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Near-orthogonal deformation sequence along the Malakand transect, NWFP, northern Pakistan

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Abstract

The Malakand transect of northern Pakistan represents a part of the regionally metamorphosed sequence of the Indian plate rocks. Field observations show that these metapelitic rocks are multiply deformed and preserved progressive bulk inhomogeneous shortening resulting in multiple generations of folds. Four near-orthogonal overprinting fabrics have been identified different than those reported previously. D_1 structures are rare, both at the meso- and microscale. This is because of the penetrative effects of the later D_2 event. D_2 not only transposed and obliterated the D_1 structures, but also reactivated the S_1 foliation. S_2 is steeply dipping foliation, dominantly towards north, and E-W striking. S_3 makes an orthogonal relationship with the S_2 and this geometrical relationship gives rise to L^2_3 intersection lineation, which is shallowly plunging either towards ENE or WSW. S_3 is generally sub-horizontal and well developed. The orientation of S_4 is very similar to that of S_2. However, S_4 is sparse and heterogeneously developed. The intersection of S_4 with S_2 (L^2_4) moderately plunging towards NE or ENE. It is interpreted that both D_2 and D_4 related fabrics were formed as a result of sub-horizontal curstal shortening with an intervening sub-vertical shortening (D_3). The sparse nature of D_4 represents waning stages of the orogenesis. Well developed near-orthogonal fabrics in these rocks revealed that, 1) deformation is always partitioned and can retain original fabric orientations, and 2) orogenic processes follow repeatedly crustal thickening (compression) coupled with decompression unless the equilibrium is attained in the mid- to upper crust.

1. Introduction

In multiply deformed orogenic belts, it is often difficult to recognize overprinting relationships of deformation fabric elements. This is partly because of the penetrative nature of the younger deformation event(s) that potentially transposed the older fabrics. In this regard, various studies from macro- to microscopic scale have been conducted across the orogenic terrains; however, there is a general lack of agreement on the number of deformation events or tectonic mechanisms involved during orogenesis (e.g. Passchier et al., 1992; Bell et al., 1992; Sayab, 2005; Williams, 2005). Most recently, detailed quantitative macro- to microstructural studies across the orogenic terrains show that the orogenic processes are far more complicated than previously recognized (see Passchier and Trouw, 1998). However, many studies have demonstrated that integrated macro-, meso- and microstructural analysis can resolve deformation events and associated tectonic processes (e.g., Reinhardt, 1992; Mares, 1998).

The purpose of this study is to decipher multiply deformed tectonic foliations, which are part of the Indian plate rocks, exposed along the Malakand transect, northern Pakistan. No detailed fabric analyses have been carried out along the transect (see also DiPietro et al., 1999). The regional strike of these rocks is generally E-W, subparallel to the regional tectonic grain of the Himalayas, however, we have identified near-orthogonal deformation sequence and associated L-S tectonites. The geometry of near-orthogonal fabrics has important implications for the newly emerging orogenic models where collisional processes may experience repeated shortening followed by decompression (e.g. Aerden, 2005).

2. Geographical location and stratigraphy

The Malakand transect is located in the north of NWFP, Pakistan (Fig. 1), and covers the Survey of Pakistan topographic sheet number 38-N/14 (lies between latitude 34°32´ to 34°34´N and longitude 71°53´ to 71°55´E). With reference to the tectonic subdivision of the northern Pakistan, the study area is bounded by the Main Mantle Thrust in the north and the Main Boundary Thrust in the south and lies north of the Peshawar basin (see Searle and Khan, 1995). The rocks exposed along the transect form part of the Indian plate that are metamorphosed and multiply deformed during the Himalayan orogeny (DiPietro et al., 1999).

DiPietro et al., (1999) and DiPietro and Isachsen (2001) revised the stratigraphy of the parts of the Pakistani hinterland rocks and divided into five age groups, each of which are associated with tectonism and are bounded by an unconformity. The rocks recorded 1) plutonism in the Early Proterozoic, 2) Late Proterozoic, 3) Early Paleozoic,

4) Late Paleozoic, and 5) Cenozoic. Similarly, deformation in the Early Proterozoic and Late Paleozoic; volcanism in the Late Paleozoic-Triassic, and strong metamorphism and deformation in the Late Cretaceous-Cenozoic (see fig. 2 in DiPietro et al., 1999). More recently, Ahmad (1999) proposed that the rocks exposed along the Malakand transect belongs to the Mesozoic Saidu Formation. The lower contact of the Saidu Formation is conformable with the Kashala Formation. The Kashala Formation is not exposed along the transect.

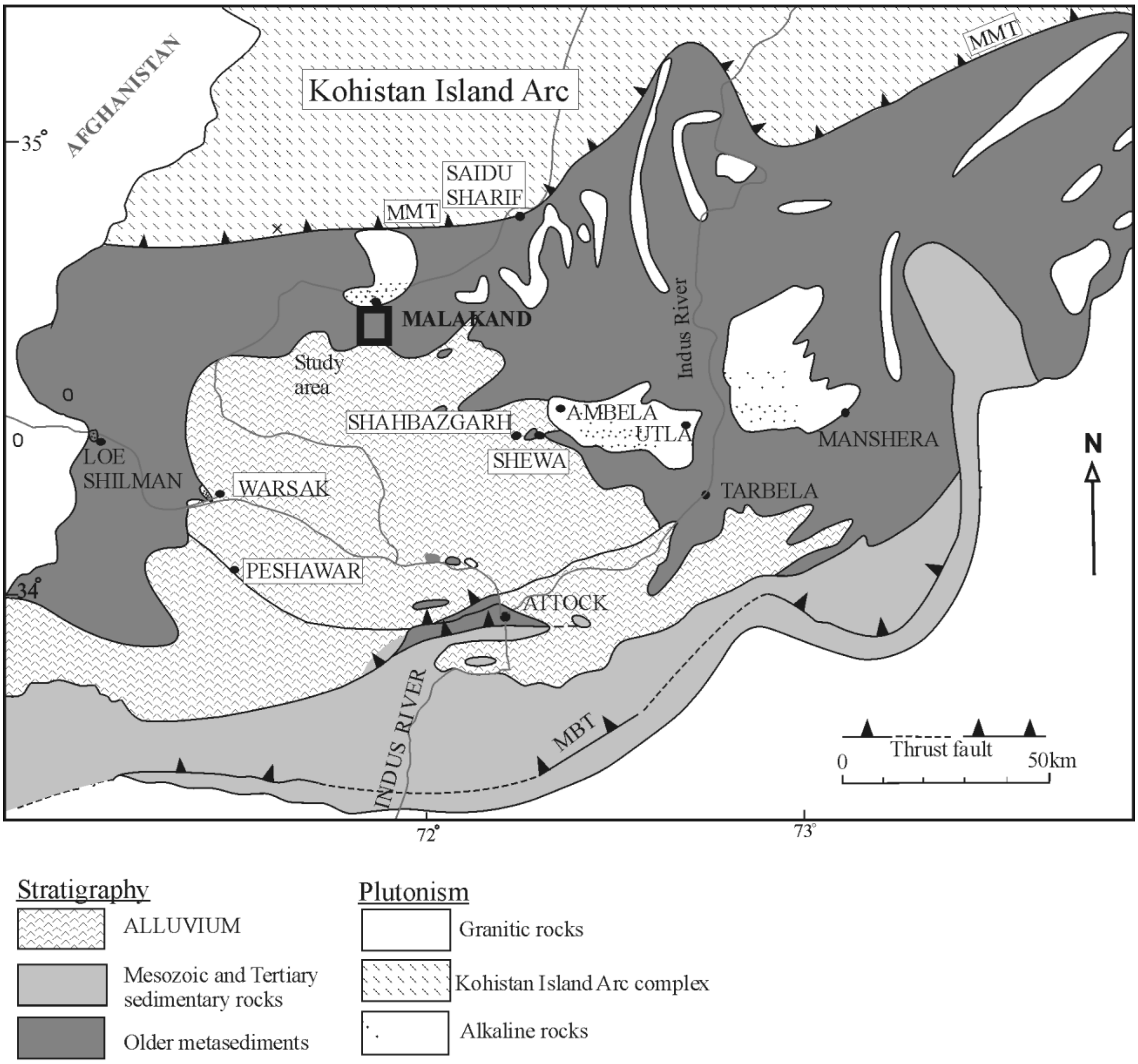

Fig. 1. Generalized geological map showing major tectonostratigraphic zones of the northern Pakistan. Box shows the location of the study area.

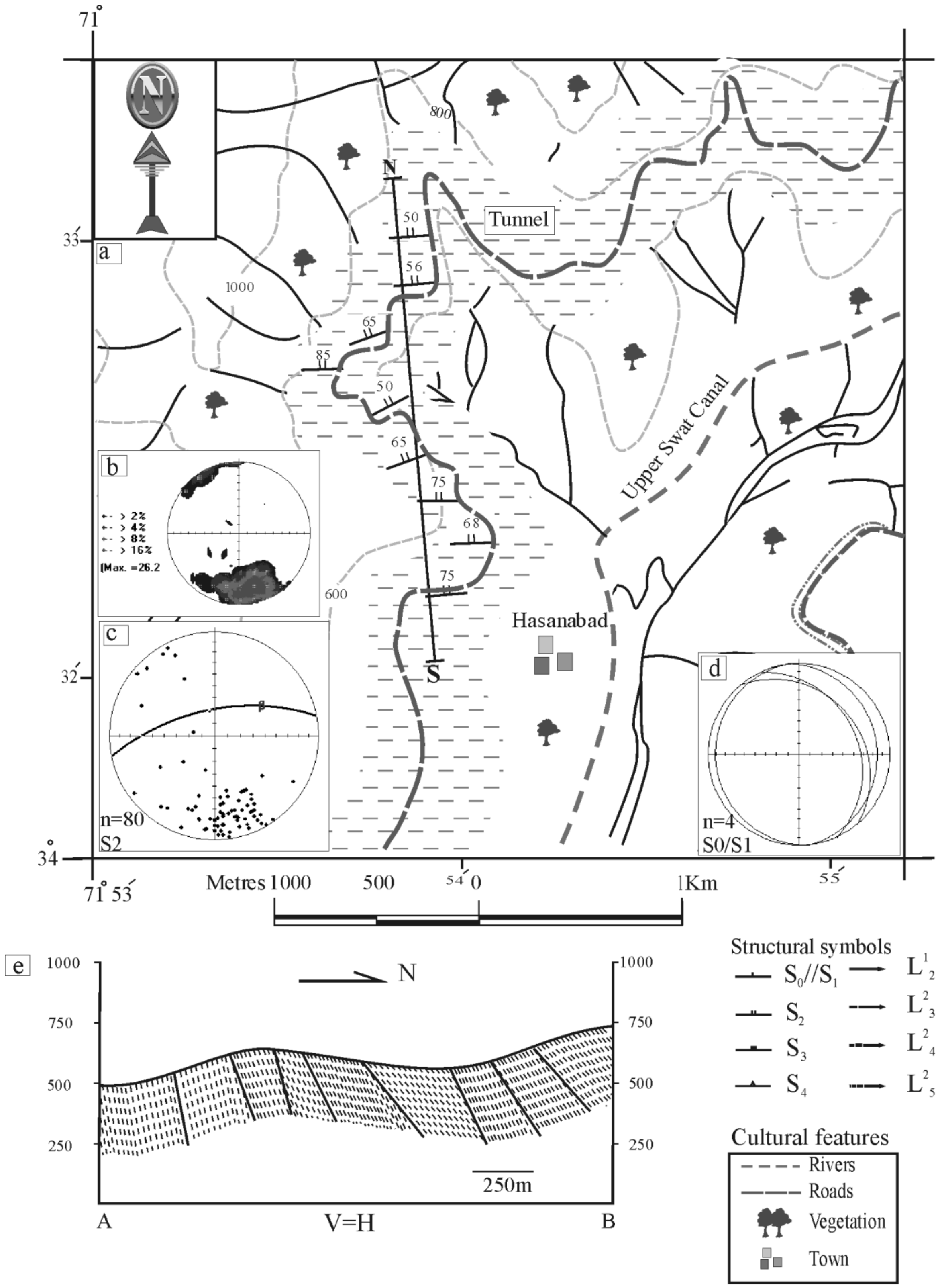

Fig. 2 (a) Geological map along the Malakand transect showing east-west striking S_2 foliation, steeply dipping towards the north. (b and c) Lower-hemisphere, equal-area stereographic plots showing density diagram and poles to the S_2 planes. (d) Stereographic measurements of S0//S1. (e) Geological cross section along the transect showing east-west striking and steeply dipping S_2 foliation.

3. Methodology

3.1. Structural map

Geological information collected during the field work was directly plotted on the enlarged version (1:25,000) of the Survey of Pakistan toposheet (38-N/14), which were used as a base map. Key stations with their geographical coordinates were plotted on the base map using MapInfo 7.0. For the nomenclature of foliation and lineation, Bell and Duncan (1978) scheme were used. In order to establish deformation and associated metamorphic phases in the area, following procedures were adopted:

a) Different generation of fabrics (foliation and intersection lineation) were identified, that is, S_1, S_2 …etc., and their respective intersection lineations $L^1{}_2$, $L^2{}_3$ … etc.,
b) Recognition of deformation events (D_1, D_2, …etc) based on fabric overprinting relationships,
c) Oriented samples were collected to understand microstructural relationships and their correlation with the mesostructures (outcrop).

3.2. Samples preparation

Oriented rock samples, which were collected during the field work, were re-oriented in the laboratory. Array of vertical thin sections at different angles and horizontal thin section were prepared for each rock to analyze microstructures in 3D view. Standard laboratory procedures were adopted for the preparation of thin sections, however, for oriented thin sections, various oriented horizontal slabs were cut for oriented thin sections. Altogether, 20 oriented thin sections were prepared, including 15 vertical and 5 horizontal.

4. Fabric overprinting relationships

Fabric overprinting relationships along the Malakand transect shows at least four deformation events. Each deformation event, in terms of foliation and lineation development, is discussed below:-

4.1. D_1 fabric

Before describing D_1 fabric, it is worth mentioning here that in most orogenic terrains, D_1 is often cryptic e.g., in Appalachians (e.g., Rosenfeld, 1968; Peterson and Robinson, 1993), European Alps (e.g. Aerden, 2004), and north Australian craton (e.g. Sayab, 2005; 2006). In these studies it has been demonstrated that across the orogenic terrains, the geometry of D_1 is always difficult to reconstruct in terms of its original orientation (e.g. Bell, 1986). This is partly because younger deformation events tend to transpose or obliterate older deformation events. Since, the rocks exposed along the Malakand transect are characterized by penetrative foliation and associated lower- to middle-amphibloite facies metamorphism, therefore, the original geometry of $S_0//S_1$ is difficult to recognized in the field. Few locations along the transect show shallow orientation of S_1//S0 (Fig. 2), however, S_1 remained in parallelism with S_0.

4.2. D_2 fabric

The most obvious fabric along the Malakand transect is characterized by continuous (terminology after Powell, 1979 and Borradaile et al., 1982) S_2 foliation or schistosity (Fig. 2). Field measurements along the transect and across the rock units broadly fall into two structural girdles with a mean calculated S_2 surface steeply dipping towards north and striking ENE-WSW (Fig. 2). Calculated β-axis plunging moderately towards ENE. In hand specimen, S_2 foliation can be classified into stage 5 or 6 of differentiated crenulations cleavage, (see Bell and Rubenach, 1983). The F_2 folds are tight to isoclinal, and where F_2 fold hinges are preserved, $L^1{}_2$ intersection lineation was taken (Fig. 3 and 4). S_1 and S_2 are near – perpendicular (Fig. 2c and d).

4.3. D_3 Fabric

S_3 fabric is heterogeneously developed. F_3 folds, that produced the S_3 foliation, are characterized by open to close interlimb angles (terminology after Fleuty, 1964) with both counterclockwise and clockwise asymmetries. The F_3 folds have shallow oriented axial planes (S_3) that are pervasive to semi-pervasive both at outcrop and hand specimen scales (Fig. 5). Stereoplots of both S_2 and S_3 show near-orthogonal fabric overprinting relationship (cf. Figs. 2 and 3). The intersection of S_3 with S_2 forms shallow plunging lineation ($L^2{}_3$) (Figs. 3 and 6).

4.4. D_4 fabric

S_4 is scarce with steep axial planes and is very much similar in orientation to S_2 (Fig. 3 and 7). However, the distinction between S_4 and S_2 is readily recognizable in those domains where D_3 is prevalent, rotating S_2 fabric to moderate dips. S_4 fabric in hand specimen show stage 3 to 4 of differentiated crenulation cleavage development (Bell and Rubenach, 1983). The intersection of S_4 over S_2 ($L^2{}_4$) is widely developed and is steeply to moderately plunging (Fig. 3). The intersection of S_4 over S_3 remains difficult to measure. Where S_3 is not exposed, S_4 is directly overprinted on S_2 (Fig. 6).

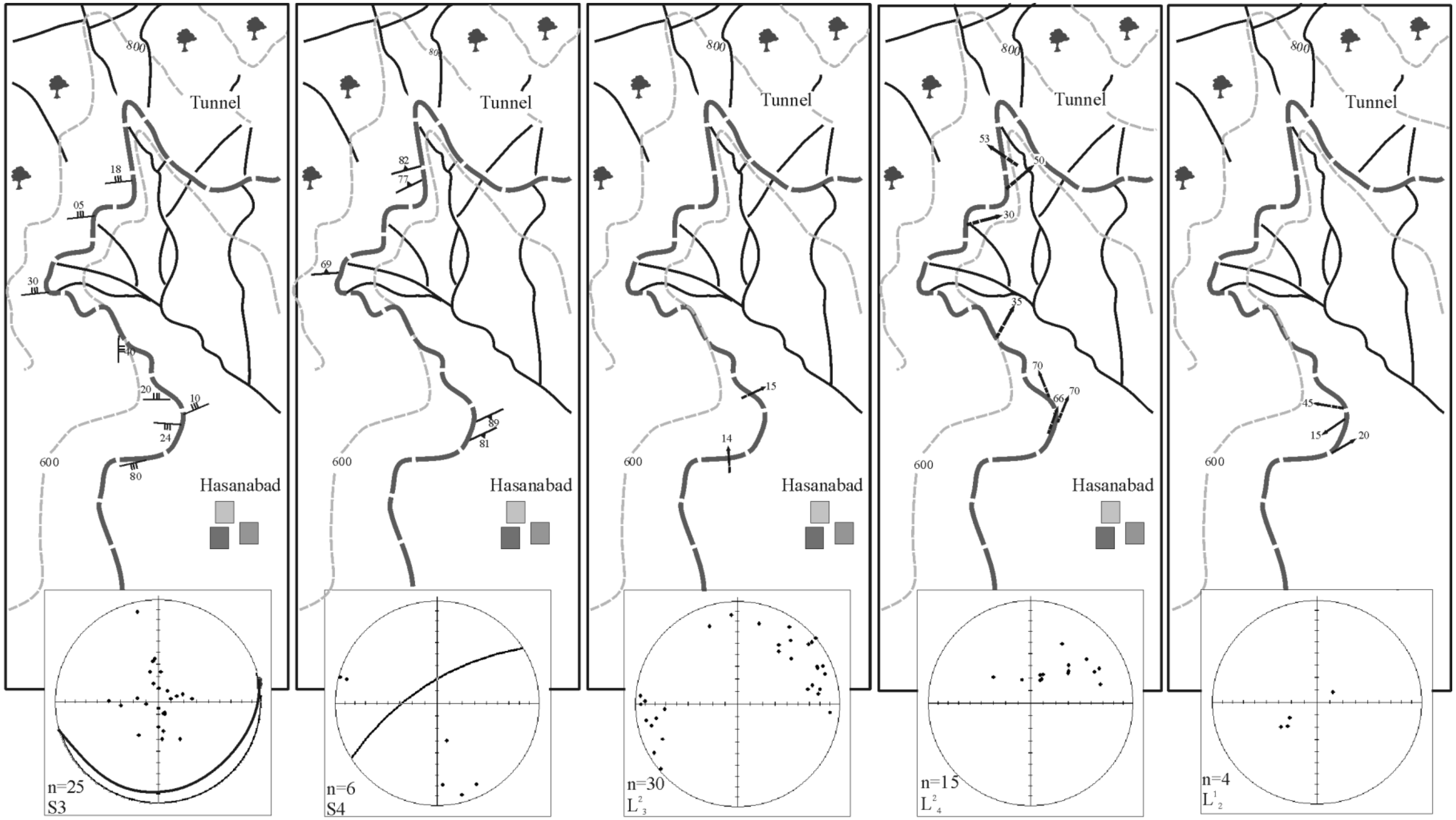

Fig. 3. Showing maps and lower-hemisphere, equal-area stereographic projectioins of planar and linear measurements recorded along the transect. For planar fabrics, stereographic plots show poles to the planes and calculated β-axes, whereas linear measurements show trend and plunge (see text for further discussion).

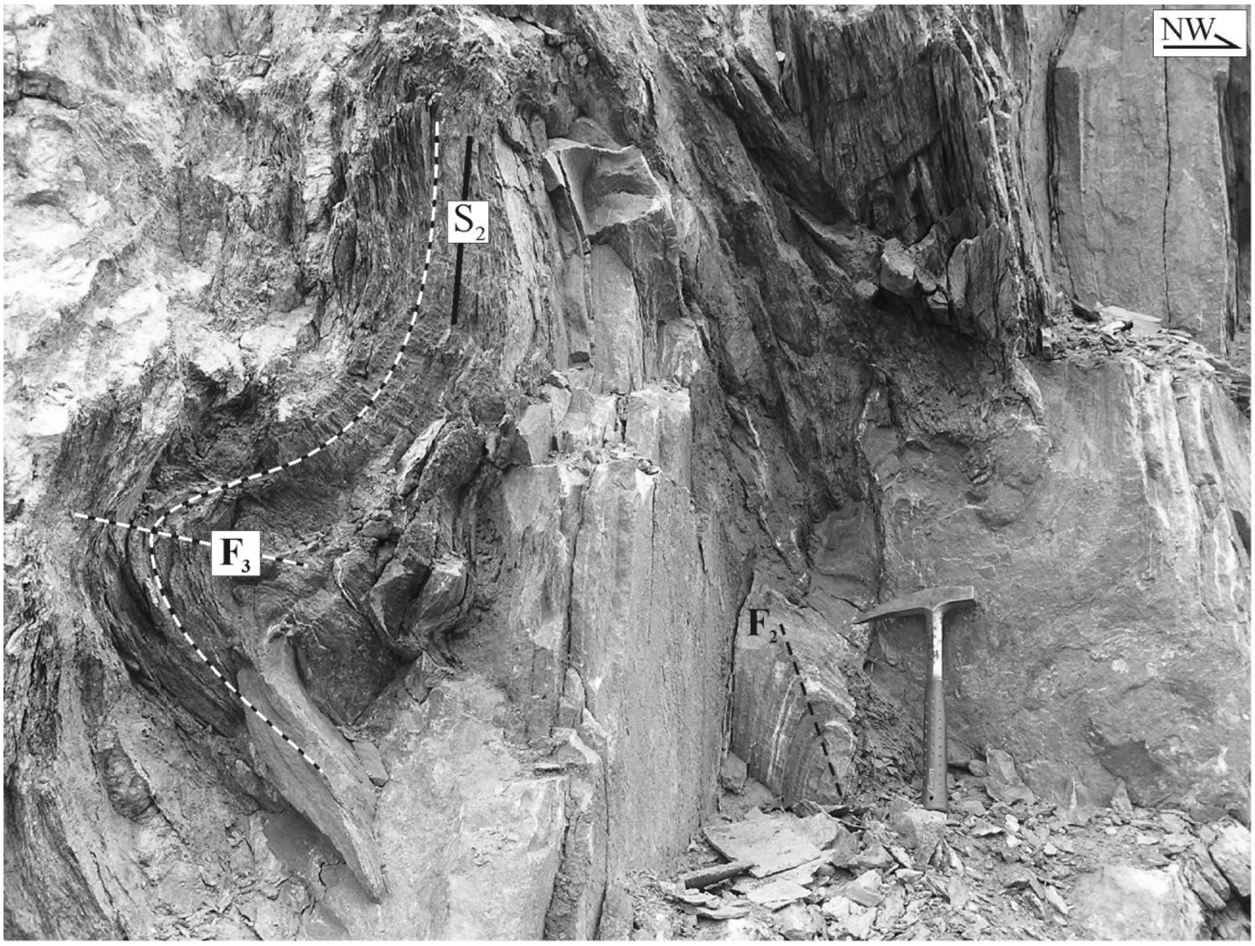

Fig. 4. Field photograph showing F_2 and F_3 folds. The F_2 predate F_3. The F_2 folds are in the low strain zone of D_2, and preserved subvertical S_2, which formed by subhorizontal shortening. The F_3 folds preserves shallow S_3 and formed by subvertical shortening.

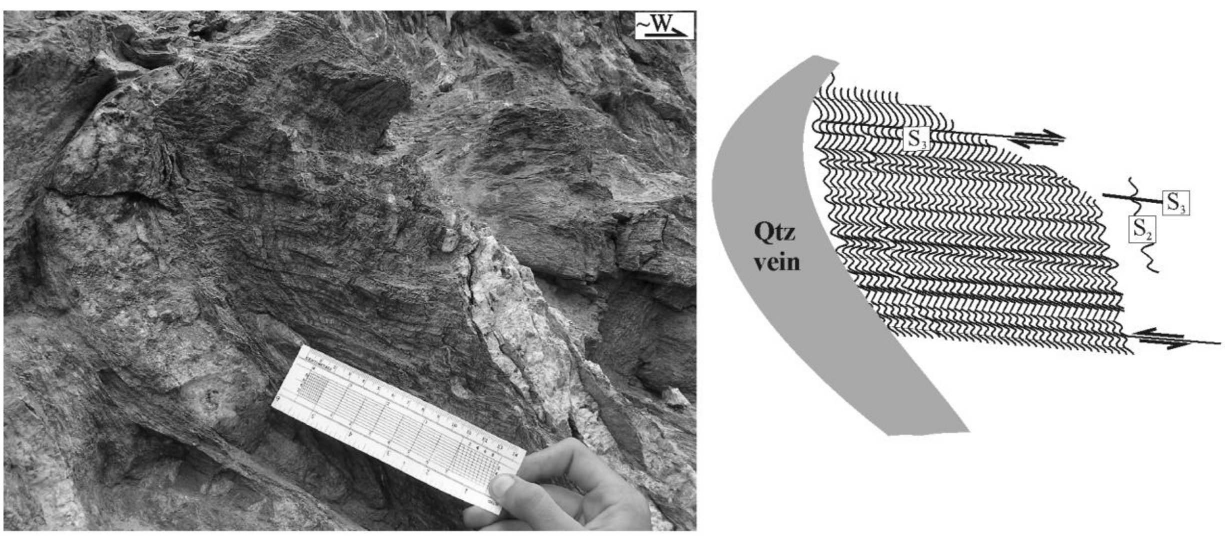

Fig. 5. Field photo showing F_3 fold with subhorizontal S_3 cleavage. Photograph taken looking towards south.

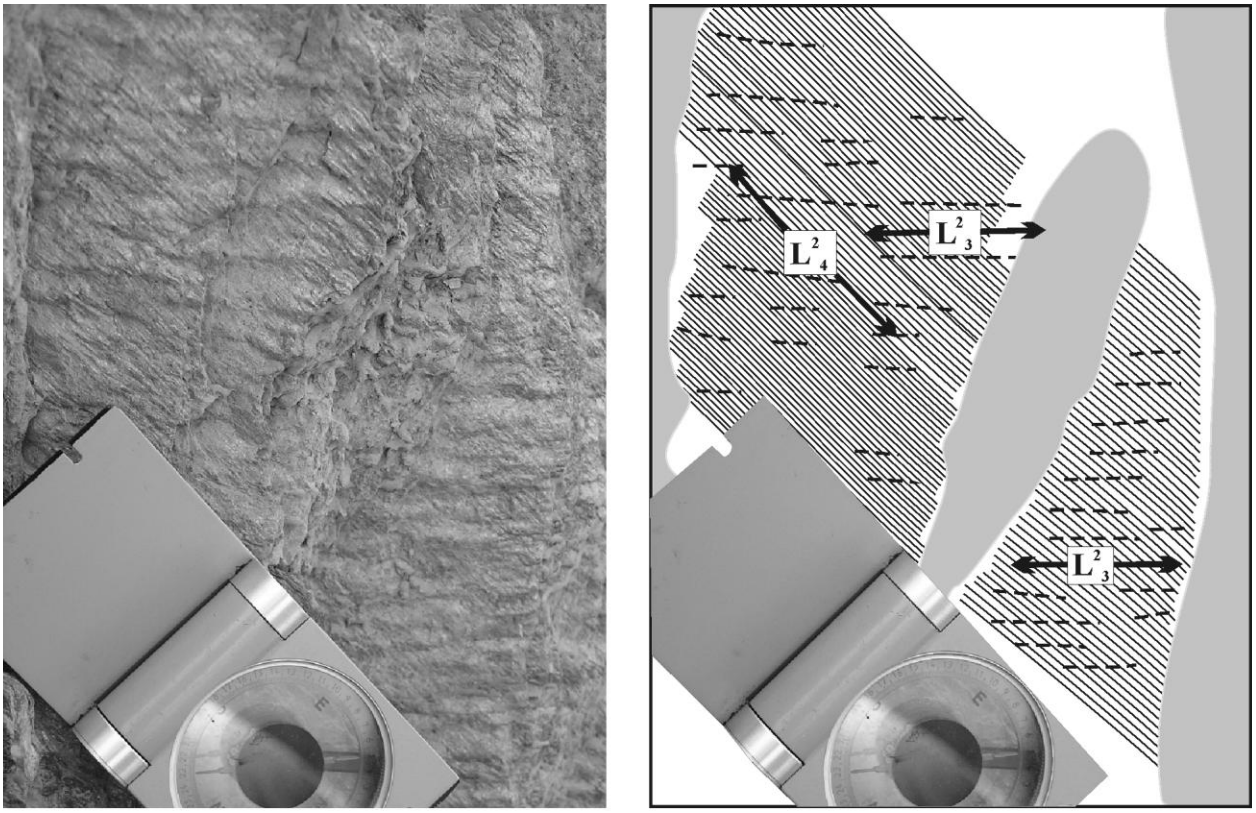

Fig. 6. Field photograph and line diagram showing L^2_3 and L^2_4 intersection lineations. The L^2_3 is shallowly plunging towards NE, whereas L^2_4 is moderately plunging towards the NE. Photograph taken looking towards NW.

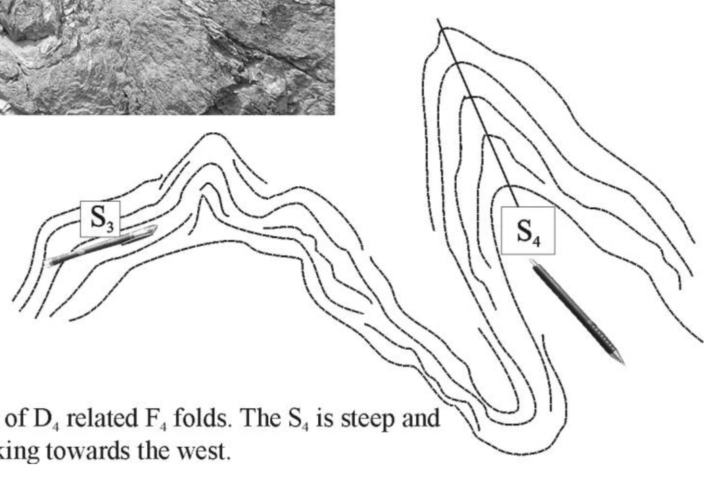

Fig. 7. Field photograph and accompanying sketch of D_4 related F_4 folds. The S_4 is steep and overprinted on shallow S_3. Photo taken looking towards the west.

5. Interpretations

5.1. D_1 fabric development

The orientation of D_1 structures are difficult to reconstruct along the Malakand transect, therefore, apparent shortening directions cannot be deduced. This is because the dominant outcrop foliation is characterized by S_2 that penetratively transposed the early D_1 related fabrics (S_0//S_1).

5.2. D_2 fabric development

The orientation of S_2 is steep and almost ENE-WSW, indicating progressive bulk NNW-SSE inhomogeneous shortening. The ENE trending calculated β-axis also supports this interpretation. The lack of F_2 fold hinges in the field indicates that D_2 was generally non-coaxial or intensely developed. However, in low strain zones of D_2, relics of F_2 are faintly preserved. From the field observations, stereoplot data and rare F^1_2 fold axis orientations, it is apparent that S_2 was the product of D_2 deformation that formed by the sub-horizontal shortening.

5.3. D_3 fabric development

The sparse distribution of F_3 folds indicate that D_3 deformation was heterogeneously developed. Since, F_3 fold hinges are well preserved with opposite asymmetries indicates that D_3 deformation was coaxial. S_3 axial planes are sub-horizontal, where the F^2_3 fold axes are shallowly plunging; this demonstrates that D_3 was formed as a result of sub-vertical shortening.

5.4. D_4 fabric development

Since the orientation of S_4 is very similar to that of S_2, indicates N-S shortening. However, the scale of D_4 is localized as compare to D_2. This means that N-S shortening was started at the onset of D_2 and last over D_4 with an intervening sub-vertical D_3 event. The heterogeneous nature of the D_4 further suggests waning stages of the overall N-S shortening event.

6. Microstructures

6.1. Background

In recent years, microstructural studies have extensively been used in low- to high-grade tectonic terrains (e.g., Passchier and Trouw, 1998). This is because studies at microscale reveals phases of deformation and associated episodes of metamorphism that cannot be identified in the field (e.g., Sayab, 2005; 2006). Based on detailed microstructural analysis alone, novel solutions have been proposed for the mechanism involved during orogenesis, which suggests that study of microstructures in structural geology is inevitable (see Johnson, 1999).

6.2. Sample description

Four oriented samples were collected (Fig. 8) using Breithaupt Kassel COCLA compass. The samples are Grt-Bt-Ms schist (abbreviation after Kretz, 1983). Garnet ranges in size from 0.5mm to 1cm, opaque in hand specimen and dark red to brown in color. Sample M22 and M23 preserve both S_2 and S_3 fabric.

6.3. Description of microstructures

The origin of crenulation cleavage in deformed rocks was first thoroughly described by Gray (1979). Differentiation by solution transfer at low grade and recrystallization at high-grade metamorphism play important role in the development of crenulation cleavage development (Gray, 1979; Gray and Durney, 1979) with increasing pressure, temperature and deformation. Six stages of crenulation cleavage development have been recognized (Bell and Rubenach, 1983) that provide basis for the identification of different fabric generations and discussed below.

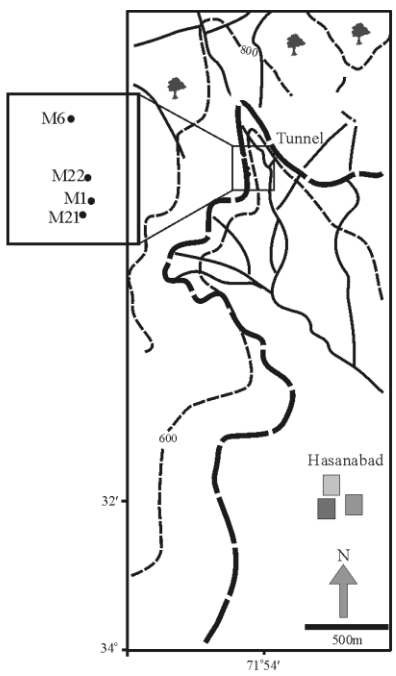

Fig. 8. Map showing sample locations along the Malakand transect.

6.4. S_1 and S_2 microstructures

S_2 in the observed thin sections appear to be stage 3 to 4 of differentiated crenulation cleavage and can best be described as pervasive spaced foliation (terminology after Powell, 1979; Borradaile et al., 1982). S_1 preserved in the microlithons as Q-domain, whereas S_2 preserved as cleavage or M-domain (Fig. 9). The spacing of the S_2 cleavage is estimated at about 0.5 to 1.0mm at microscale and is characterized as parallel, planar and smooth foliation (terminology after Gray, 1978) and occupy ~30 to 40% of the total volume of the rock and can also be termed as zonal foliation (see Passchier and Trouw, 1998). The transition from microlithon to cleavage is gradational. Since S_2 is steeply pitching with respect to the vertical oriented thin sections, the shear sense along the S_2 cleavage is either north-side-up or south-side-up. The parallelism of S_1 with S_2 in high strain zones suggests that S_1 was reactivated during D_2 event.

6.5. S_3 microstructures

S_3 is pitching near-orthogonal to the S_2 cleavage. It is characterized by stage 1 to 2 of crenulation cleavage development with average cleavage spacing estimated around ~1.0 to 2.0 mm (Fig. 10). This indicates that D_3 deformation was immature. The F_3 microfolds are generally gentle to open and rarely close in terms of their fold interlimb angle or tightness (e.g. Fleuty, 1964). The F_3 microfolds are typical double hinge folds (box microfolds) with two hinge points and an intervening closure surface (Fig. 10). The shape of the S_3 cleavage is not smooth and appears to be rough. Shear sense along the S_3, which rotated the limbs of the F_3 folds, is either top-to-the north or top-to-the south. This suggested that the deformation during D_3 was coaxial and consistent with the mesostructures.

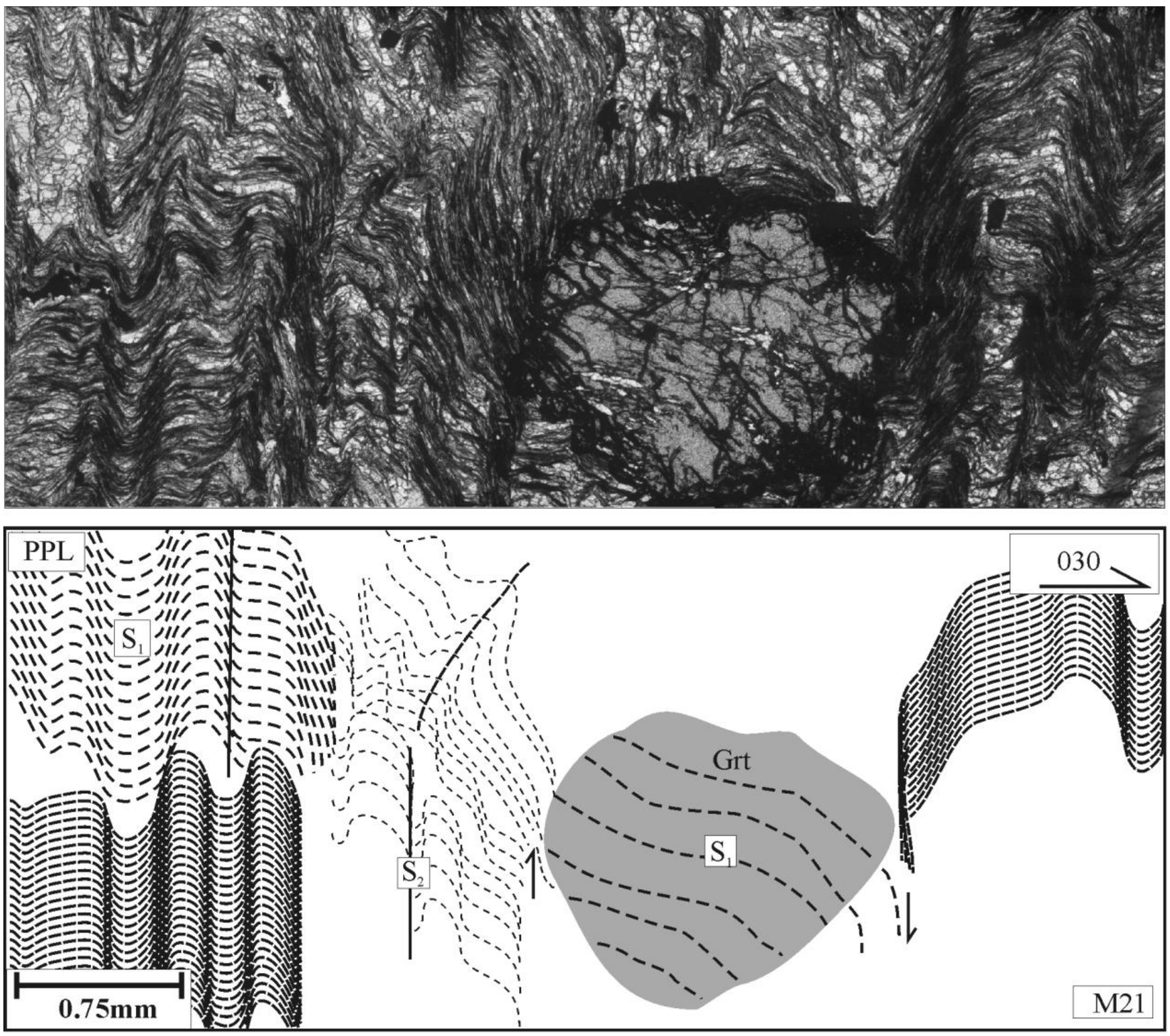

Fig. 9. Photomicrograph and line diagram of D_2 generated S_2 cleavage. S_1 preserved in the mirolithons as Q-domain, whereas S_2 preserved as cleavage or M-domain. The average calculated foliation spacing is ~1.0mm. Shape of the S_2 cleavage is planer and smooth. The S_2 is steeply pitching. The trails preserved within the garnet are shallow to steep and partially continuous. Vertical oriented thin section with single barbed arrow and scale bar.

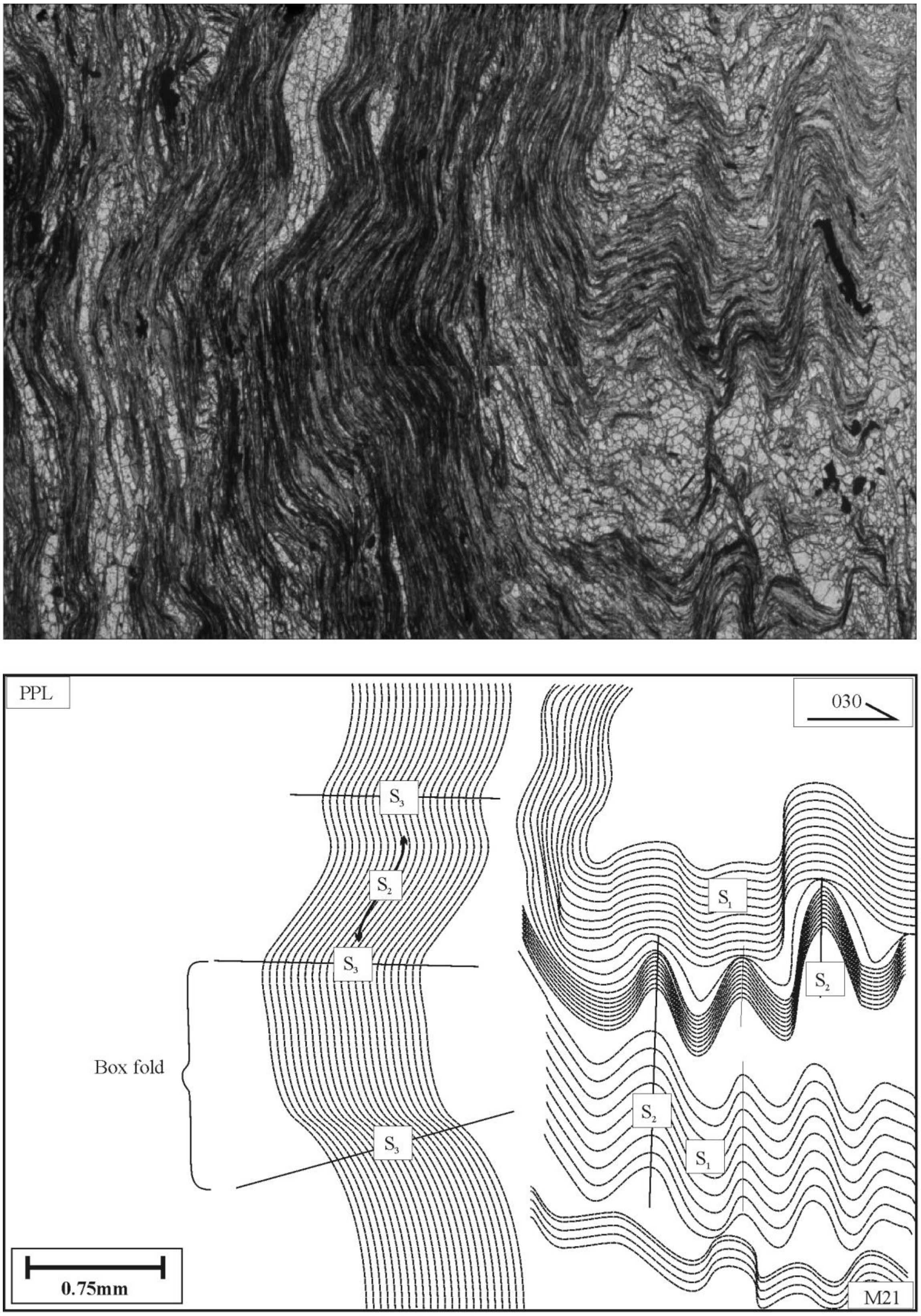

Fig 10. Photomicrograph showing F_3 and F_2 microfolds. The F_3 folds are close to box in shape with double hinge zones and an intervening closer surface. This fold is formed by D_3 subvertical shortening. S_3 is slightly curved and non-pervassive.

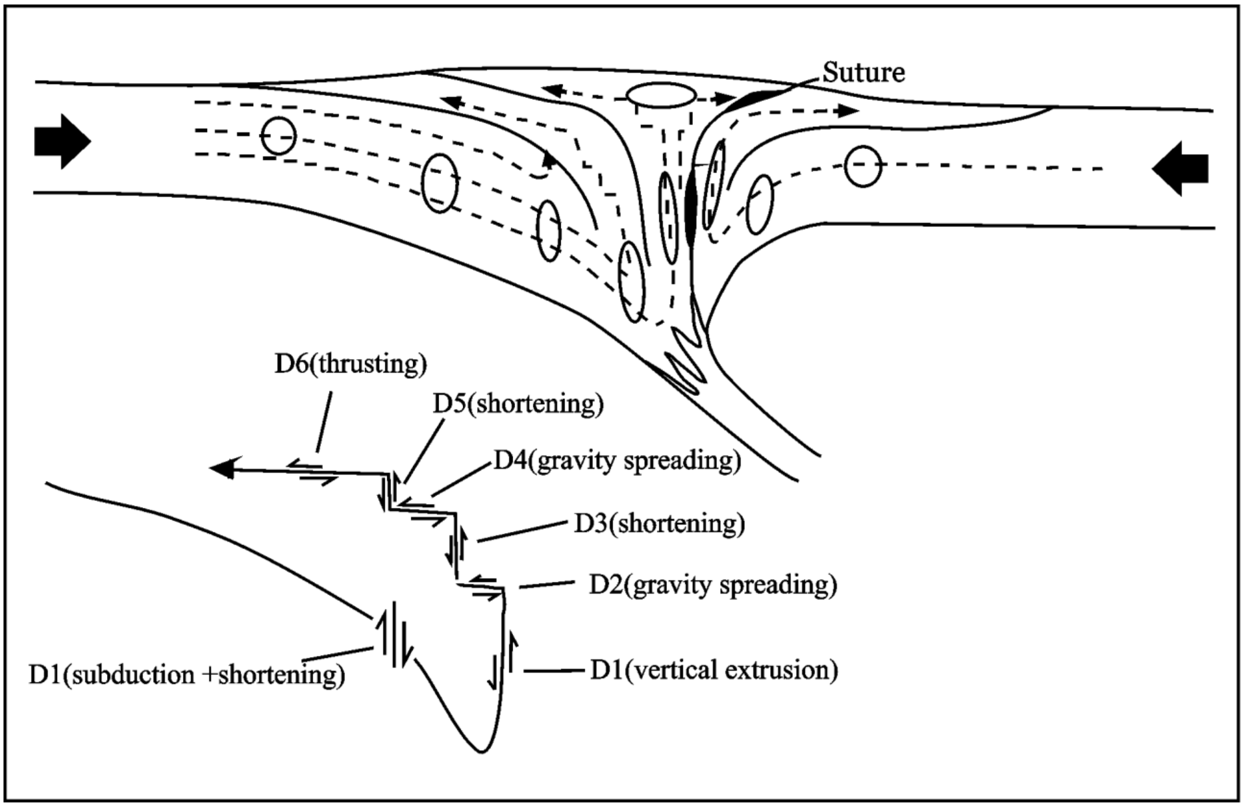

Fig. 11. Conceptual model of an orogen where progressive subvertical and subhorizontal shortening occur in the mid crust (after Aerden, 2005). The model appears to be consistent with the observations and data presented in this paper.

6.6. S_4 microstructures

F_4 microfolds are not common in thin sections as compare to F_3 microfolds. This is because of the heterogeneous distribution of D_4 deformation, as described above. In sample M21, F_4 microfolds were observed that is oriented upright and overprinted on F_3 microfolds.

7. Correlation of microstructures to mesostructures

Overprinting relationships of cleavage have extensively been used to reconstruct the histories of deformation in orogenic terrains (e.g., Cihan and Parsons, 2005). This means understanding different generations of fabrics in a group of oriented rocks will not only resolve the tectonic evolution of the area but will help to understand the mechanisms of deformation (Reinhardt, 1992). Thus, by combining micro- to macrostructural work together can provide important insights to observe deformation mechanism at different scales. The orientation of S_2 cleavage both in the field and in the oriented thin sections is sub-vertical. This suggests not only self-similarity of D_2 structures from outcrop to thin section scale (Turcotte, 1997), but the same deformation mechanism operating at all scales. As the rocks exposed along the Malakand transect belong to the Saidu Formation (Triassic to Jurassic, Ahmed, 1999; DiPietro et al., 1999), this implies that the S_2 fabric was the product of the Himalayan orogeny.

The D_3 related S_3 cleavage was also observed at the outcrop as well as in thin sections, suggesting that the scale of deformation was also self-similar. S_3 was shallowly oriented as a result of D_3 deformation because of the sub-vertical shortening. S_4 was steep and parallel to S_2. However, S_4 was very heterogeneously developed as observed at the outcrop. Structural observations, from thin section to outcrop scale, revealed that the deformation mechanisms and the fabric overprinting geometries of D_2, D_3 and D_4 were same at all scales.

Recent studies across the orogenic terrains have showed that gravity driven processes can generate sub-horizontal fabrics (e.g., Bell et al., 1998). Multiple generations of sub-vertical and sub-horizontal fabric form as a result of episodic sub-horizontal and sub-vertical crustal shortening, respectively (Fig. 11; Aerden, 2005). The mechanism of this phenomena has recently been illustrated through numerical simulations by Schulmann et al. (2002), computing (Aerden, 2004) and theoretical models (Aerden, 2005).

8. Porphyroblast growth

Three modes of porphyroblast growth have been described in the literature i.e., pre-, syn- and post-tectonic (e.g. Passchier and Trouw, 1998). The classification is based on the geometry of the matrix and inclusion trail patterns preserved within porphyroblasts. Pre-tectonic porphyroblast growth occurs before the major tectonic event. Inclusions in the pre-tectonic porphyroblasts are generally randomly oriented or sectored zoned and found along contact aureoles (Rice and Mitchell, 1991). Syn-tectonic porphyroblasts grow during the deformation and associated metamorphism. The growth of syn-tectonic porphyroblasts depends upon finite strain, the ratio of growth rate and the stages of the progressive deformation (Bell, 1981; Passchier and Trouw, 1998). Inclusion patterns in the syn-tectonic porphyroblasts are generally curved, sigmoidal or spiral shaped (generally refereed to as 'Si') with respect to matrix foliation or 'Se' (Schoneveld, 1979). Porphyroblast growth during progressive or regional metamorphism is generally characterized as syn-tectonic. Post-tectonic porphyroblasts are defined by the lack of deflection of the inclusion trails, pressure shadows or strained extinction. Inclusions within the post-tectonic porphyroblasts are generally straight and continuous with the matrix foliation.

Garnet porphyroblasts have been observed in the field and under the microscope. By using the above mentioned porphyroblast growth criteria, the sigmoidal pattern of inclusion trails preserved within the garnets suggests that they are syn-tectonic. The trails observed within the core of the garnet are shallowly pitching (Fig. 9), whereas at the rim the trails are curved and tend to steep. The inclusion trails are continuous with the matrix.

Regarding garnet porphyroblast rotation, we are not sure whether the observed garnet porphyroblasts from the Malakand area are rotated or not. This needs extensive microstructural work, for example measurements of foliation intersection axes (FIA) preserved within the porphyroblasts (Bell et al., 1998), measurements of pitches of the inclusions trails (e.g. Sayab, 2005), numerical simulations (Stallard et al., 2002) and/or FIA controlled monazite dating (Bell and Welch, 2002). However, the shallow and steep orientation of Si (preserved within the garnet porphyroblast) requires 90^o rotation. While applying the rotation model of Schoneveld (1979), the shear senses across the garnet are not consistent with respect to the matrix foliation. The orientation of Si in the core of the garnet is similar in orientation with respect to the Q-domain of the matrix and the steep nature of Si at the rim of the porphyroblast is similar in orientation with respect to the M-domain. Based on these observations, it is inferred here that the garnet porphyroblasts are not rotated with respect to the bulk N-S shortening during the Himalayan orogenesis. The non-rotation model explains well the shear senses across the porphyroblasts with respect to the matrix crenulations (Fig. 9). The garnet preserved shallow $S_1//S_0$ and grew early during the D_2 event. As the S_2 become progressively differentiated the garnet growth was stopped.

9. Conclusions

a) Distinct near-orthogonal fabrics have been identified in the rocks exposed along the Malakand transect, NWFP, northern Pakistan. S_1 is sub-horizontal that formed during D_1. D_2 produced E-W striking and steeply dipping pervasive S_2 foliation. D_3 is characterized by sub-horizontal spaced S_3 foliation. S_4 is very similar in orientation to that of S_2. It is interpreted that both S_2 and S_4 are formed by sub-horizontal crustal shortening, whereas, S_3 formed by sub-vertical shortening. These fabrics are formed as a result of four discernible fabric generating deformation events namely D_1 to D_4.
b) Three sets of intersection lineations $L^1{}_2$, $L^2{}_3$ and $L^2{}_4$ have been identified that formed contemporaneously with D_1, D_2, D_3 and D_4. The intersection of S_3 with S_2 formed shallow plunging lineation, $L^2{}_3$. $L^2{}_4$ is heterogeneously developed, steeply to moderately plunging either towards NE or NW.
c) The consistent deformation patterns of foliations and lineations observed at the outcrop as well as in thin sections suggest that the tectonic mechanism and fabric overprinting geometry were similar at all scales. It is interpreted that the near-orthogonal fabrics formed due to the progressive sub-horizontal and sub-vertical bulk crustal shortening events and appear to be consistent with the new conceptual tectonic model proposed by Aerden (2005) (Fig. 11).
d) Based on the porphyroblast growth criteria, the sigmoidal inclusion trail patterns preserved within the garnet porphyroblasts suggest that they are syn-tectonic. Regarding porphyroblast rotation, it is inferred here that garnets are not rotated with respect to the bulk N-S shortening. Our model explains well the shallow nature of $S_1//S_0$ and the steep orientation of S_2 both in the porphyroblast and in the matrix.

Acknowledgments

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