (‘C-planes’ of Passchier & Trouw 2005) that dip towards northeast. This sense of shearing is also rarely documented from mineral fish in micro-scale (Mukherjee 2007). Mukherjee (2010a) documented these shear senses from micro-scales and deciphered an oldest top-to-SW shearing of ~22-16 Ma; subsequent top-to-NE sense of shearing and finally a top-to-NE (down) sense of ductile shearing of ~18-16 Ma. On the other hand, based on mica cooling ages and ^40Ar/^39Ar hornblende ages as given by the previous workers, the southwesterly shearing in the Higher Himalaya including the ZSZ was interpreted by Jain et al. (2002) to initiate during the early phase of the Neo-Himalayan Period ~ 25 Ma. Northeastern steeply dipping brittle normal faults cut across the C-planes (Patel et al. 1993). Thin-sections of sheared rocks from the ZSZ, southeast to the locality Padam oriented perpendicular to the C-planes and parallel to the northeasterly plunging stretching lineations were studied.

3. FLANKING MICROSTRUCTURES

Both the type 1 and the type 2 varieties of the FM (Mukherjee & Koyi 2009) are observed in the ZSZ- but the former type occurs more frequently. The CE minerals of the type 1 FM are commonly parallelogram-shaped with a pair of opposite margins parallel to the external HE. In order to present their geometry and orientation, a few parameters of these CE are defined (Fig. 4), similar to mineral fish of ten Grotenhuis et al. (2002) and Mukherjee (2011). The aspect ratio of the CE is the ratio between the length of its diagonal (inclined at the external HE in the same direction as the grain itself) to that of the line contained inside the grain through the corner and perpendicular to that diagonal. The inclination of the diagonal is the acute angle between it and the external HE. The inclination of the CE grain is the acute angle between the external HE and its parallel sides. For individual CE, the side is more steeply inclined than the diagonal. To explain further, let ABCD be the grain with the side AD parallel to the external host fabric element EF (see Fig. 4). DT is a line perpendicular to the diagonal AC. The ratio of the distances between AC and DT is defined as the aspect ratio. The acute angle between CD and EF is the inclination of side of the grain. The acute angle between CA and EF is the inclination of the diagonal. In case the grain is nearly parallelogram-shaped such as ABMND (Figs. 5b, 6a-b, -d, grains ‘1’ and ‘3’ in Fig. 7a as natural examples), the parallelogram shape ABCD is first constructed and the parameters are measured.

The CE of the observed FM are more often micas (muscovite and biotite, Figs. 5b-d, 6a-d, 7a, -d, 8a) but can also be tourmaline (Fig. 5a) and alkali feldspar (Fig. 8b). The type 1 FM are defined in two ways. These are (i) nucleated minerals that cut across cleavages and grain margins of the host minerals (Figs. 5a-d, 6a-d, 7a); and (ii) northeasterly steeply dipping fault planes that drag and slip the foliation planes (Fig. 7d). The former kinds of the type 1 FM are rather common in the ZSZ. A train of irregular-shaped sheared minerals (Fig. 5a) or more commonly a single mineral (Figs. 5b-d, 6a-d, 7a) act as the CE. The CE are thicker than the associated internal HE zones. In some cases, the CE geometries are a little irregular and are neither perfectly parallelogram (Figs. 5b, 6a-b, -d) nor sigmoid (Fig. 5a). These type 1 FM are constituted by the CE minerals that have either more competency than the host minerals (Fig. 5a) or are nearly the same (Figs. 5b-d, 6a-d, 7a). The aspect ratios and the inclination of the sides and the diagonals of the CE of the type 1 FM in the ZSZ are within the ranges of 1.61-15, 30-88° and 25-80°, respectively. Interestingly, from Figs. 2 to 4 of Mukherjee & Koyi (2009) of other sections of the western Indian Higher Himalaya, these ranges are obtained as 2.18-7.68, 29-60° and 18-38°, respectively. On the basis of these, and along with the individual observations (especially Figs. 5b-d, 6a-d, 7a),

![Fig. 4: Aspect ratio and inclination of a parallelogram-shaped cross-cutting element (CE) mineral.](image-url)
Fig. 5(a): Photo in plane polarized light (Thin-section number-P9/N) showing type 1 flanking microstructure is defined by three nearly sigmoid-shaped tourmaline grains as the cross-cutting elements (CE) and deflected much thinner biotite grains as the host fabric elements (HE). The near sigmoidality of the CE minerals indicates a top-to-SW sense of ductile shearing that acted along the external HE enveloping those grains. Opposite senses of drag of the internal HE across the CE is noted, e.g. concave-up at arrow ‘p’ and convex-up at arrow ‘q’. The approximate inclination of the side AB of one of the CE grains is ~ 36°. Photo width: 1 mm.

Fig. 5(b): Photo in plane polarized light (Thin-section number-P9/G) showing type 1 flanking microstructure where a biotite grain acts as the cross-cutting element (CE). The cleavage planes of the host biotite grain are the host fabric elements (HE). The right margin of the CE shows the internal HE to be strongly convex-up. Warped cleavages of the CE mineral indicate that it underwent some amount of internal deformation. Nearly parallelogram shape of the CE indicates a top-to-SW sense of ductile shearing. The aspect ratio and the inclination of the side and the diagonal of the CE are 4.82, 34° and 25°, respectively. Photo in plane polarized light. Photo width: 0.5 mm.

Fig. 5(c): Photo in plane polarized light (Thin-section number-P9/D) showing type 1 flanking microstructure where a muscovite grain acts as the cross-cutting element (CE). The cleavage planes of the muscovite host grain are the host fabric elements (HE). A few HE at the left margin of the CE are strongly convex-up (arrow). The right margin of the CE shows straight HE (arrow). The parallelogram shape of the CE indicates a top-to-SW sense of ductile shearing. The aspect ratio and the inclination of the side and the diagonal of the CE are 2.66, 55° and 31°, respectively. Photo in plane polarized light. Photo width: 0.5 mm.

Fig. 5(d): Photo in plane polarized light (Thin-section number-P9/A) showing type 1 flanking microstructure where a muscovite grain acts as the cross-cutting element (CE). The cleavage planes of the muscovite host grain are the host fabric elements (HE). The left margin of the CE shows a rather thick hazy internal HE zone with convex-up drag (arrow). The HE at the right margin of the CE are straight (arrow). The parallelogram shape of the CE indicates a top-to-SW sense of ductile shearing. The aspect ratio and the inclination of the side and the diagonal of the CE are 1.81, 53° and 31°, respectively. Photo in plane polarized light. Photo width: 0.5 mm.
Fig. 6(a): Photo in plane polarized light (Thin-section number-P9/O) showing type-1 flanking microstructure where a nearly parallelogram-shaped muscovite grain acts as the cross-cutting element (CE). The cleavage planes of the host biotite mineral are the host fabric elements (HE). At the right margin of the CE, strongly convex-up (arrow ’m’) and gently concave-up (arrow ‘n’) internal HE are noted. At the left margin of the CE (arrow ‘r’) the internal HE are gently concave-up. The aspect ratio and the inclination of the side and the diagonal of the CE are 2.95, 68° and 57°, respectively. Photo width: 0.5 mm.

Fig. 6(b): Photo in plane polarized light (Thin-section number-P9/K) showing type 1 flanking microstructure with muscovite as the cross-cutting element (CE). The cleavage planes of the biotite host grain are the host fabric elements (HE). The right margin of the CE shows concave-up internal HE. The HE at the left margin of the CE are indistinct. Nearly parallelogram shape of the CE indicates a top-to-SW sense of ductile shearing. The aspect ratio and the inclination of the side and the diagonal of the CE are 6.5, 50° and 44°, respectively. Photo width: 0.5 mm.

Fig. 6(c): Photo in plane polarized light (Thin-section number-P9/C) showing type 1 flanking microstructure with muscovite as the cross-cutting element (CE). The cleavage planes of the muscovite host grain are the host fabric elements (HE). The HE are concave-up only at a part of the left margin of the CE- right to the blue line. Nearly parallelogram shape of the CE indicates a top-to-SW sense of ductile shearing. The aspect ratio and the inclination of the side and the diagonal of the CE are 3.13, 65° and 40°, respectively. Photo width: 0.5 mm.

Fig. 6(d): Photo in plane polarized light (Thin-section number-P9/N) showing type 1 flanking microstructure with muscovite as the cross-cutting element (CE). The cleavage planes of the biotite host grain are the host fabric elements (HE). The HE is gently concave-up only at a part of the left margin of the CE (arrow). The right margin of the CE shows straight HE. The left margin of the CE is hazier than the other margins. A pair of opposite corners of the CE has notches. Nearly parallelogram shape of the CE indicates a top-to-SW sense of ductile shearing. The aspect ratio and the inclination of the side and the diagonal of the CE are 3.44, 42° and 27°, respectively. Photo width: 0.5 mm.
Fig. 7(a): Photo in plane polarized light (Thin-section number-P9/D) showing flanking microstructure defined by elongated muscovite grain as the cross-cutting element (CE). The cleavage planes of the host muscovite grain define the host fabric element (HE). The internal HE is cryptically convex-up at the hazy left margin of the CE (arrow ‘p’). The CE also underwent internal deformation as evidenced by its departure from a true parallelogram shape (arrow ‘q’). Nearly parallelogram shape of the CE indicates a top-to-SW sense of ductile shearing. The aspect ratio and the inclination of the side and the diagonal of the CE are 15, 87° and 80°, respectively. Photo width: 0.5 mm.

Fig. 7(b): Photo in plane polarized light (Thin-section number-P9/K) showing parallelogram-shaped muscovite grain nucleated inside a biotite host mineral. The cleavages of the biotite grain are undragged at their contacts with muscovite- hence they do not form a flanking microstructure. Nevertheless, the shape of the nucleated mineral indicates a top-to-SW sense of ductile shearing. The aspect ratio and the inclination of the side and the diagonal of the CE are 6.36, 45° and 32°, respectively. Photo width: 0.5 mm.

Fig. 7(c): Photo in plane polarized light (Thin-section number-P9/A) showing pair of adjacent nearly parallelogram-shaped (‘1’ and ‘2’) and an irregular-shaped muscovite grain (‘3’) nucleated inside a biotite host grain. The cleavages of the host mineral show no decipherable drag at their contacts with the nucleated grains; therefore they do not form a flanking microstructure. The shape of the nucleated grains indicates a top-to-SW sense of ductile shearing. The cleavage plane of the host mineral bounding the nucleated minerals (arrow ‘p’ that act as ductile shear plane is gently curved. The margin of grain ‘1’ is hazy (arrow ‘q’). The aspect ratio and the inclination of the side and the diagonal of the CE grains ‘1’, ‘2’ and ‘3’ are 1.84, 65°, 47°; 2.69, 64°, 40°; and 2.67, 60°, 59°, respectively. Photo width: 0.5 mm.

Fig. 7(d): Photo in plane polarized light (Thin-section number-P9/D) showing type 1 flanking microstructure where a fault zone at high-angle ~ 85° to the foliation plane defines the cross-cutting element (CE). The foliation plane (white line) defines the host fabric element (HE). A faulted biotite marker grain is zoomed in inset, which shows brittle-ductile normal faulting of the mineral. Based on the relative senses of slip and pronounced drag of its margins and cleavage planes, the flanking structure can also be categorized as ‘s-type’. The quartzofeldspathic minerals in the matrix are undragged. Photo width: 0.5 mm.
it can be said that (i) the CE of the ZSZ have a much broader range of aspect ratio, which denotes that some of them are more squarish or and some are more elongated, (ii) the inclinations of the sides and the diagonals of the CE that are elongated are also steeper.

The CE are bounded by a pair of external HE defined by brittle cleavage planes of the host minerals. Shearing along the external HE crystal-plastically deformed the CE of the type 1 FM. None of the HE can be identified as a marker, therefore, the terms ‘convex-up’ and ‘concave-up’ are used to describe their senses of drag similar to the usage of Mukherjee & Koyi (2009). Variation in the degree- and the sense of drag of the HE along the individual HE zones of the type 1 FM are noted (Figs. 5c, 6a, -c). This could be due to (i) pronounced rotation (≥ 140°) of the CE, (ii) heterogeneous displacement field along the CE, or (iii) mechanical anisotropy in the ductile shear regime (Mukherjee & Koyi 2009 and references therein). The last two situations arise from deformation partitioning during ductile shearing in the grain-scale. The relic top-to-SW sense of ductile shearing (Patel et al. 1993; Mukherjee 2007) that initiated presumably ~ 25 Ma (cf. Jain et al. 2002 and references therein) or around 22-16 Ma (see Mukherjee and Koyi, 2010 for the rationale) is corroborated by the CE of these FM. Some amount of internal deformation is also evident in the CE from their warped cleavage planes (Fig. 5b) or margins that deviate from true parallelogram shapes (Fig. 7a). As in Mukherjee & Koyi (2009), (i) no rheologic weakening at internal HE zones of these FM were observed indicating a strong bond between the nucleated CE and the host minerals; and (ii) one of the internal HE zones of few of the CE are hazy (Figs. 5d, 6d, 7a). Therefore, these characteristics of the FM seem to be characteristic to any ductile shear zone.

Thin hazy zones were, however, also observed for few of those nucleated minerals, either in isolation (photo in collection with the author) or in a train (Fig. 7c) that merely cut across the cleavages of the host minerals but do not serve them- thus which are not FM. Such cross-cutting minerals can well be crystal-plastically deformed into parallelogram shapes and display a top-to-SW sense of ductile shearing same as the CE mineral grains of the type 1 FM.

Few of the HE minerals of the second variety of the type 1 FM underwent pronounced brittle-ductile slip and dragging. The CE in this case is a curved fault plane that steeply dips towards northeast, cuts the C-plane at ≥ 75°, and is the microscopic manifestation of the brittle fault reported by Patel et al. (1993). The CE is devoid of any gouge materials in contrary to Passchier & Trouw’s (2005) expectation in micro-scale. Few of the faulted minerals that define the C-plane can be identified on either side of the fault plane and can act as markers. As both the sense of drag and slip can be categorized from these minerals, such FM can be classified more specifically into either s- or a-types (vide Fig. 7d). Only less rigid minerals such as micas are vulnerable to dragging along the CE fault. Rigid quartzofeldspathic minerals in the matrix, even though faulted remain undragged. Thus, depending on the competency of the adjacent minerals that act as the HE, the drag may or may not be developed along the CE micro-fault.

Unlike Mukherjee & Koyi (2009) where a single direction of growth is reported along them, the CE minerals of the type 2 FM grew in two directions 170-175° apart from each other (Figs. 8a-b). The HE in this case is the C-plane (and fabrics parallel to it) for the top-to-SW and the top-to-NE senses of shearing. The directions of growth of the CE are at 50-78° with the external HE. The extent to which the internal HE are dragged is seemingly proportional to the amount of directional growth of the CE. As the extents of drag of the internal HE at the opposite directions of the CE are different, the intensity of growth of the CE in those directions must be unequal. The CE cuts across fabrics that are parallel to, hence formed simultaneous with the C-planes. The general consensus is that the ductile shear C-planes form during the shearing event itself (Bèrthe et al. 1979; Passchier & Trouw 2005). Therefore, from their cross-cutting relation with the fabrics parallel to the C-planes along with the fact that they themselves are not ductile sheared into sigmoid- or parallelogram shapes, the CE of the type 2 FM are inferred to nucleate post-tectonically (after the 18-16 Ma top-to-NE ductile shearing). The growth of these CE minerals is exclusively a micro-structural phenomenon.

4. CONCLUSIONS

XZ oriented thin-sections of rocks of the Zanskar Shear Zone (ZSZ), western Indian Higher Himalaya, under an optical microscope in high magnification reveal spectacular flanking microstructures (FM). The cross-cutting elements (CE) of the type-1 FM are either curved fault planes/zones indicating brittle-ductile to brittle extensional shearing (normal faulting) or are individual minerals. The former type of the CEs are usually isolated, more often micas but can also be tourmaline and feldspar deformed crystal-plastically into more commonly parallelogram- and rarely sigmoid-shapes, and seldom are internally deformed. Such CEs denote a top-to-SW sense of ductile
Fig. 8(a): Photo in plane polarized light (Thin-section number-P9/O) showing type 2 flanking microstructure is defined by a biotite grain as the cross-cutting element (CE) and the foliation plane defined by a layer of recrystallized quartz (arrow ‘q’) as the host fabric element (HE). By growing preferentially along arrows ‘m’ at ~ 68° and ‘n’ at ~ 77° to the foliation plane (blue line), the CE strongly warps the foliation plane locally at arrows ‘o’ and ‘p’, respectively. The growth directions ‘m’ and ‘n’ are ~ 171° apart from each other. Photo width: 0.5 mm.

Fig. 8(b): Photo in plane polarized light (Thin-section number-P9/G) showing type 2 flanking microstructure is defined by an elongated grain of alkali feldspar as the cross-cutting element (CE). The foliation plane defined by discrete quartz grains in preferred orientation (blue line) act as the host fabric element (HE). By growing preferentially along arrows ‘p’ and ‘q’ at ~ 50° and 60° with the foliation plane, the CE strongly warps the foliation locally at arrows ‘r’ and ‘s’, respectively. Since the amount of drag of the foliation plane at ‘r’ is more than that at ‘s’, the grain grew more intensely along ‘p’ than along ‘q’. The growth directions ‘m’ and ‘n’ are ~ 170° apart from each other. Photo width: 0.5 mm.

Shearing along the external HE as ~ 22-16 Ma relict deformation event of the ZSZ. The degree and the sense of dragging of the HE vary along the same margin of the CE either due to strain partitioning or pronounced rotation of the later. The internal HE zones are hazy and are characterized by a lack of rheologic softening. The CE could either be squarish or elongated with the latter grains oriented at higher angles to the external HE. The CE with a wide aspect ratios and the inclination of the sides and the diagonals were encountered. Where the fault plane devoid of any gouge defines the CE, the cleavages and the margins of the less competent minerals are prominently dragged and brittle-ductile normal faulted. The CE of the type 2 FM grew in two directions ~ 170° apart from each other with different degrees. The facts that these CE are unsheared and cut across fabrics parallel to the C-plane indicate their growth post-tectonically after ~ 18-16 Ma top-to-NE ductile shearing event.

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