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Porphyroblast-Matrix Relationships: A Case Study from Metapelitic Formation of Shillong Group, Meghalaya, India

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Abstract

Porphyroblast-Matrix relationship is an important way to correlate deformation with respect to metamorphism. Garnet is considered as rigid porphyroblast set in a matrix of quartz-biotite -muscovite schist from Sumer, Mawmaram and Manai areas of RiBhoi and West Khasi Hills districts of Meghalaya, India. Foliations are considered as diagnostic reference fabric, where different generations of garnet from pre-tectonic to post-tectonic were encased during different deformational phases. The main impetus of present work is to study the porphyroblast-matrix relationships in metapelites of the Lower Metapelitic Formation of Shillong Group around Sumer, Mawmaram and Manai areas of Meghalaya, NE India.

Keywords: Shillong plateau, Shillong basin, Porphyroblast-Matrix, Metapelite

Introduction

Porphyroblast-matrix relationship has been widely used as one of the most significant tool to evaluate structural and metamorphic history in a poly-deformed terrain, since the days of Zwart (1960, 1962), Spry (1963), Ferguson and Harte (1975) and Vernon (1978). Usually porphyroblast- matrix relationship can be best studied in metapelites having garnet and staurolite minerals. Garnet bearing amphibolite also displays S_i–S_e fabric to evaluate metamorphic history. Porphyroblast with inclusion trails may indicate relative age of mineral growth to deformation. For regional tectonic interpretation, a close systematic study of porphyroblast-matrix relationship in garnet bearing metapelites and metabasites is very useful (*e.g.* Karanth, 1985; Gururajan, 1994; Mamtani and Karanth, 1997; Mamtani *et al.*, 1999, 2001; Chattopadhyay and Ghosh, 2007 amongst others). Mamtani and Karanth (1997) have given an introduction of recent development of porphyroblast-matrix relationship and advocated that syntectonic porphyroblasts can grow over crenulated cleavages during the same period of deformation which resulted in the formation of the crenulation cleavage. Johnson (1999) has elaborated ten current applications of microstructures and forwarded a review of current and future trends. In this communication, we attempt to decipher deformational history and growth of porphyroblasts / minerals and rock fabrics under metamorphic conditions from metapelites of the Shillong Group of rocks of Meghalaya, where highest index minerals are marked by garnet and micas encased within the highly ductile anisotropic shear foliation developed during first phase deformation itself.

Shillong Group comprises of two notable formations- Lower Metapelitic Formation (LMF) and Upper Quartzitic Formation (UQF). Sumer (25°40’ - 25°45’ N and 91°50’ - 91°55’ E) and Mawmaram (25°30’ - 25°32’ N and 91°41’ - 91°43’ E; Fig.1) are the two sites of Proterozoic Shillong Basin of Meghalaya where garnet bearing metapelites are observed. Garnets are associated with quartz sericite schist, phyllite, mica schist, massive and schistose quartzite and metadolerite (Medlicott in 1869 designated this metadolerite as Khasi greenstone). These rock associations belong to Lower Metapelitic Formation (Manai Formation of Bhattacharjee and Rahman, 1985) and the generalised regional trend of the lithounits is NE-SW with steep to moderate dip towards SE.

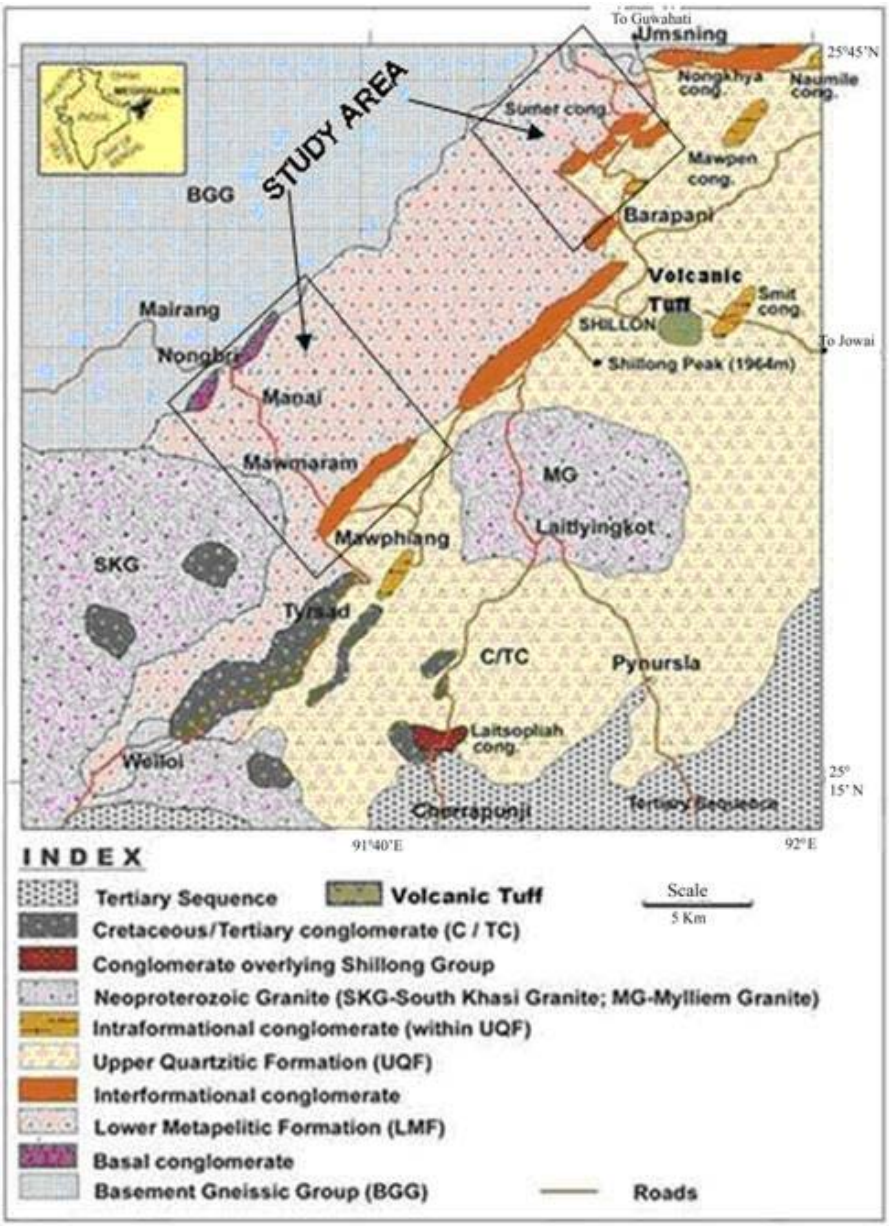

Fig.1: Geological map of the Shillong Basin (after Devi and Sarma, 2010).

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Regional Geology

Shillong plateau (covering approx. 47614 sq. km.) is the singular representative of Precambrian cratonic block of northeast India tectonically detached from the mainland of Indian Peninsula. This cratonic block is girdled by dextrally moving Dauki fault to the south, Brahmaputra lineament to the north, Garo-Rajmahal graben, Dhubri / Madhupur lineament to the west and belt of schuppen to the east. It consists of high to medium grade Paleoproterozoic basement gneisses and schist designated as Basement Gneissic Group (BGG) overlain by Mesoproterozoic metasediments and metavolcanics of the Shillong Group, both being intruded by Neoproterozoic acidic intrusives such as Mylliem pluton, South Khasi pluton, Umroi granite, Nongpoh pluton and a few others enlisted by Mazumdar (1976); Ghosh *et al.* (2005); Devi and Sarma (2006, 2010). The plateau is a near rectangular Assam-Meghalaya block with 300 km (approx.) length and 120 km width in the E-W and N-S directions respectively, while the Karbi Anglong block of Assam (earstwhile Mikir massif) is 150 km long in the NE-SW direction and 75 km along N-S direction. This craton is considered to be an uplifted block (Poornachandra Rao and Ravi Kumar, 1997; Bilham and England, 2001). Before detachment from Indian Peninsula, it was an integral part of Godwanaland of the southern hemisphere both being separated during Middle Cretaceous time with the formation of Indian Ocean (Mckenzie and Sclater, 1971). The Shillong plateau along with Indian Peninsula migrated towards north at a rate of about 15 – 20 mm year (Mukul *et al.*, 2010) in an anticlockwise motion during Late Cretaceous (Klootwijk, 1979). The total drifting is reported to be about 9000 km. The rate of movement is decreasing up to 5 mm/year and this change of movement rate is considered to be the cause and effect of India-Eurasia collision tectonism (McElhinny, 1968) as against Mukul *et al.* (2010) who have claimed 1.5 to 3.5 mm/yr. The northeastern part of the plateau is further separated by NW-SE trending Kopili mini graben and this detached block was named as Mikir massif after Mikir tribe (at present Mikir tribe is substituted by Karbi tribe, therefore, Sarma and Dey (1996) renamed the massif as Karbi Anglong massif).

The study area belongs to Shillong Basin, an intracratonic basin, covering an area of 2500 sq. km. and filled with Mesoproterozoic metasedimentary and metavolcanic rocks forming two notable formations– Lower Metapelitic Formation (LMF) and Upper Quartzitic Formation (UQF). These two formations, constituting Shillong Group (SG), are separated by an interformational Sumer-Mawmaram conglomerate (Devi and Sarma, 2006). The Shillong Group of rocks are affected by multiple phases of deformation and metamorphosed under greenschist to lower amphibolite facies (Devi and Sarma, 2006, 2010 and references therein). In addition to Neoproterozoic acidic intrusions, the basin witnessed multiple phases of basic, alkaline and acidic intrusions during Cretaceous time *e.g.* Sylhet Trap, Sung valley alkaline complex, Jesra, Chamchampi and acidic volcanic tuff of Smit area (for the first time the rhyolitic tuff is reported by Venkateshwarlu *et al.*, 2012). Towards southern margin of the basin, Mahadek basin host the country's first sandstone type of uranium deposit around Domiasiat (Upper Cretaceous). Mahadek Formation is again overlain by Jadukata Formation in the south of Raibah Fault. Tertiary sediments deposited under stable shelf environment in turn unconformably overlie the Mahadek Sandstone.

Thus, this physiographically uneven, relatively stable but seismically sensitive and geodynamically restless block can be cited as a classic geotectonic domain of diversified history registering many tectonic events from Precambrian to Cenozoic.

Structure and Microstructure of Metapelites of the Shillong Basin

Beddng, cross-stratification, ripple marks and graded bedding are the main primary features of which bedding is the most dominant planar fabric (S_0) and acted as tape recorder where entire history of deformational events is registered. Sumer - Mawmaram interformational conglomerate and overlying quartzitic sequence, display graded bedding, cross stratification, ripple marks and the top parts of the conglomerate gradually grades into coarse to medium quartzite. Based on the overprinting relationships of planar, linear and fold fabrics on mesoscopic and macroscopic scales, multi phase of deformations were established by earlier workers (Bhattacharjee and Rahman, 1985; Barooah, 1976; Mitra, 1998). Sarma (2002), Sarma *et al.* (2001) and Devi and Sarma (2006) have established three phases of folding in LMF and two phases in UQF of the SG. First phase of folding of LMF is absent in the UQF and second and third phases of LMF are correlated with the first and second phases of UQF. Three stages of deformation - pre-tectonic, syn-tectonic and post-tectonic to D_1 (post-tectonic to D_1 is referred to here as inter tectonic between D_1 and D_2 deformations) are identified from metapelites and they are marked as M_1, M_2 and M_3. Similarly syn-tectonic to D_2 deformation is marked as M_4. No significant metamorphic growth is traceable during D_3 rather insignificant reorientation of earlier planar fabric or partial growth of mica along axial orientation of F_3 during D_3 phases are observed in the metapelites.

In metapelites and associated schistose quartzites, both penetrative and non-penetrative structures are observed. The bedding after transposition or the regional stratification with layer parallel colour banding and lamination are designated as S_o and is the most dominant planar fabric. F_1 is the earliest recognisable structure preserved in the form of small intrafolial, isoclinals folds marked by thin quartzite layers (Figs. 2, 3) which is tectonically detached in the direction of tectonic flow associated with highly penetrative axial plane foliation (S_1). S_1 is highly pervasive in nature marked by quartz, micaceous minerals and feldspar. F_1 shows both S and Z senses plunge being at moderate angle towards NE or SW and is particularly developed in Sumer, Krang, Mawmaram and Sohiong areas. Stretching lineation is observed and such lineation is traceable parallel to the x-axis of the finite strain ellipsoid. The dominant foliation (S_1) is often accompanied by intensive linear fabric as a result of stretching. As F_1 is rarely preserved, therefore S_0 and S_1 are considered as the key structure and is considered as the XY plane of tectonic strain of first deformation (D_1) where imprints of later deformations are identified.

F_2 folds are essentially asymmetric, recumbent type observed in mesoscopic to microscopic scales (Figs. 4, 5). Such F_2 asymmetric folds are considered as a shear sense indicator and accordingly top to the NW shear is noted (Fig. 5). F_2 folds and associated S_2 foliation show varied patterns and superposed by later D_3 deformations (Figs. 5, 6. 7). F_2 folds maintain enechelon tendency. Folds of second deformation are associated with poorly developed fracture cleavage in competent rocks and axial plane foliation (S_2) in incompetent rocks of LMF (Fig. 5). They are accompanied by S_2 either along axial plane or short limbs of small asymmetric

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folds (Fig. 6). Hinges are sharp to semi rounded showing dextral pattern with variation in orthogonal thickness. Under microscope, quartz mica schist characteristically developed M and Q domains (Fig.8) and the micaceous layers are highly crenulated showing the development of zonal crenulations cleavage and discrete crenulations cleavage (Figs.9,10). F_2 folds are upright showing low plunge towards NE and / or SW (Fig.11). Both 'S' and 'Z' senses are observed. F_2 folds are of similar in nature with thickened hinges and thin limbs (Fig.11). Both F_1 and F_2 folds are coaxial or nearly coaxial.

F_3 folds are broad warp type showing high wave length-amplitude ratio. Small digitations of F_3 are superimposed over F_2 crenulations (Fig.7) in the hand specimens and on the outcrop scale such interference leads to the formation of dome and basin structure. F_3 also indicates conjugate nature. In the competent rock of LMF sequence, F_3 folds show open warp type with asymmetric nature, axial orientation being NW-SE and show sinistral vergence. Broad and short muscovite flakes are superimposed over dominant matrix foliation S_1 and they may be due to reorientation of the earlier fabric during syn D_3 deformation (Figs. 12, 13), hence cannot be correlated with M_5 metamorphism.

N-S trending kink fold, minor faulting, joints and fractures are considered as last deformational imprints along with intragranular kinking in mica and they are designated as fourth phase of deformation (Fig. 13).

Porphyroblast-Matrix Relationship

A few oriented samples of garnet bearing metapelites were cut in the laboratory along XZ and YZ sections and oriented thin sections were prepared for porphyroblast study. S_i fabrics of garnet are categorically marked as straight, curved, sigmoidal, continuous, and partial and their relationships with respect to external foliation (S_e) are worked out. S_i fabrics are observed as left lateral or right lateral shear senses. Some garnets are rounded, some are slightly elongated (flattened parallel to the direction of x-axis of strain ellipse (=flow direction of matrix foliation) and a few garnets are showing two prominent stages of growth history. Such rigid bodies with different inclusion patterns floating within the ductile sheared matrix under non-coaxial deformation are considered as best signature of metamorphic growth history before, after and during their multideformational history. S_i fabric in porphyroblast indicates their original orientation at the time of their growth even though the rocks have undergone repeated metamorphism under non-coaxial deformation (Johnson, 1990). It is generally accepted that porphyroblasts act as rigid body and matrix as Newtonian fluid under simple shear and the rotation of the porphyroblasts helps deciphering the shear sense (Ramsay and Huber, 1987). There are two schools of thoughts about rotational aspects of rigid porphyroblasts. One school favours that porphyroblasts with spiral / sigmoidal inclusion trails rotate during syntectonic stage (Spry, 1969; Rosenfeld, 1968, 1970) where as Bell *et al.* (1986, 1992), Passchier *et al.* (1992) advocate non-rotational mechanism. Porphyroblasts always postdate any foliation that is preserved within them as internal fabric but Bell and Hobbs (2010) have suggested that growth

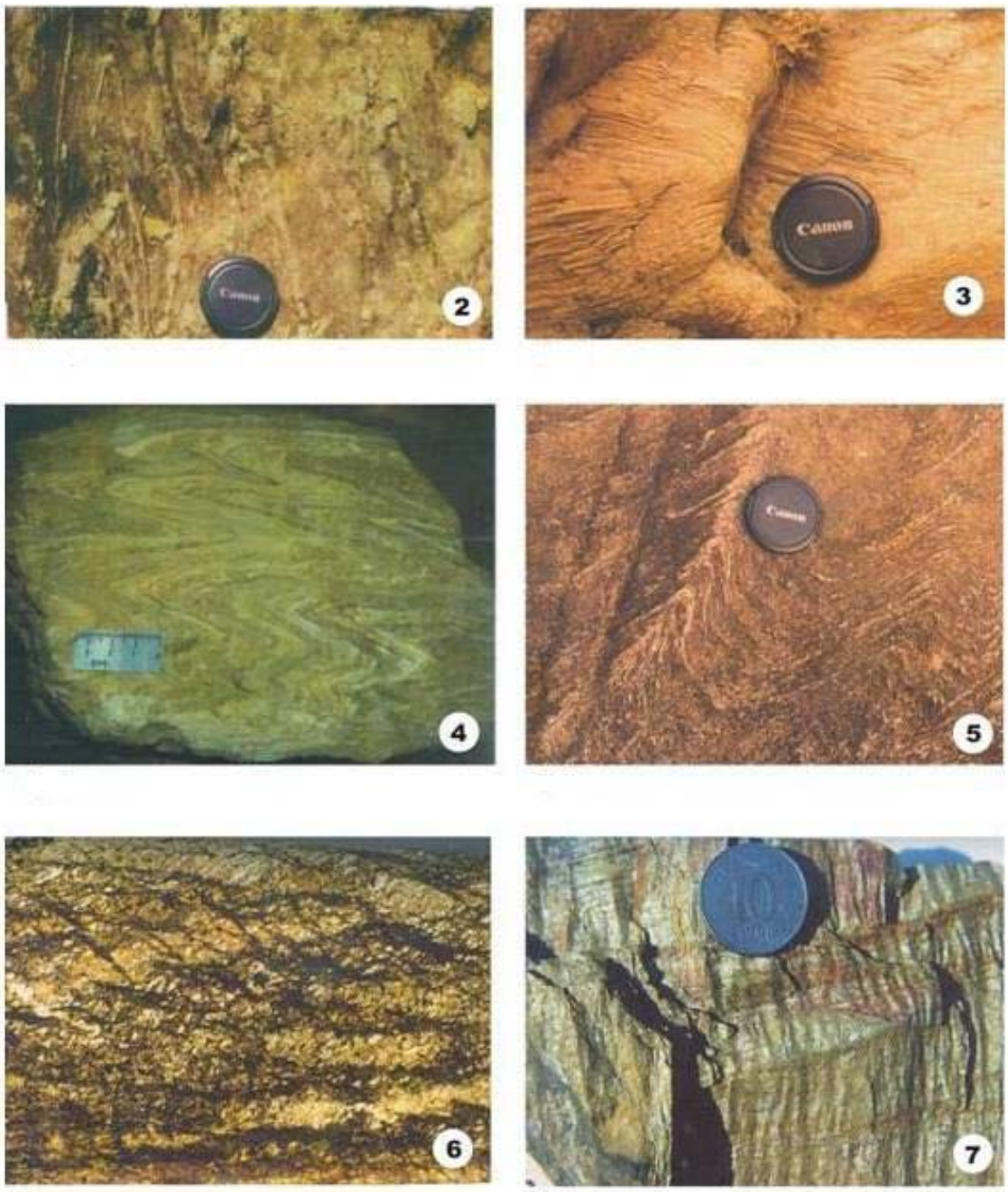

Fig. 2 and 3: Closely appressed F_1 fold marked by thin quartzite layer in metapelite from Mawmaram and Sumer areas respectively. **4:** F_2 fold of recumbent type refolded by open F_3 fold. **5:** Tight asymmetric F_2 folds associated with S_2 foliation from Sumer area. **6.** Strain slip, spaced S_2 foliation transecting S_1 at low angle from Mawmaram area. **7:** Two sets of lineation –L_2 and L_3 at high angle in phyllite; from Sumer area.

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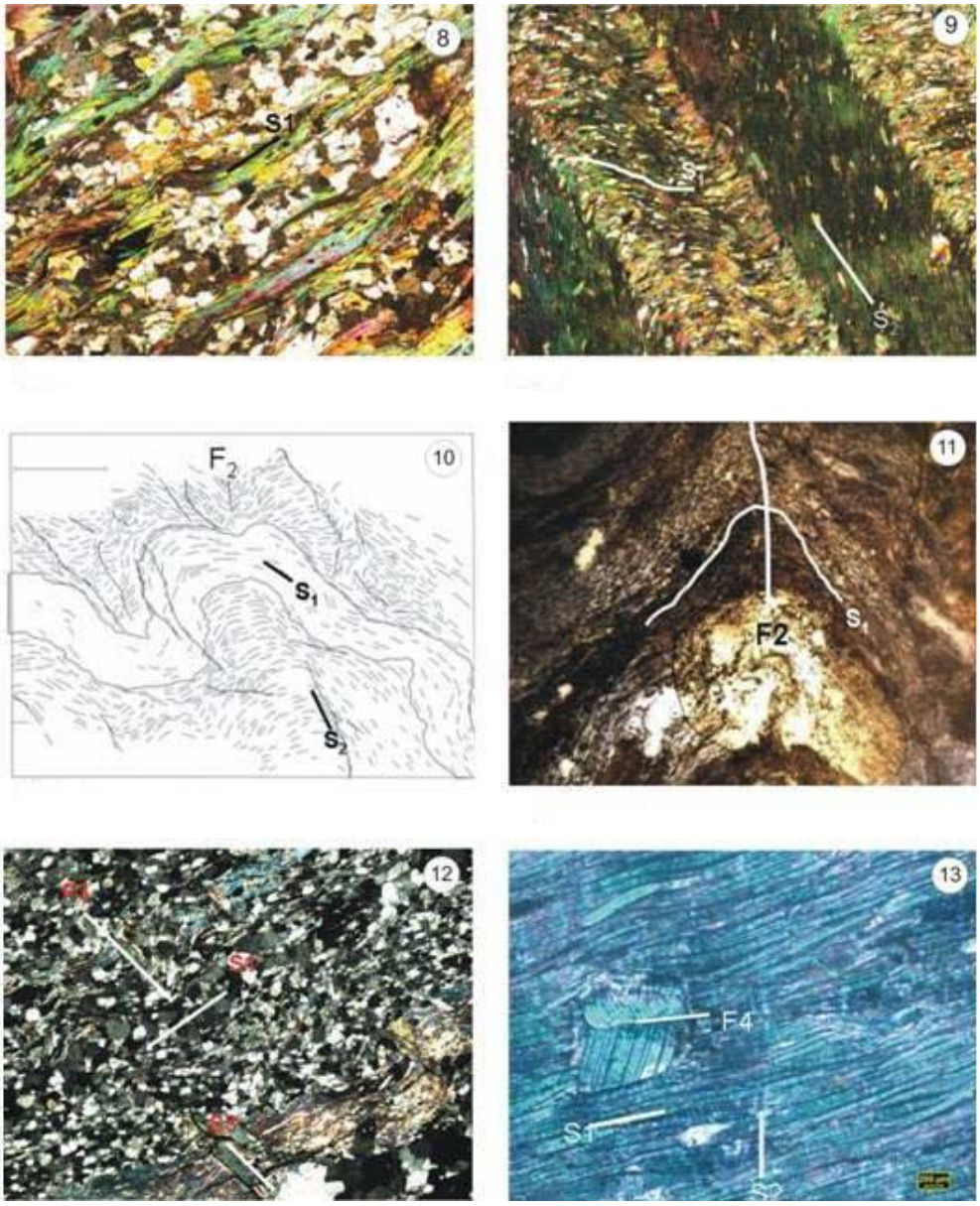

Fig. 8: Regional foliation (S_1) is marked by mica flakes and elongate quartz in quartz mica schist from Mawmaram area. **9:** Development of zonal cleavage (S_2) in metapelite. In M domain small mica flakes lie parallel to S_2. S_1 makes different angles to S_2. **10:** Regional pervasive foliation (S_1) is folded by F_2, showing development of discrete crenulation cleavage (S_2) axial planar to F_2. **11:** Axial plane foliation (S_1) is folded by F_2 fold in metapelite. **12:** Alternate Q and M domains in quartz mica schist. A few muscovite flakes parallel to F_3 crenulation lie at high angle to S_1, **13:** Intragranular kinking in muscovite may be referred to as D_4 event superposed on micas of syn D_1 phase. (All photomicrographs are taken under 200 µm)

of porphyroblasts occur during crenulations of a pre-existing foliation and never during reactivation. On the other hand, it has been stated that simply making angular relationships between S_i and S_e fabrics, one can not justify rotational mechanism. Rather porphyroblast growth is localized in low strain zones surrounded by coarse grained schistosity (S_e) which is considered as the cause and effect of high shear strain (Stelinhardt,1989).

Internal fabric (S_i) in the porphyroblast is marked by quartz ($quartz_1$) grain of relatively small, inequant to slightly equant grain size whereas quartz ($quartz_2$) grains of the external foliation (S_e) are elongated, ribbon type, coarse and occasionally show polygonal habit. S_i fabric marked by such small, tiny quartz and some opaque grains in garnet porphyroblasts may be considered as relict of initial bedding or layering or slaty cleavage and their growth history may be correlatable with pre-tectonic stage of metamorphism (M_1) before onset of the major recrystallisation history *i.e.* M_2 stage of D_1 deformation (Figs. 14,15). Porphyroblasts that have grown comparatively in fine grain matrix containing inclusion trails as (S_i) similar to Se, sometimes become difficult to interpret whether they are pre-, or post-tectonic to major shearing during D_1 deformation. It is also generally accepted that in low grade metamorphism, garnet porphyroblast bears passive inclusions representing earlier fabrics, hence considered as pre-tectonic to major recrystallising phase and matrix foliation is deflected round such rigid body (Passchier and Trouw, 2005). After careful observation in thin section of garnetiferous mica schist it can be inferred that the internal schistosity (S_i) of the garnet makes angle with the outer fabrics (S_e) (Figs. 14, 15). Again in the same porphyroblast, the S_i fabrics are planar and fine grained whereas the S_e fabrics are curvilinear, coarser and swerve round garnet porphyroblasts maintaining asymmetric habit. This means that the garnet ($garnet_1$) is developed prior to the development of the external foliation (pre-tectonic to D_1 deformation) and marked as M_1 metamorphic indicator. Hence, it is apparent that the S_i fabric of the $garnet_1$ porphyroblast bears the evidence of earlier foliation as relict (pre S_1) but such foliation either is totally transposed or obliterated during syn-tectonic stage of intensive D_1 deformation.

Metapelites are characterised by alternate bands of quartz (Q-domain) and micas (M-domain) showing variable thickness from cm to mm scale (Figs. 8, 12). Biotite and muscovite are dominantly interleaved in M- domain ($biotite_1$ and $muscovite_1$) and they lie in the x-direction of strain ellipse defining highly penetrative foliation (S_1) which is syngenetic to M_2 metamorphism of D_1 deformation (Fig. 8).

Curve or sigmoidal trails of inclusions are more useful than straight trails of inclusions in correlating deformation to metamorphism. Garnet developed during M_2 stage of D_1 deformation is often marked by sigmoidal trails of inclusion and is designated as $garnet_2$ (Fig. 16). Strain shadow zone is not well defined but still can be inferred in some garnet porphyroblasts. Such coarse grained quartz in shadow zone confirms that garnet acts as rigid body rotated during the formation of matrix foliation (S_1) and may be referred to as $quartz_3$ indicative of either post tectonic to D_1 phase (intertectonic) or slightly late phase of syngenetic to D_2 deformation itself (Figs. 16, 17). Similarly some of the garnet ($garnet_2$) bears evidence of sigmoidal inclusion

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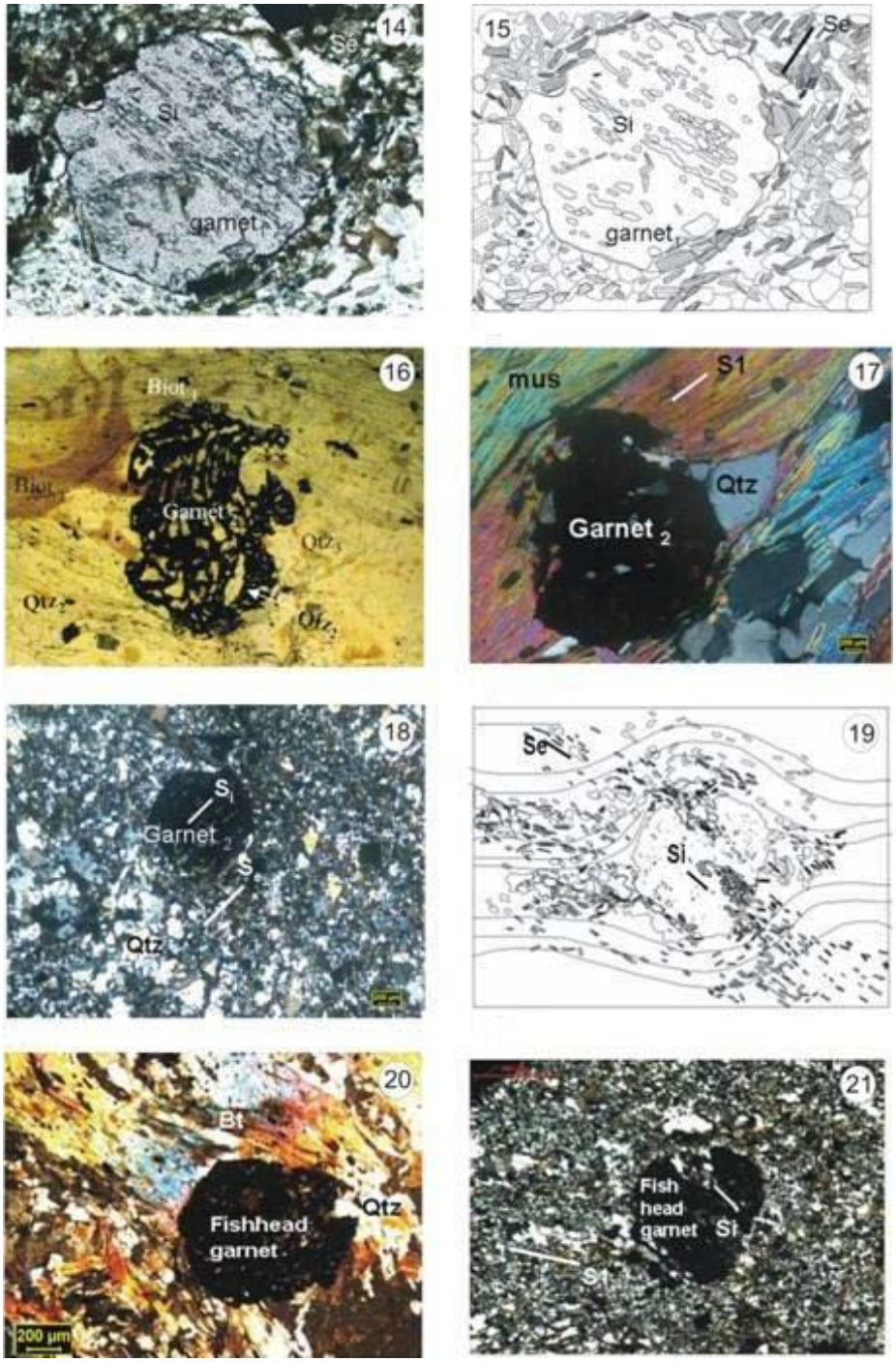

Fig. 14 and 15: Photomicrographs and line diagram of Pretectonic garnet (M_1) with straight trails of inclusion of S_i fabric in metapelite. S_e fabric is coarser and makes angular relationship with S_i. **16:** Photomicrograph of syntectonic garnet (M_2) with sigmoidal trails (S shaped) of inclusion of S_i fabric in metapelite. S_e fabric is coarser and makes angular

relationship with S_i. **17:** Truncation and deflection of S_e with sigmoidal (S) S_i trails in garnet porphyroblast indicating syntectonic stage of D_1 deformation (M_2 stage). **18:** Photomicrograph of Pretectonic garnet (M_1) with straight trails of inclusion of S_i fabric in metapelite. S_e fabric is coarser and makes angular relationship with S_i. **19:** Line diagram of a post tectonic garnet ($Garnet_3$) showing how external foliation (S_2) is passing through Fish head garnet continuously indicating posttectonic stage to D_1 deformation. **20:** Truncation and deflection of S_e with sigmoidal (S) S_i trails in garnet porphyroblast indicationg syntectonic stage of D_1 deformation (M_2 stage). **21:** Photomicrograph of a post tectonic garnet ($Garnet_3$) showing how external foliation (S_2) is passing through Fish head garnet continuously indicating posttectonic stage to D_1 deformation (M_3 stage).

pattern at the core while the outer rim is inclusion free. Such two stages of growth of garnet are designated as $garnet_2$ and $garnet_3$ of M_2 and M_3 stages respectively. Similar observation is also referred to by Toteu and Macaudiere (1984).

Truncation and deflection of S_e around garnet porphyroblasts indicate growth history of the garnet after the formation of regional schistosity (S_e) during D_1 deformation and hence treated as post tectonic garnet ($Garnet_3$) or intertectonic between D_1 and D_2 ($garnet_3$) representing M_3 stage of metamorphism (Figs. 17-20).

Fish-head garnet always developed after the formation of regional schistosity (Passchier and Trouw, 2005) and they are observed in metapelites (Figs. 19, 20, 21). The static phase between D_1 and D_2 is marked by the growth of garnet porphyroblasts and regional foliation S_1 truncate and / or deflected round such rigid porphyroblasts ($Garnet_3$) under M_3 metamorphism.

Many porphyroblasts grow during penetrative deformation but when porphyroblasts grow during non-penetrative deformation either they do not rotate or grow without inclusions. Bell and Hobbs (2010) have suggested that growth of porphyroblasts occur during the formation of crenulations of a pre-existing foliation and never during reactivation. Development of chlorite is noted along fractures and peripheral zone of garnet in association with Fe-oxides and such association is considered as post-tectonic to first phase of deformation. The regional foliation (S_1) is folded by F_2 and differentiated into M-domain and Q-domain forming zonal, discrete and extensional crenulation cleavage (S_2) (Figs.8, 10) and they are considered as M_4 metamorphic stage.

S_2 is marked by growth of large, short and broad flakes of $mica_4$ (M_4 metamorphism synchronous to D_2 deformation) and sometimes by slender mica flakes truncating S_1 at varied angles (Figs.12, 13). In no garnet porphyroblast, the imprint of crenulation folds (F_2) is traceable as S_i fabric which may indicate that the growth of garnet is restricted to M_1, M_2 and M_3 stages only. Some of the broad and short flakes of muscovite plates are observed at high angle to S_1 following the orientation of F_3 folds which may be due to reorientation of the earlier muscovite mineral and cannot be correlatable with the growth history of M_5 stage of metamorphism. Intragranular kinking of such micas may be treated as late phase of deformational history without metamorphic growth (Fig.13).

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Table-1: A tentative model for successive stages of deformational events and their correlation with growth and/ or reorientation of minerals indicative of grade of metamorphism (see text for detail).

M_1	M_2	M_3	M_4	M_5 (?)
Pretectonic to D_1	Syntectonic to D_1	Intertectonic between D_1 and D_2	Syntectonic to D_2	Syntectonic to D_3
$Garnet_1$	$Garnet_2$	$Garnet_3$	-----	------
-------	$Biotite_1$	$Biotite_2$	$Biotite_3$	------
-------	$Muscovite_1$	$Muscovite_2$	$Muscovite_3$	$Muscovite_4$ (?)
$Quartz_1$	$Quartz_2$	$Quartz_3$	$Quartz_4$	$Quartz_5$
$Chlorite_1$	-----	------	-------	$Chlorite_2$

Conclusion

Growth of porphyroblasts and their sequential relationships to deformations are attempted and summarized as follows. Garnet ($garnet_1$ and $garnet_2$) were treated as the most significant and diagnostic tool and developed before and during intensive transposition of initial lithological layering (S_0) resulting most pervasive planar schistosity (S_1). Such mechanism is related to first phase of deformation (D_1) under layer parallel shear couple. Most of the rotational garnets ($garnet_2$) with sigmoidal trails of inclusions were produced during this transposition under prograde metamorphic events (lower part of amphibolite facies) under medium pressure condition. Inclusion free rim around syntectonic sigmoidally trailed garnet ($garnet_2$) probably developed during the intertectonic static phase between D_1 and D_2 and designated as garnet ($garnet_3$) representing M_3 metamorphism under comparatively low pressure condition. Garnet porphyroblasts grew apparently in three different stages: (a) pretectonic to major, highly penetrative D_1 phase, (b) syntectonic to D_1 phase and (c) intertectonic between D_1 and D_2 phases of deformation. Different phases of deformation, their associated metamorphism and growth and / or reorientation of different porphyroblasts and large crystals are shown in the tabular form (Table-1)

Both biotite and muscovite show rough parallelism and mostly interleaved together during the formation of regional foliation (S_1) and were apparently the product of D_1 strain and hence syn D_1 and belong to M_2 stages of metamorphism. Micas, particularly $muscovite_2$ developed into coarser broad and short plates lie at high angle to S_1 and occasionally enclose $quartz_2$ as S_i similar to S_e. Such $biotite_2$ and $muscovite_2$ were developed during D_2 deformation and corelatable as M_4 stage of metamorphism. Similarly, muscovite flakes are also lie transecting S_1 along axial orientation of F_3 folds which may be due to reorientation of the earlier muscovite flakes and not by re growth, hence classified as the end product D_3 deformation. Formation of chlorite after mica and probably garnet, represents retrograde phase during D_3 deformation.

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