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Unfolding of refolded fabrics using Foliation Intersection Axes (FIA) preserved within the porphyroblasts: an example from the Michni area, Mohmand Agency, NWFP, Pakistan

ASGHAR ALI[1], MOHAMMAD SAYAB[2], MUHAMMAD SADDIN[3], ZAHOOR AHMAD[4]
[1]Department of Geology, University of Peshawar.
[2]National Centre of Excellence in Geology, University of Peshawar.
[3]Geological Survey of Pakistan, Shami Road, Peshawar.
[4]Mineral Testing Laboratory, Hayatabad, Directorate General of Mineral & Mines, Peshawar.

ABSTRACT: *Integrated macro-, meso- and microstructural analysis of the part of the Michni area, located in the Mohmand Agency of NWFP, Pakistan, revealed at least five fabric- generating deformation events. The study area is characterized by a regional scale NNE-SSW trending synformal structure with moderately dipping pervasive foliation. Detailed microstructural analysis using Foliation Intersection/Inflection Axis technique (FIA) showed that the geometry of this regional fold postdates at least two bulk-shortening directions. The youngest FIA set 3 trends parallel to the axis of the synform, whereas FIA set 2 and 1 trend at high angle to the fold axis. Orientation of the FIA set 1 suggests early NNE-SSW shortening followed by NNW-SSE shortening. The trend of the FIA set 3 implies ESE-WNW bulk shortening. The orientation of FIA set 1 and 2 were obtained from inclusion trails preserved within the porphyroblasts. This suggests that the matrix foliation was the end product after extensive recycling of foliations, where the remains of early deformations were only preserved within the porphyroblasts. Unfolding of foliations using FIA technique has important implications to determine early bulk shortening directions, which is not possible by any other means. Moreover, the results of this study signify multiple shortening directions prior to or synchronous with the Himalayan orogenesis, which were not reported previously.*

INTRODUCTION

Inclusion trails preserved within the porphyroblasts are interpreted as pre-, syn- or post-tectonic depending on their geometry (e.g., Passchier & Trouw, 1998) and have extensively been used for the understanding of orogenic processes (e.g., Johnson, 1990; Bell et al., 1998; Ilg & Karlstrom 2000, Sayab, 2005). Despite great efforts put forth by theoretical and experimental work, the mechanisms controlling the development of inclusion trails are still not well understood. Therefore, the interpretation of inclusion trails preserved in the porphyroblasts have received much attention and been the subject of ongoing controversy regarding porphyroblast rotation versus non-rotation (cf. Ikeda, et al., 2002; Bell & Welch, 2002). Two models exist in the literature for the inclusion trail geometries. The rotation model suggests that the porphyroblasts and their inclusion trails rotate relative to the external matrix foliation (S_e) (e.g. Passchier, et al., 1992); whereas non-rotation model argues that these objects do not rotate and preserve inclusion trails as successive multiple foliations (e.g. Hayward, 1990; Sayab, 2005).

To understand porphyroblast growth versus inclusion trail geometry, a detailed integrated micro- to macroscopic scale structural analyses have been carried out in the multiply deformed metamorphic rocks of the Mohmand Agency, NWFP, northern Pakistan (Fig. 1). Foliation Intersection/ Inflection Axes technique (FIA) has been used to unfold the refolded fabrics that are preserved either in the matrix or in the porphyroblast. The microstructural data were compared with the field observations and orientation data to resolve the kinematic evolution of the study area, which is rather poorly documented in the literature. This in turn puts important insights for porphyroblasts to test whether these geological objects rotate or not in the viscous flow rotational paths.

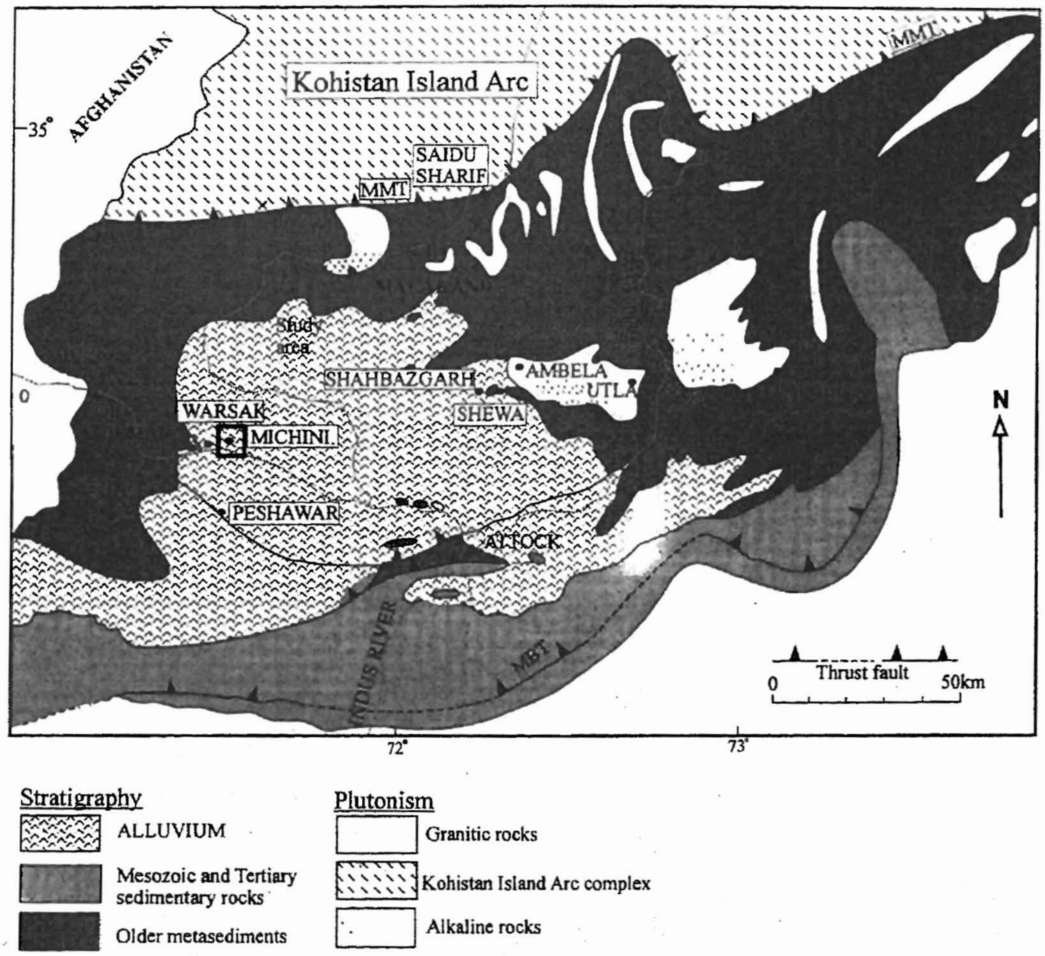


Fig. 1. Map showing major tectonostratigraphic zones of the northern Pakistan. Box shows the location of the study area.

GEOLOGICAL SETTING

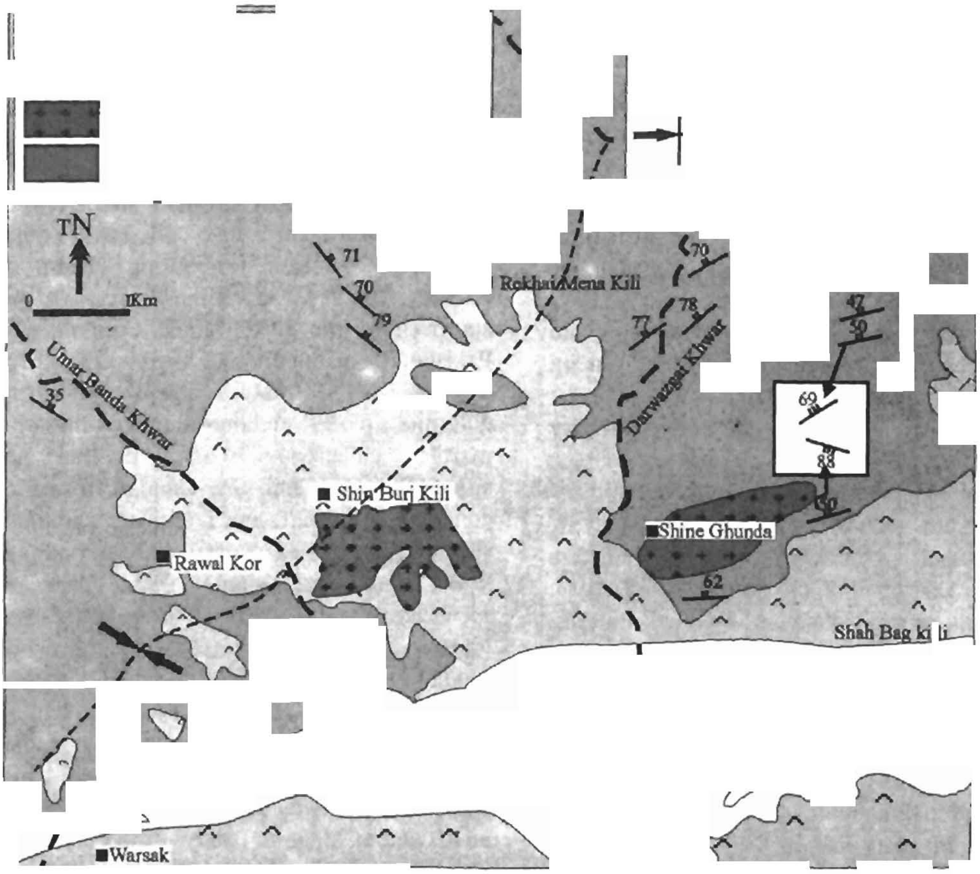
Himalayas are one of the best examples of curstal- scale continent-continent collision, i.e., the closure of Tethys Ocean and the collision of Indian with the Asian plate (e.g., Tahirkheli, 1979). The collision was episodic in terms of magmatism, deformation, regional metamorphism and exhumation. Most of the field, petrographic and geochronological studies provide adequate evidences to suggest that the main metamorphic event in the rocks of the Himalayas is associated with the Tertiary Himalayan Orogeny (e.g. Treloar et al., 1989ab). Regional scale litho-tectonic maps of northern Pakistan show distinct geologic entities that are made up of (1) the northern margin of the Indian plate i.e., Tethyan sediments and Himalayan foreland molasse basin, (2) one or more Asian microcontinents in its north and northwest, and (3) a series of island arcs and ophiolites between (1) and (2). In the northern Pakistan, the Indian plate is separated from the Karakoram by the Kohistan magmatic arc, which was welded to Karakoram plate during the Late Cretaceous (100-85Ma; Coward et al., 1987; Treloar et al., 1989ab) and to the Indian plate during Paleocene (66-56Ma; Beck et al., 1996).

Pre-Himalayan metamorphic rocks are exposed as discontinuous patches around the Peshawar basin, south of the Main Mantle Thrust (MMT) and are poorly documented in the literature (e.g. DiPietro, et al., 1999). Some of these patches belong to the primitive Hazaran Orogeny (Baig et al., 1988). The study area appears to be the part of the Pre-Himalayan metamorphism and deformation, understanding of which will intuit to the recognition of pre-Himalayan deformation events (see below). The study area is a part of the Mohmand Agency locally known as Michni and located in the west of the Peshawar city (Fig. 1). The area covers 71°20′ and 71° 30′ East longitude and 34° 10′ and 34° 15′ North latitude and lies between the Khairabad-Panjal thrust and Main Mantle Thrust (MMT). The area consists of two dominant but undifferentiated litho-tectonic units of Silurian (?) age called as Yousaf Khel and Gandao formations (Sadin & Aslam, 1987). The names are not yet approved by the Stratigrahpic Committee of Pakistan (pers. comm., M. Sadin, 2005). The Yousaf Khel formation consists of meta-dolomite, partly metamorphosed limestone, marble, calcareous schist, phyllite and siliceous schist and the Gandao formation consists of quartz-mica schist, graphitic schist, garnet-mica schist and amphibolite schist (Sadin & Aslam, 1987). The area forms roughly NNE-SSW trending and northeastward plunging synformal structure (Sadin & Aslam, 1987). Both the Yousaf Khel and Gandao formations are folded along this structure. Because of its abundant porphyroblastic assemblage and nice exposure of L-S tectonites, the area provides an excellent sight to study the behavior of porphyroblasts during folding.

METHODOLOGY

Mesoscopic studies

The geological information was plotted on the Survey of Pakistan toposheet No. $38^{N}/8$ at 1:12,000. In this regard, a generalized geological map prepared with special emphasis on structural overprinting relationships (Figs. 2 & 3). Structural elements, both foliations and lineations, were plotted on the map and on the lower-hemisphere, equal-area stereographic projections. 18 spatially oriented porphyroblastic, garnet-bearing samples were collected for detailed microstructures analysis (Fig. 4).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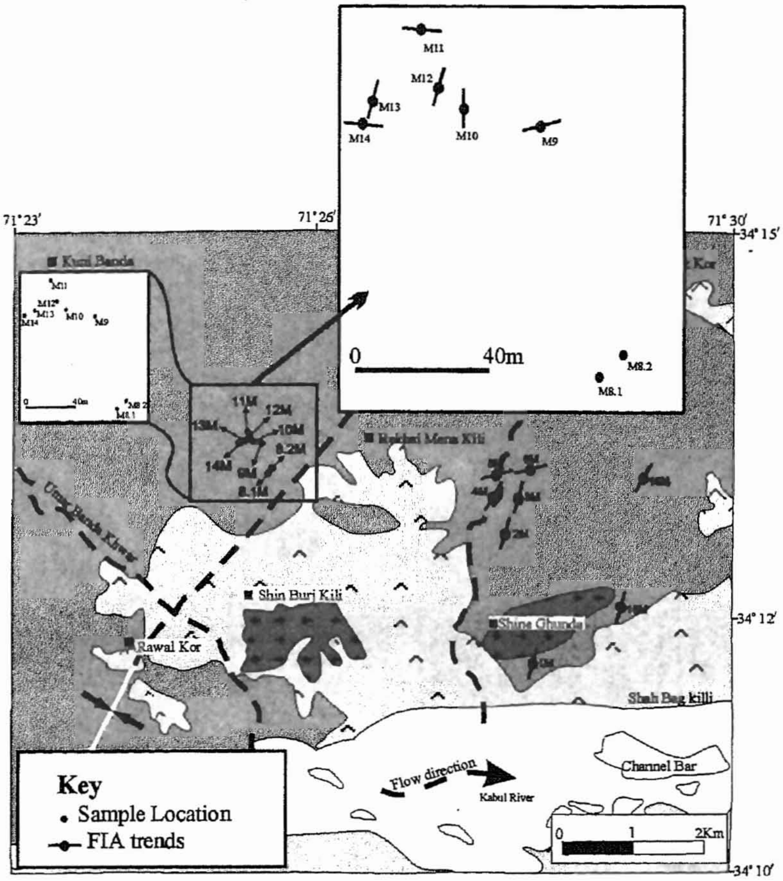


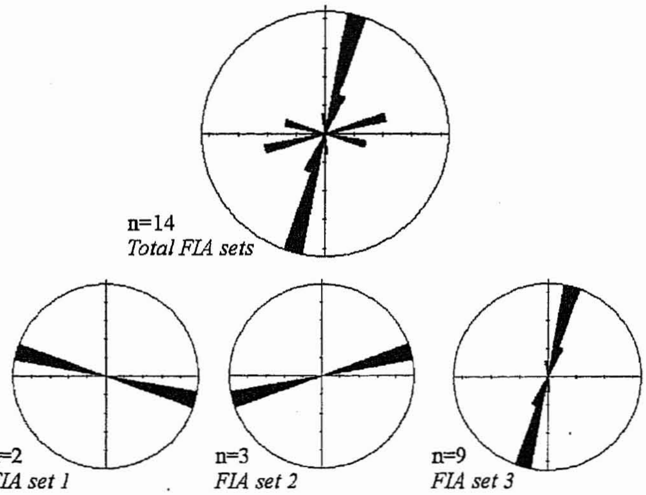
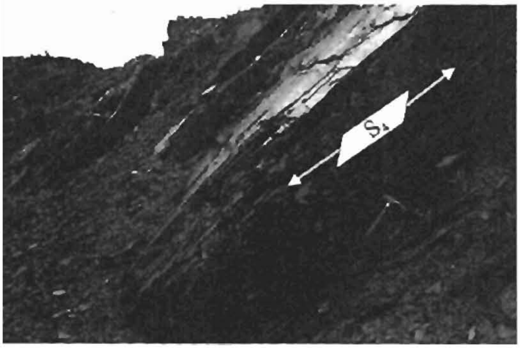


Fig. 4. Map showing the spatial distribution of oriented rock samples and FIA trends. FIA trends are plotted on rose diagrams. Note, distinct FIA orientations with respect to North.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Micro-structural studies

14 oriented rock samples were studied for detailed microstructural analysis. To establish overprinting relationships, all microstructural observations were carried out on thin sections that were cut perpendicular to the foliations or 'A' sections (see e.g., Johnson et al., 2006). The foliations are numbered in chronological order with respect to successive deformations, that is, S_1, S_2, S_3..., as D_1, D_2, D_3..., respectively. S_1, where preserved, is flat lying and has only been observed as inclusion trails in the cores of the porphyroblasts (Fig. 8). S_2 is observed as steep foliations at the core-median region of the garnet porphyroblasts. S_3, very similar in orientation to that of S_1, is subhorizontal and preserved in the median-rim region of the garnet. S_4 in all the oriented thin section is moderately to steeply pitching and observed in the rim of the porphyroblasts and continuous with the matrix. The S_4 in the matrix is typically identical to stage 5 or 6 of Bell and Rubenach (1983) differentiated crenulation cleavage classification scheme. This suggests that D_4 obliterated and/or transposed early formed fabrics. However, older fabrics were only preserved as inclusion trails in the porphyroblasts. Moderately pitching S_5 was observed in few rock samples (Fig. 9), which appears to be the younger deformation fabric and correlates well with the outcrop shallow lying S_5 (cf. Figs. 6 & 9).

FIA measurements are made relative to both geographic coordinates and a line perpendicular to the earth's surface. To measure FIAs in three dimensions, a minimum of six vertical oriented thin sections were cut from each spatially oriented sample, with one cut every 30° around the compass. The trend of the FIA is located where the flip occurs between two adjacent vertical oriented thin sections when viewed in one direction (Fig. 10). Where both asymmetries are observed equally (both 'S' and 'Z'), but the asymmetry in vertical thin sections to either side are switched, the FIA is considered to lie in the plane of that section (e.g. Sayab, 2005). In this study 115 oriented thin sections were prepared to obtain the FIA trends.

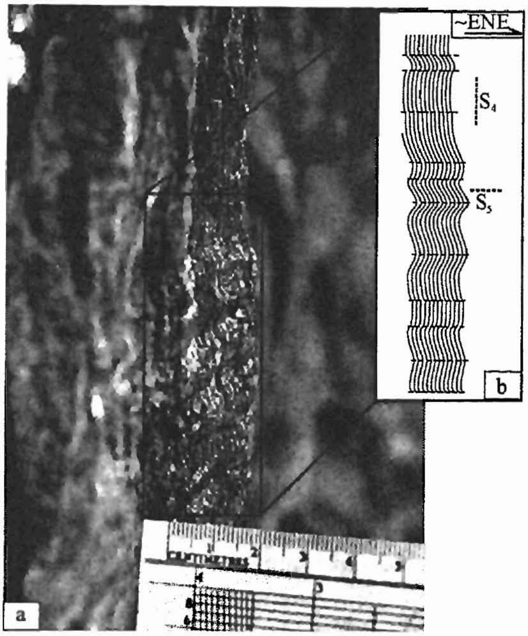

Fig. 6. Photo and associated line sketch showing NNW striking subvertical foliation S4, which formed by subhorizontal shortening. The S4 in turn is overprinted by ENE-WNW striking S5, which formed during subvertical shortening. Photo taken looking NNW.

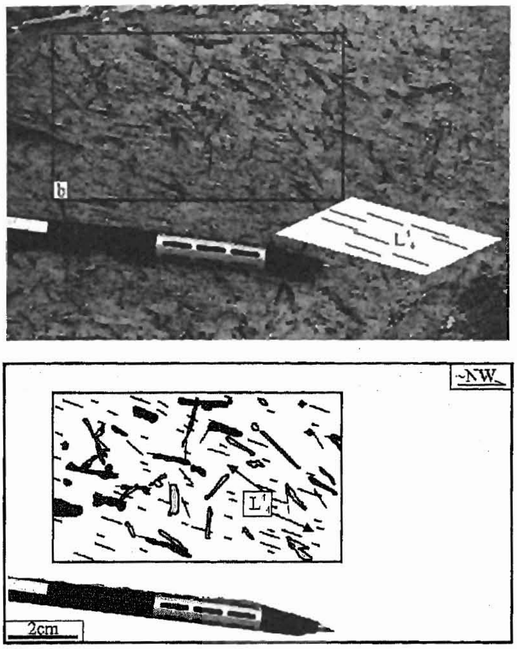

Fig. 7. Photo showing biotite mineral stretching lineation, L44. The lineation is shallowly plunging towards NW. Amphibole needles overprinted L44 and randomly oriented. Photo taken looking towards SW.

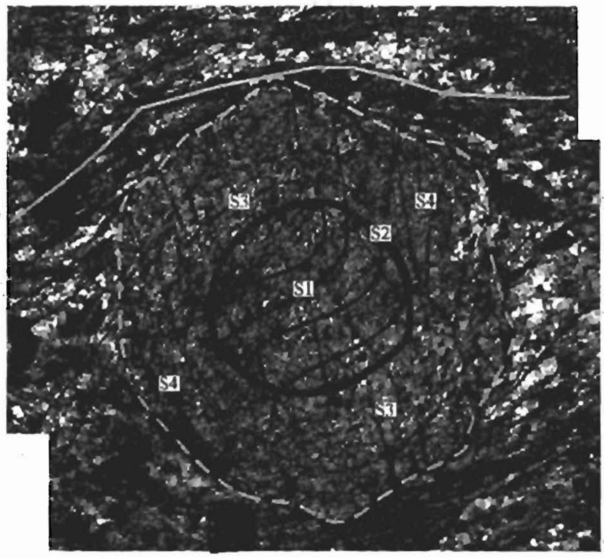

Fig. 8. Four near-orthogonal fabrics identified within the garnet porphyroblast. Garnet core preserves shallow S1, followed by steep S2 in the core-median, shallow S3 and steep S4 in the median-rim region. S4 is partially continuous with the matrix. See text for further discussion.

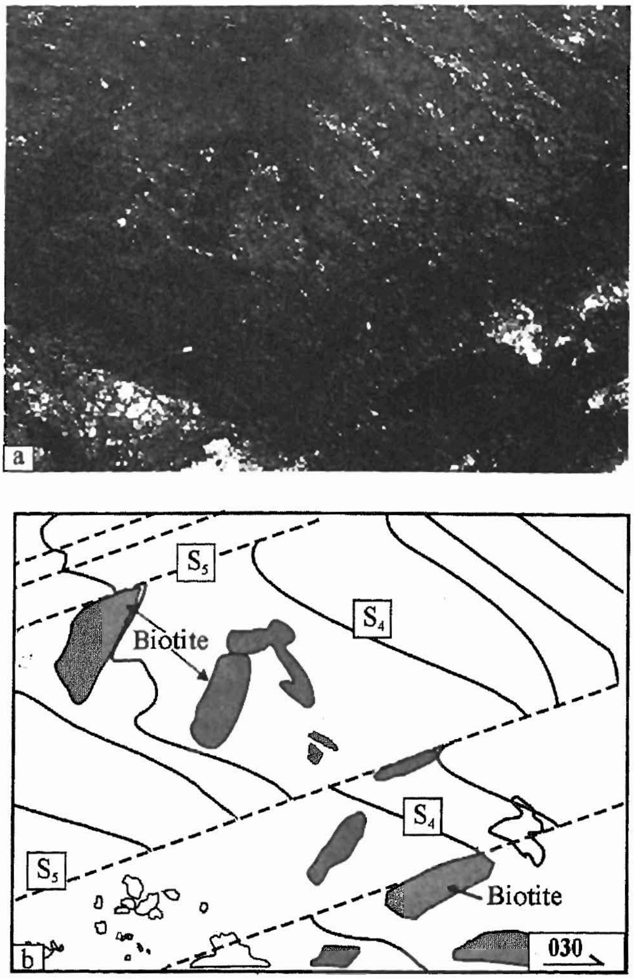

Fig. 9. Photomicrograph (a) and line diagram (b) showing matrix foliation in sample M04. The matrix foliation S4 is overprinted by a weak subhorizontal crenulation S5. Note, biotite flakes re-oriented in S5 direction. Vertical thin section with single barbed arrow showing 030° strike and way up.

Foliation Intersection/Inflection Axes preserved in the porphyroblasts (FIAs)

The Foliation intersection/ inflection axis (FIAs) technique was first established by Hayward (1990) and modified by Bell et al., (1995). FIAs have successfully been used to: (1) link deformation and folding events (e.g., Timms, 2003) (2) understand complex structural histories in the rocks (e.g., Cihan, 2004), and (3) to determine the multiple shortening directions (e.g., Sayab, 2005). Studies involving FIAs have the advantage that FIAs form in response to shortening, irrespective of whether porphyroblasts rotate relative to one another or not (e.g., Johnson, 1999). Thus, focusing in FIA trends, rather than inclusion trails orientation can be used as a tool for the controversy over porphyroblasts kinematics and rotation verses non-rotation models.

FIAs from garnet porphyroblasts

14 FIA measurements were obtained from garnet porphyroblasts. Three sets were recognized after plotting the FIA data on rose diagrams (Fig. 4; Table 1). The FIA sets were distinguished based on the 1) continuity of inclusion trails with the matrix foliation (e.g. Adshead-Bell & Bell, 1999), and 2) orientation of the FIA trend with respect to the regional foliation. The younger set, FIA 3, trends parallel to the present day matrix foliation and is trending NNE-SSW. Almost all the inclusion trails preserved within the garnet porphyroblasts belonging to the FIA set 3 are continuous with the matrix foliation. FIA set 2 oriented ENE-WSW and lies at an acute angle to the FIA set 3, whereas FIA set 1 is trending ESE-WNW and makes an obtuse angle to the youngest FIA set 3. FIA 1 garnets are generally characterized by those having truncated inclusion trail geometries with the matrix.

Unfolding of overprinted fabrics using FIA approach

Three FIA sets have been recognized both on the eastern and western limbs of the synformal structure and indicate three independent shortening directions (Fig. 4). FIA set 3 formed as a result of ESE-WNW, FIA set 2 by NNW-SSE and FIA set 1 by NNE-SSW. The orientation of both FIA set 1 and 2 are close to each other suggesting bulk N-S shortening. Thus, before ESE-WNW bulk shortening, there was a period of N-S shortening event. This primitive bulk N-S shortening event was recognized based on the inclusion trail geometry form oriented rock specimens using FIA approach and is not possible by any other means. It is concluded here that before ESE-WNW shortening, there was at least one major N-S shortening event in the Michni area.

TABLE 1. SAMPLES WITH GEOGRAPHICAL COORDINATES AND FIA SETS

S.No	Northing	Easting	Garnet FIA Core- Rim	FIA1	FIA2	FIA3
M1	3413192	7127741	15			15
M2	3413192	7127741	15			15
M3	3413750	7127830	15			15
M4	3413292	7125546	30			30
M5	3413292	7125546	75		75	
M6	3413541	7125456	75		75	
M9	3413647	7125326	75		75	
M10	3413647	7125326	0			0
M11	3413647	7125326	105	105		
M12	3413647	7125326	15			15
M13	3413586	7125343	15			15
M14	3413586	7125343	105	105		
M15	3413558	7125281	15			15
M16	3413549	7125250	30			30

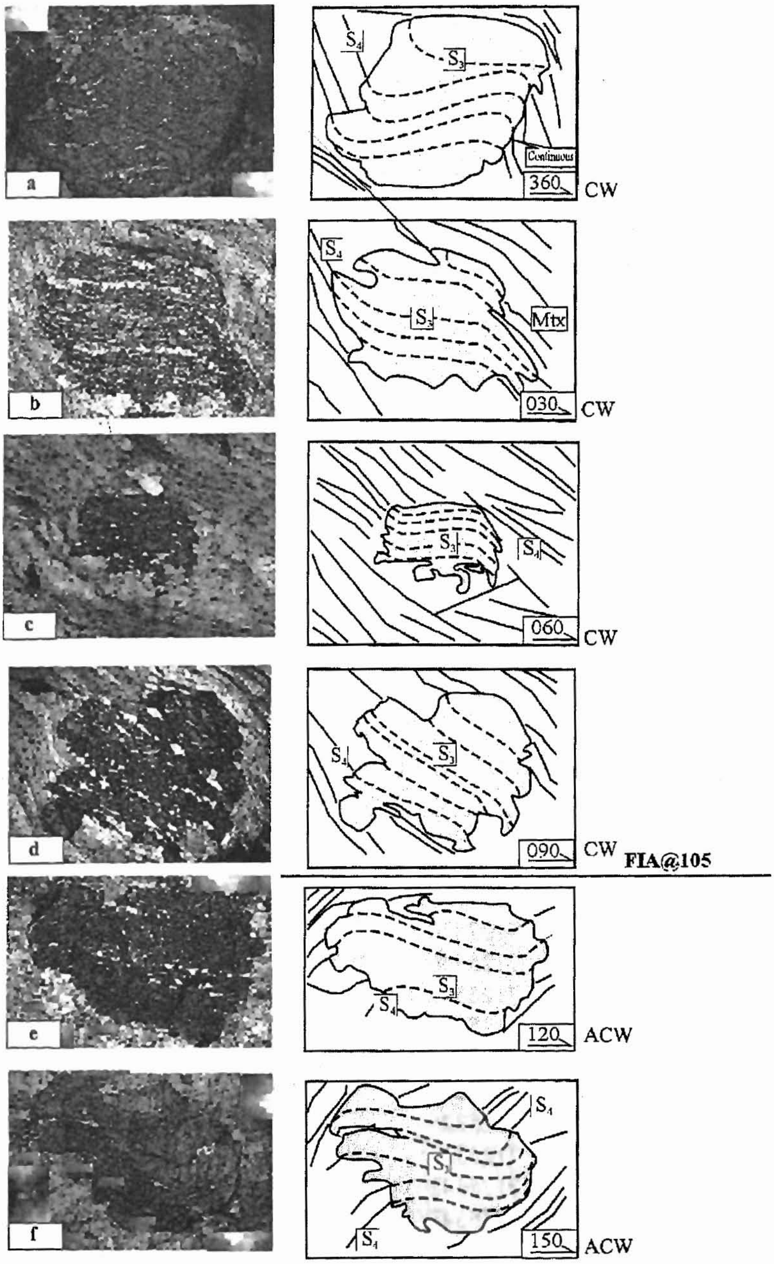

Fig. 10. Photomicrographs and line diagrams from vertical oriented thin sections showing asymmetry method to determined the FIA (Sample M11; see Fig. 4 for location). (a), (b), (c) and (d) show garnet porphyroblasts with clockwise asymmetry (CW) in sections striking 360^0, 030^0, 060^0 and 090^0 respectively. (e) and (f) show garnet porphyroblasts with anticlockwise (ACW) asymmetry in thin sections striking 120^0 and 150^0 respectively. In this case, FIA lies between 090^0 and 120^0 thin sections at 105^0.

DISCUSSION AND CONCLUSIONS

In highly tectonized terranes, tracking back the deformation events are always problematic because of the penetrative effects of the younger deformations. Albeit, early fabrics tend to either transposed or obliterate during younger ductile deformations, their remains may be preserved as inclusion trails in low strain zones, e.g. porphyroblasts (e.g., Ramsay 1962; Fyson, 1980; Aerden, 1995). Therefore, the geometry of the inclusion trails can potentially be used to reconstruct the shortening directions of primitive deformation events that are no longer preserved in the matrix foliation (e.g. Sayab, 2005).

In this study, three independent FIA sets have been determined and used to reconstruct the bulk shortening directions. The consistency of the FIA data across the map-scale synform has important implications for crustal scale processes. The primitive N-S shortening was not reported previously. The orientation of FIA sets 1 and 2, which are trending at high angle to the youngest FIA set 3 and the regional strike of the foliation in the area, suggests that garnet porphyroblast did not rotated and behaved as rigid objects (see also Bell et al., 1998). If they were rotated then both the FIA set 1 and 2 must have aligned parallel to the FIA set 3. This is not clearly the case and further suggests that porphyroblasts, especially the garnets, grew episodically and preserved the deformation events as successive inclusion trails. Further research is required to date these early N-S and younger E-W deformation to put these events into the regional Himalayan orogenesis.

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REFERENCES

Adshead-Bell, N.S. & Bell, T.H., 1999. The progressive development of a macroscopic upright fold pair during five near-orthogonal foliation-producing events: complex microstructures versus a simple macrostructure. Tectonophys., 306, 121-147.

Aerden, D.G.A.M., 1995. Porphyroblast non-rotation during crustal extension in the Variscan Pyrenees. J. Struct. Geol., 17, 709-726.

Baig, M.S., Lawrence, R.D. & Snee, L.W., 1988. Evidence for late Precambrian to Early Cambrian orogeny in northwest Himalaya, Pakistan. Geol. Mag., 125, 83-86.

Beck, R.A., Burbank, D.W., Sercombe, W.J., Khan, A.S. & Lawrence, R.D., 1996. Late Cretaceous ophiolite obduction and Paleocene India-Asia collision in the westernmost Himalaya. Geod. Acta., 9, 114-144.

Bell, T.H. & Rubenach, M.J., 1983. Sequential porphyroblast growth and crenulation cleavage development during progressive deformation. Tectonophys., 92, 171-194.

Bell, T.H. & Welch, P.W., 2002. Prolonged Acadian orogenesis: revelations from foliation intersection axis (FIA) controlled monazite dating of foliations in porphyroblasts and matrix. Am. J. Sci., 302, 549-581.

Bell, T.H., Forde, A. & Wang, J., 1995. A new indicator of movement direction during orogenesis: measurement technique and applications to the Alps. Nerra Nova, 7, 500-508.

Bell, T.H., Hickey, K. A. & Upton, J.G., 1998. Distinguishing and correlating multiple phases of metamorphism across a multiply region using the axes of spiral, staircase and sigmoidal inclusion trails in garnet. Jour. Meta. Geol., 16, 767-794.

Cihan, M., 2004. The drawbacks of sectioning rocks relative to fabric orientations in the matrix. A case study from the Robertson

River Metamorphics (Northern Queensland, Australia). J. Struct. Geol., 26, 2157-2174.

Coward, M.P., Butler, R. W. H., Khan, M. A. & Knipe, R. J., 1987. The tectonic history of Kohisttan and its implications for Himalayan structure. J. Geol. Soc. Lon., 144, 377-391.

DiPietro, J.A., Pogue, K.R., Hussain, A. & Ahmad, I., 1999. Geologic map of the Indus syntaxis and surrounding area, northwest Himalaya, Pakistan. Geol. Soc. Am. Sp. Pap., 328, 159-178.

Fyson, W. K., 1980. Fold fabrics and emplacement of an Archean granitoid pluton, Cleft Lake, Northwest Territories. Canadian J. Earth Sci., 17, 325-332.

Hayward, N., 1990. Determination of early fold axis orientation within multiply deformed rocks using porphyroblasts. Tectonophys., 179, 353-369.

Ikeda, T., Shimobayashi, N., Wallis, S. R. & Tsuchiyama, A., 2002. Crystallagraphic orientation, chemical composition and three-dimensional geometry of sigmoidal garnet: evidence for rotation. J. Struct. Geol., 24, 1633-1646.

Ilg, B.R. & Karlstrom, K.E., 2000. Porphyroblast inclusion trail geometries in the Grand Canyon: evidence for non-rotation and rotation? J. Struct. Geol., 22, 231-243.

Johnson, S. E., 1990. Lack of porphyroblast rotation in the Otago schists, New Zealand: implications for crenulation cleavage development, folding and deformation partitioning. J. Meta. Geol., 8, 13-30.

Johnson, S.E., 1999. Porphyroblast microstructures: a review of current and future trends. Am. Min., 84, 1711-1726.

Johnson, S.E., Duppee, M.E. & Guidotti, C.V., 2006. Porphyroblasts rotation during crenulation cleavage development: an example from the Mooselookmeguntic pluton, Maine USA. J. Meta. Geol., in press.

Kretz, R., 1983. Symbols for rock-forming minerals. Am. Min., 68, 277-279.

Passchier, C.W. & Trouw, R.A.J., 1998. Micro-tectonics. Springer-Verlag, Berlin.

Passchier, C.W., Trouw, R.A.J., Zwart, H.J. & Vissers,R.L., 1992. Porphyroblast rotation: eppur si muove? J. Meta. Geol., 10, 283-294.

Ramsay, J.G., 1962. The geometry and mechanics of formation of similar type folds. J. Geol., 70, 309-327.

Sadin, M. & Aslam, M., 1987. Minerals Reconnaissance in Mohmand Agency, FATA, Pakistan. Geol. Surv. Pak. Inf. Rel. No., 284.

Sayab, M., 2005. Microstructural evidence for N-S shortening in the Mount Isa Inlier (NW Queensland, Australia): the preservation of early W-E trending foliations in porphyroblasts revealed by independent 3D measurement techniques. J. Struct. Geol., 27, 1445-1468.

Tahirkheli, R.A.K., 1979. Geology of Kohistan and adjoining Eurasian Indo-Pakistan continents, Pakistan. Geol. Bull. Univ. Pesh., 11, 1-30.

Timms, N.E., 2003. Garnet porphyroblast timing and behaviour during fold evolution: implications from a 3-D geometric analysis of a hand-sample scale fold in a schist. Jour. Meta. Geol. 21, 853-873.

Treloar, P.J., Rex, D.C., Guise, P.G., Coward, M.P., Searle, M. P., Windley, B.F., Petterson, M.G., Jan, M.Q. & Luff, I.A., 1989a. K-Ar and Ar-Ar geochronology of the Himalayan collision in NW Pakistan: Constraints on the timing of suturing, deformation, metamorphism and uplift. Tectonophys., 8, 881-909.

Treloar, P.J., Williams, M.P. & Coward, M.P., 1989b. Metamorphism and crustal stacking in the north Indian plate, North Pakistan. Tectonophys., 165, 167-184.