Correlation of multiple deformation events in an area: Example from schistose rocks of Lesser Himalayas, NW Pakistan

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Integrated micro-, meso- and macro-structural investigations were carried out in the multiply deformed rocks of the Mula Gori area, northeastern Khyber Agency, Lesser Himalayas. These investigations revealed an intricate history of deformation events that have not been formerly recognised. These structural examinations show four successive deformations. These events were identified in the field as well as in oriented vertical thin sections. The first deformation event D_1 is preserved in the form of inclusion trails in garnet porphyroblasts of foliation intersection axis 1 (FIA 1) and the fold axis of the macroscopic fold indicates NW–SE orogeny-oblique shortening. The D_2 event produced N–S trending foliations, fold axes and mineral lineations indicating E–W shortening. The D_3 is preserved as FIA 2 in garnet porphyroblast and E–W trending foliations, mineral lineations and fold axes in the field representing N–S shortening. The D_4 created NNW–SSE fabrics, which post-dates the main mantle thrust and the main boundary thrust, and likely resulted from the ENE–WSW bulk shortening related to development of the Hazara–Kashmir syntaxis.

Keywords. Porphyroblast; microstructures; mesoscopic structures; Mula Gori area; Lesser Himalayas.

1. Introduction

Eurasian and Indian plates are directly in contact with India and Nepal (Mukherjee *et al.* 2013, 2015; Mukherjee 2013, 2015), but are separated from one another by the sequence of rocks of the Kohistan arc in Pakistan (Gansser 1964). Northern Pakistan encompasses three major tectonostratigraphic components (DiPietro and Pogue 2004). These are (i) the Kohistan island arc, (ii) the main mantle thrust (MMT, mélange group) and (iii) the Indian plate rock sequence. These blocks are separated by the MMT and the main boundary thrust (MBT) (Tahirkheli 1979; Pogue *et al.* 1999).

The MMT separates the rocks of the Indian plate from Kohistan island arc (Tahirkheli 1979; Treloar *et al.* 1992). The tectonic block present between the MMT and the MBT is termed as the Himalayan foothills that accounts for the increase in the grade of metamorphism and deformation towards the north (Pogue *et al.* 1999). This tectonic unit is divided by the east trending Panjal–Khairabad Fault by an internal zone in the north and an external zone to the south (Coward *et al.* 1988). DiPietro *et al.* (2008) designate the internal zone as the western hinterland zone. The present study area (Mula Gori $\sim 36 \text{ km}^2$) lies in the NE Khyber Agency and consists of deformed metasedimentary

Figure 1. Regional tectonic map of Pakistan demonstrating the tectonic terrain separated by the MMT and MBT. The box (square) shows the location of the study area at the left of the map while the dashed arrows represent the increase in the grade of metamorphism and deformation from the south towards the north (after Kazmi and Rana 1982; Ali *et al.* 2016).

rocks (Silurian–Devonian Lowara Mena Formation and Warsak Metamorphic Complex; figure 1; Kazmi and Rana 1982; Khan *et al.* 1989). The study area comprises metasediments of greenschist and lower amphibolite facies (Ahmad *et al.* 1969; Ali *et al.* 2016). The tectonic and structural relationship of the western part of the western hinterland zone is poorly understood because of the cover of younger sediments of the Peshawar basin on Palaeozoic rocks of the Mula Gori area (Burbank 1983). The type of current tectonic scenario in the area has been established on regional geological traverses and random petrography (cf. Ahmad *et al.* 1969; Shah *et al.* 1980; Khan *et al.* 1989). This research uses detailed mesoscopic structures at an outcrop scale supplemented with microscopic structures preserved in porphyroblasts and matrix from a part of the NE Khyber Agency to establish the interrelationship between structures in the western part of the western hinterland zone, Lesser Himalayas, Pakistan.

2. Sample description

For detailed petrographic studies, 50 oriented samples were collected from metamorphosed pelitic rocks exposed in the study area (figure 2). A total of 385 oriented vertical thin sections were prepared with different strikes from these oriented

samples for petrographic and microstructural interpretations. Mineral assemblages in the studied rock samples consist of quartz, graphite, ilmenite, chlorite, chloritoid, biotite, muscovite, garnet, staurolite and pyrite. Microstructural data were mainly collected from garnet porphyroblasts due to nicely preserved sigmoidal inclusion trails and matrix foliations.

2.1 Mineral assemblages

2.1.1 Garnet

Garnets, present mainly in the form of porphyroblasts, are idioblast, hypidioblast and xenoblast and range in size from 0.5 to 2.5 mm. These garnet porphyroblasts contain sigmoidal inclusions of quartz, muscovite, ilmenite and biotite, which are either continuous or discontinuous with respect to the matrix foliation (figure 3). These sigmoidal inclusion trails preserved in garnet porphyroblasts are much finer grained than similar grains in the matrix.

2.1.2 Staurolite

The staurolite porphyroblasts exist only in three samples. The matrix foliation strongly wraps the porphyroblast and contains poorly preserved inclusion trails of quartz (figure 4).

Figure 2. Detailed geological map of the Mula Gori area, northeastern Khyber Agency showing major stratigraphic units and sample locations (after Khan *et al.* 1989).

Figure 3. Photomicrograph of a vertical thin section showing continuous inclusion trails in an idiomorphic garnet porphyroblast that are passing continuously into the matrix. Single barbed arrow shows strike and way up.

Figure 4. Photomicrograph showing elongated staurolite porphyroblast in the zone of a strong non-coaxially deformed matrix. Single barbed arrow shows strike and way up.

Figure 5. Photomicrograph showing differentiated crenulated cleavage with chlorite flakes in microlithon in graphitic schist. Single barbed arrow shows strike and way up.

Figure 6. Photomicrograph showing inclusion trails of chloritoid porphyroblast that are truncated by later deformation in the matrix. Single barbed arrow shows strike and way up.

2.1.3 Chlorite, biotite and muscovite

Chlorite is primarily found in differentiated cleavages with a few large flakes in crenulation hinges (figure 5). Biotite mostly defines the main matrix foliation. Stauroilite and garnet porphyroblasts are largely enclosed by biotite in the differentiated crenulation cleavages. Muscovite is generally less and finer grained than biotite in the studied thin sections.

2.1.4 Chloritoid

Chloritoid exists in two samples in the form of porphyroblast (figure 6). It occurs in close association with chlorite. The development of a differentiated

crenulation cleavage in the matrix truncates/cuts poorly preserved inclusion trails within the chloritoid porphyroblast.

3. Foliation intersection axes (FIA)

The FIA technique was first introduced by Hayward (1990) and refined by Bell and Hickey (1998) and Bell *et al.* (1995, 2004). This technique involves observing the shift in the asymmetries of curved inclusion trails, preserved in porphyroblasts, in a series of differently oriented vertical thin sections. In the beginning, from every sample six oriented vertical thin sections were cut at every 30° interval from true north (figure 7). Extra thin sections were cut at 10° interval to limit the FIA range within $\pm 5^\circ$ from the same sample (see for detail Bell and Hickey 1998; Bell *et al.* 2004). The FIA trend is regarded as the mid between two oriented vertical thin sections across which the change in the asymmetries of inclusion trails occurs.

The relative timing between different FIA sets is decided on the following rules:

- (1) Numerous FIAs investigation, i.e., change in the trends of FIAs from core to rim (Bell and Hickey 1998; Bell *et al.* 2004; Bell and Welch 2002).
- (2) Continuity and truncation of inclusion trails in porphyroblast with the matrix foliation (cf. Adshead-Bell and Bell 1999; Ali *et al.* 2016).
- (3) Trend of inclusion trails whether it is at high angle or parallel with respect to the matrix foliation (Sayab 2005, 2008; Sanislav 2010; Sharib and Bell 2011).

3.1 FIA sets

Total 31 FIAs were measured from garnet porphyroblasts present in 26 oriented samples (table 1). The remaining oriented samples do not have porphyroblasts. The schistose rocks of the study area contain two FIA sets with NNE–SSW and ENE–WSW orientations.

3.1.1 FIA set 1

This trends NNE–SSW and exists in the core of garnet porphyroblasts and in garnets where the inclusion trails are sharply or partially truncated by the matrix (figure 8). This FIA set was not detected in garnets containing inclusion trails

Figure 7. Sketches illustrating the FIA measurement technique in a series of six vertically oriented thin sections cut from a horizontally oriented block. Note the thin sections are viewed in a single direction across the compass (modified after Ali 2010).

continuous with the matrix foliation. FIA 1 trends at an average of 035–045°.

3.1.2 FIA set 2

This trends ENE–WSW and occurs in the rim of garnet porphyroblasts containing nicely developed core and from garnets with well-developed inclusion trails that are passing continuously into the matrix foliation. FIA 2 orientation varies from 070 to 085° (figure 9). The orientation of these FIAs is

shown in a rose diagram (figure 10; cf. Ali *et al.* 2016).

4. Structural field/outcrop data

Foliation overprinting relationships in the Mula Gori area show four successive deformation events named D_1 , D_2 , D_3 and D_4 . Each deformation event in terms of foliation i.e., S_1 , S_2 , S_3 and S_4 is discussed below. Field data are given in table 2.

Table 1. Sample locations and foliation intersection axes.

Sl. no.	Easting	Northing	FIA 1	FIA 2
M1	71 22 55.4E	34 07 06.3N	40	80
M2	71 22 54.3E	34 07 06.4N		90
M4	71 22 54.0E	34 07 06.0N	35	70
M6	71 20 57.9E	34 08 09.0N	40	
M7	71 20 58.6E	34 08 06.9N	35	
M8	71 21 04.8E	34 08 04.9N	40	
M9	71 21 06.1E	34 07 59.9N		90
M10	71 20 54.3E	34 08 13.8N	55	
M11	71 20 53.1E	34 08 13.7N	35	
M12	71 20 54.5E	34 08 08.6N		70
M13	71 20 52.3E	34 08 08.0N		85
M14	71 20 51.2E	34 08 00.8N		70
M15	71 20 45.4E	34 08 00.5N		70
M18	71 20 38.8E	34 07 54.5N	40	
M19	71 20 12.7E	34 07 51.5N		70
M37	71 22 24.5E	34 05 19.9N		75
M38	71 22 22.1E	34 05 22.7N	35	75
M39	71 22 20.5E	34 05 22.4N	35	
M40	71 22.3 28E	34 05.3 71N		85
M41	71 22 17.7E	34 05 21.5N	40	
M42	71 22 15.6E	34 05 20.7N		90
M43	71 22 11.6E	34 05 19.9N		95
M45	71 22 13.5E	34 04 59.1N		70
M48	71 22 33E	34 05 27.6N	35	70
M49	71 22 45.4E	34 05 25.9N	35	
M50	71 21 23.6E	34 08 20.8N	35	75

4.1 D_1 deformation/ S_1 fabric

The recognition of an earliest S_1 is often very confusing to decode in a tectonic terrain in terms of its original orientation because of the obliteration of S_1 due to subsequent deformation events (Bell 1986). The evidence for S_1 cleavage only exists in thin sections where early formed porphyroblasts (e.g., garnet) contain oriented inclusion trails of quartz. S_1 trending NNE–SSW is well preserved in the form of inclusion trails and predate all the deformation events in the study area hence regarded as the product of D_1 .

4.2 D_2 deformation/ S_2 fabric

The D_2 deformation event produced N–S striking upright tight folds at the outcrop associated with N–S oriented S_2 axial plane foliation. It is moderately to steeply dipping. S_2 is generally parallel to bedding (S_0) (figure 11A and B). S_2 is locally developed and observed at a few places.

Lithology controls the orientation of cleavages in rocks (Huston 1990). Cleavages are usually parallel

to bedding in less competent rocks but may tend to refract up to 60° as they enter into more competent lithology. In the interbedded sequence of pelites and psammities, most of the strain associated with folding is absorbed/stored in the pelitic rocks (cf. Huston 1990). In the study area, D_2 associated cleavages are parallel to bedding in the pelitic unit (figure 11A and B) but as they enter the marbleised limestone unit they become steeply dipping in the form of axial planar foliation of tight folds in the area (figure 11C).

4.3 D_3 deformation/ S_3 fabric

The S_3 fabric is well developed and sub-vertical in the region (figure 12A and B). S_3 are best seen in the southern part of the Lowara Mena Formation. The S_3 foliations are orthogonal to the S_2 foliations in the pelitic unit and intersect S_2 in the region (figure 12C). The intersection lineation of S_3 and S_2 trends ENE–WSW and is parallel to D_3 -related fold axes (figure 12D). D_3 -related folds are upright close fold, slightly overturned and show southward vergence. Similarly, the mineral stretching lineation associated with D_3 trends ENE–WSW.

4.4 D_4 deformation and S_4 fabric

The D_4 produced gently dipping S_4 foliation which crenulates S_2 and S_3 in the region (figure 13). Mesoscopic folds associated with D_4 exist across the Mula Gori region and are equally developed in the metapelitic, marbleised and metapsammitic rock units. The general trend of the axial plane foliation related with D_4 is 340° and dips gently towards NE at $\sim 45^\circ$.

Distinct cleavages observed mesoscopically in the field are S_2 , S_3 and S_4 , which developed during D_2 , D_3 and D_4 deformation events and their orientations are plotted in a rose diagram (figure 14). S_3 and S_4 are the most dominant and well preserved foliations of the area.

5. Correlation of meso- and micro-scale structures

Indications of numerous deformations were noticed both in meso- and micro-scale. Structures/foliations associated with successive deformation events in the porphyroblast and matrix were correlated from thin sections to outcrop scale in

Figure 8. Inclusion trails in differently vertical sections of sample M11 showing FIA at 040° . Photomicrograph (f) showing truncated inclusion trails, which is approximately perpendicular to FIA.

terms of orientation, overprinting and cross-cutting relationships.

5.1 S_1 meso- and micro-structures

S_1 is not preserved at the outcrop as it is primarily preserved in the form of sigmoidal inclusion trails in garnet porphyroblast. This cleavage has been obliterated/demolished by D_2 , D_3 and D_4 deformations within the matrix foliation apart from that preserved in the garnet porphyroblasts. S_1 is preserved in the microlithon as the Q-domain (figure 15). The inclusion trails are mostly defined by oriented fine-grained quartz. S_1

trends NNE–SSW, similar to the main macroscopic scale fold.

5.2 S_2 meso- and micro-structures

S_2 is moderately to steeply dipping and trends $\sim N$ (figure 11), parallel to bedding (S_0) as noted at the outcrop. Correspondingly, in the studied vertical thin sections, S_2 appears to be steeply dipping, oriented $\sim N$ and preserved as cleavage or M-domain (figure 16A). The S_2 cleavage in the metapelitic unit is mainly defined by biotite and graphite in the matrix. Mica concentrated in the form of cleavages around competent porphyroblasts leading to the

Figure 9. Inclusion trails in differently vertical sections of the sample M2 showing FIA at 090° . Photomicrograph (a) showing continuous inclusion trails, which is perpendicular to FIA.

development of symmetric strain shadows within the matrix (figure 16A). The symmetric strain shadows (cf. Mukherjee 2017) around porphyroblasts comprise quartz and mica.

5.3 S_3 meso- and micro-structures

At the outcrop scale, S_3 is steeply dipping, ENE–WSW trending and intersecting S_2 at high angle (70 – 80°). In the oriented vertical thin sections S_3 is steeply dipping, 070 – 090° trending similar to that of field orientation (figure 17). S_3 is preserved

both as Q-domain in garnet porphyroblast and as M-domain in the matrix.

5.4 S_4 meso- and micro-structures

The S_4 occurs as axial planar foliation at the outcrop and trends 330 – 340° . It dips moderately towards NE. Consequently, S_4 is observed as axial planar foliation too in the oriented thin section and moderately dipping towards 070° . S_4 is mainly preserved in the matrix (figure 18).

Figure 10. Equal area rose diagrams showing FIA sets 1 and 2 trends preserved within garnet porphyroblasts of at least two different generations in the Mula Gori area (after Ali *et al.* 2016).

6. Discussions

The NNE–SSW oriented FIA set 1 shows NW–SE horizontal bulk shortening. The D_2 designed N–S oriented foliations, mineral lineations and fold axes and indicates E–W shortening (see figure 11). ENE–WSW oriented foliations at outcrop and FIA 2 is the product of a D_3 event. FIA set 2 is conserved in the rim of porphyroblasts containing FIA 1 in the core and in the porphyroblast where the sigmoidal inclusion trails are continuous with the matrix foliation, boudin lineation axes, intersection lineation (L_3^3) and mineral lineations (L_3^3) indicating N–S shortening. Folds related to the D_3 deformation event show southward vergence (see figure 12). The transposition of the gently dipping NNW–SSE oriented D_4 deformation fabrics, boudin lineation axes, L_4^4 mineral lineations and axial planar foliation shows a NE–SW horizontal bulk shortening within

the study area. The NNE–SSW trending regional fold (Khan *et al.* 1989; Ali *et al.* 2016) is parallel to FIA 1 in the southwestern hinterland and pre-date all younger deformation events in the region. Formerly, regional-scale folds were decided on the basis of asymmetries of mesoscopic scale folds across the fold hinges and axial plane foliations. The transposition of foliations during the younger deformation events post-dates regional fold and can lead to incorrect information regarding the origin of a macroscopic scale fold in an area (cf. Bell *et al.* 2003). Bell *et al.* (2003) and Ham and Bell (2004) stated that once the large macroscopic folds initiate, they may tighten/shorten further during subsequent periods of shortening events but the main fold axis orientation remains the same as in the case of the Type-0 folding (see figure 19). The Kunar Fault which is the extension of main Karakorum thrust (MKT) predates all the deformation events in northern

Table 2. Showing trends of meso-scale structures at the outcrop.

Sl. no.	S ₂ foliation, L ₂ ² lineation	S ₃ (foliation), L ₃ ³ (lineation)	S ₄ (foliation), L ₄ ⁴ (lineation)
1	360	260	340
2	355	265	330
3	10	90	340
4	180	270	340
5		100	320
6		100	320
7		270	340
8		90	340
9		90	340
10		70	340
11		90	340
12		80	340
13		90	330
14		100	
15		80	
16		80	
17		80	
18		80	
19		270	
20		105	
21		70	
22		70	
23		75	
24		85	
25		90	
26		95	
27		90	
28		80	
29		70	
30		80	

Pakistan (cf. Rehman *et al.* 2011) and produced an early structure in the study area thus strengthening the Ham and Bell (2004) statement. The Kunar Fault in Afghanistan (represents the side-wise collision of the Eurasian and Indian plates) lies ~80 km to the NW of the study area trending NNE–SSW and have an impact on the area thus resulting in the production of a macro-scale fold having the same orientation as that of Kunar Fault (figure 20). In figure 20 the rose diagrams between A and B parts show the trends of FIA 1 and FIA 2. The upper rose diagram FIA 1 depicts the same orientation as Kunar Fault in figure 20(A) and macroscopic scale fold in figure 20(B). FIA 1, macro-scale fold axis and MKT show harmony in orientation in this part of the western hinterland zone. The fabric

related with D₂, D₃ and D₄ does not indicate any genetic relationship with the initial development of the main NNE–SSW trending fold. S₂ foliation trending ~N can also be tentatively correlated with the main macroscopic fold in the area because the trend of the main fold changes from NNE–SSW to N to the south of the study area (figure 20B). FIA 2 and S₃ at the outcrop show similar E–W orientation. This D₃ deformation can be better correlated with that of MBT (almost E–W trending). The S₄ fabric trending NNW–SSE in the thin sections and at an outcrop scale shows resemblance in orientation to that of the Hazara–Kashmir syntaxis which has been rotated counterclockwise (see figure 20).

Various deformations are reported by numerous researchers in the northeastern part of the western hinterland zone. The present study area (the southwestern part of the hinterland zone) is correlated with the northeastern part of the western hinterland zone in terms of deformation. A regional map of the northeastern part of the western hinterland zone (cf. figure 1B by Shah *et al.* 2011, 2012) exhibits two sets of main structures: (i) E–W trending south verging mega- to micro-scale folds and (ii) NNE–SSW and NNW–SSE trending upright to overturned, west vergent, regional to meso-scale folds. The relative timing of these structures and their tectonic implication were argued by DiPietro and Lawrence (1991) and DiPietro *et al.* (2008) and it was interpreted that the NNE–SSW/NNW–SSE folds are older than the E–W trending folds, *vs.* Coward *et al.* (1988), Treloar *et al.* (1989), Anczkiewicz *et al.* (1998), Llana-Funez *et al.* (2006) and Shah *et al.* (2011, 2012) who proposed an opposite relationship. The current structure analysis resolves this problem in favour of the first group of authors on the basis of FIA trends and meso-scale structures.

The D₁-, D₂- and D₃-related structures in this part of the western hinterland zone show a remarkable resemblance to the F1/F2, F3 and F4 described by DiPietro and Lawrence (1991) and DiPietro *et al.* (2008) in the eastern part of the western hinterland zone. According to DiPietro *et al.* (2008) the northeastern part of the western hinterland has been affected by at least four events of deformation. The exposed parts of the western hinterland in Warsak, Nawagai, Malakand, Swat, Besham, Kaghan, Naran, Burawai, Rustam and Swabi have nicely preserved evidence of regional scale folds F1/F2, F3 and F4 that occurred during

Figure 11. (A, B) Field photograph showing the S_2 trend parallel to the bedding in the pelitic unit, (C) field photograph showing the S_2 cleavage, which is perpendicular to the marbled unit in the western part of the Lowara Mena Formation.

Figure 12. (A) Field photograph showing the steeply dipping S_3 foliations and minerals lineation parallel to the S_3 , (B) field photograph showing L_3^3 mineral lineation defined by aligned quartz/feldspar. L_3^3 mineral lineation is trending parallel to the S_3 foliation in the region, (C) field photograph illustrating steeply dipping S_3 and intersecting S_2 in the area and (D) field photograph looking towards west showing the F_3 sub-vertical fold in the marbled limestone unit to the south of the study area.

Figure 13. Field photographs (A, B) showing NW–SE trending and moderately dipping foliations (C) field photograph showing D₄-related mesoscopic folds. Length of the white marker is 13.2 cm.

Figure 14. Equal area rose diagram showing the trends of mesoscopic structures preserved in the metapelite schist of the Mula Gori area, northeastern Khyber Agency.

separate tectonic events (DiPietro and Lawrence 1991; DiPietro *et al.* 2008). The generally NE–SW trending pervasive S₂ crenulation cleavage of

Figure 15. S₁ is present only as inclusion trails in garnet porphyroblast.

~47 ± 3 Ma age is associated with the F₁/F₂ deformation event in the northeastern part of the western hinterland zone (see for details DiPietro *et al.* 2008). The map scale upright Eocene to the Early Oligocene F₃ folds overprints both

Figure 16. (A) Photomicrograph and (B) field photograph showing the resemblance of S_2 in the vertical thin and at outcrop.

Figure 17. (A) Photomicrograph and (B) field photograph illustrating the similar trends of S_3 in the studied vertical thin section and at outcrop.

the F1/F2 folds and crenulates the pervasive S_2 crenulation cleavage in the northeastern part of the western hinterland. The regional scale F3 folds trend NNE–SSW in the Nawagai region, Pinjkora Anticline (PA), Dargai, Kotah Dome (KD), Saidu, Loe Sar Dome (LD), Indus River Anticline (IA), Indus Syntaxis (IS) and Hazara before bending to the NE direction near the Kohistan fault in the north (cf. figure 1B of DiPietro *et al.* 2008). The map scale E–W trending structures and lineations in the western hinterland developed during the F4 deformation event. The E–W trending fold axes related to F4 are nicely exposed in Pinjkora, Swat, Malakand, Rustam and Swabi (cf. figure 1B of DiPietro *et al.* 2008). The E–W trending structures associated with F4 developed during the N–S horizontal bulk shortening at ~31–23 Ma and thus overprinted the NNE–SSW trending structures

related with F3 across the northeastern part of the western hinterland zone (DiPietro *et al.* 2008). D_1 (FIA 1) trending NNE–SSW of the present study resembles in orientation F3 of DiPietro *et al.* (2008) and FIA 3 of Shah *et al.* (2011, 2012). D_2 resembles in orientation almost with F3 of DiPietro *et al.* (2008). D_3 (FIA 2) trending ENE–WSW resembles in orientation with F4 of DiPietro *et al.* (2008) and with FIA 2 (E–W trending) of Shah *et al.* (2011, 2012). D_4 resembles almost in orientation F1/F2 of DiPietro *et al.* (2008) while Shah *et al.* (2011, 2012) did not deduce this deformation event. It appears that D_4 NNW–SSE fabrics that formed in the Mula Gori area resulted from the ENE–WSW bulk shortening related to the Hazara–Kashmir syntaxis tectonic event after the collision of the Kohistan island arc and the Indian plate.

Figure 18. (A) Photomicrograph and (B) field photograph illustrating the same orientation of S_4 in the studied vertical thin section and at outcrop. (C) Photomicrograph and (D) field photograph exhibiting the similar trends of S_4 in the studied vertical thin section and at the outcrop level. In both the cases S_4 is dipping towards the east.

Figure 19. Series of sketches of cross-sections of a large regional fold showing tightening, reduction in size and modification in shape during the successive periods of subhorizontal and subvertical shortening. Note the main fold axis orientation remains same throughout the deformation events (after Ham and Bell 2004).

Figure 20. (A) Study area with a red box showing proximity to the Kunar Fault on the left trending (NNE–SSW) in the vicinity of Afghanistan (after Pogue *et al.* 1992) and (B) demarcating the geological map of the study area. The upper rose diagram shows the orientation of FIA 1 and the lower one is representing the orientation of FIA 2 while the rose diagram (to the left) in A shows trends of S_4 foliations and D_4 fold axes.

7. Conclusions

Micro, meso and macroscopic structures in the Mula Gori area not only show resemblance in orientation relative to each other in a sequential manner but also to the tectonic features of the region that resulted from the collision of the Indian and Eurasian plates. These structures seem to have developed at the same time in the bulk shortening trend in this southwestern part of the western hinterland zone. Microscopically S_1 is only preserved as inclusion trails in the garnet porphyroblasts and is regarded as the product of D_1 deformation events, showing remarkable resemblance with the macroscopic scale fold axis and Kunar Fault (extension of MKT), trending NNE–SSW in the region. In another words, the main macroscopic fold axis shows the earliest event of deformation in the area rather than being considered as the product of the latest deformation event. F_2/S_2 in field trending $\sim N$ exhibits the same orientation to that of S_2 in thin sections. D_3 deformation events produced FIA 2 trending ENE–WSW in garnet porphyroblasts, S_3 foliation and fold axes at the outcrop scale indicate NNE–SSW horizontal bulk shortening. D_3 deformation is the most dominant event and shows resemblance in orientation to that of MBT. D_4 events produce NNW–SSE foliations/fold axes at micro and mesoscales resulting from the ENE–WSW bulk shortening, similar to the Hazara–Kashmir syntaxis. S_4 foliations and fold axes

and mineral lineations are the imprint of the Hazara–Kashmir syntaxis in this part of the Lesser Himalayas.

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