

## POLYPHASE DEFORMATION AND GARNET PORPHYROBLAST - MATRIX RELATIONSHIP IN BANDED IRON FORMATIONS OF MARU SCHIST BELT, NW NIGERIA

Aliyu Abdu Ibrahim and Umar Adamu Danbatta  
Department of Geology, Ahmadu Bello University, Zaria Nigeria

### ABSTRACT

*Petrographic and microstructural study of oriented thin sections using reflected and transmitted light microscopy and chemical mapping on the Banded Iron Formation of Maru Schist Belt was carried out. The result shows that polyphase deformation and metamorphism led to the formation of garnet porphyroblasts in a predominantly grunerite-iron oxide matrix. The garnet has different growth histories and the porphyroblasts share complex relationship with the matrix. Garnet shows at least two phases of growth - first inter-tectonic between  $D_1$  and  $D_2$  (pre- $D_2$  phase) and then syn-tectonic to post-tectonic with respect to  $D_2$  deformation. Growth of later phase of garnet on the earlier (pre- $D_2$ ) garnet grains has led to the discordance of grunerite trails between the garnet porphyroblast. The peak metamorphic temperature thus coincided with  $D_1$  deformation, while the  $D_2$  phase developed the dominant crenulation schistosity ( $S_1$ ), regionally persistent in the terrain. The mineral paragenesis identified in the BIFs indicates that the metamorphic grade reached up to amphibolite facies in the study area.*

**KEYWORDS:** *Reflected light, Transmitted light, Microstructure, Inter-tectonic, Post-tectonic, Syn-tectonic*

### INTRODUCTION

Porphyroblasts are a valuable source of information on deformation and metamorphic evolutionary history of rocks. Porphyroblasts with inclusion patterns reveal information on the nature of deformation and on the relative age of mineral growth and deformation. It is therefore usually advantageous to decipher the porphyroblast-matrix relationship in metapelites (and metabasites, especially if they are garnet-bearing) in any area for large-scale tectonic studies. Microstructural studies of inclusions in porphyroblasts by numerous workers have led to the conclusion that they are mostly included in a 'passive' manner, without being significantly displaced by the growing porphyroblasts (Zwart 1962; Vernon, 1975; 1976; Bell 1985; Barker 1994). In most cases, and especially at low to medium-grade metamorphism, minerals that do not participate in the metamorphic reaction are not removed completely from the reaction site because of slow diffusion rates, and are overgrown and enclosed by porphyroblasts as 'passive' inclusions (Passchier and Trouw, 2005). If the matrix around the growing porphyroblasts had a compositional layering or a preferred orientation of mineral grains, this fabric may be partly preserved when the grains are included in the porphyroblasts, leading to an inclusion pattern, which mimics the pre-existing fabric.

Understanding the timing of porphyroblast growth relative to the development of surrounding metamorphic foliations is a fundamental requirement for useful applications of porphyroblast microstructures in regional deformation-metamorphic studies (Passchier and Trouw 2005). Porphyroblasts which are formed prior to a specific deformation episode ('pre-tectonic' porphyroblasts) generally show strong

deflection of matrix foliation around the porphyroblast that indicates the pre-existence of the 'rigid' grain prior to the deformation causing the development of the matrix foliation (Zwart, 1962; Vernon, 1976; Yardley, 1989; Barker, 1998). Intertectonic porphyroblasts grow passively over a fabric in the absence of deformation and protect the resulting inclusion pattern from later deformations. Syn-tectonic porphyroblasts grow during an on-going phase of deformation. Inclusion patterns in such cases are usually curved and continuous with the matrix foliations outside the porphyroblasts and show evidence of having been rotated and/or reoriented during porphyroblast growth. Porphyroblasts grown after cessation of deformation are termed as 'post-tectonic'. The inclusion pattern within post-tectonic porphyroblasts is identical to and continuous with the external fabric (Passchier and Trouw, 2005). However, it should be kept in mind that the inclusion trail geometry observed in thin sections is essentially two-dimensional and depends on the position and orientation of the plane of section with respect to the porphyroblast.

Great care should be taken to orient the sections at a high angle to the porphyroblast rotation axis and cut ideally through the porphyroblast near its centre (Powell and Treagus, 1970; Busa and Grey, 1992).

In areas of repeated deformation and metamorphism, the angular relationship between the inclusion trails preserved in the porphyroblasts (internal schistosity -  $S_i$ ) and the matrix foliation (external schistosity -  $S_e$ ) provides key evidences for understanding the nature of the superposed deformational and metamorphic events.

A discordant relation between the inclusion trails preserved in the core and those near the rim of the same porphyroblast may indicate metamorphic mineral growth overlapping more than one of the discrete deformation phases (Bell and Rubenach, 1983; Passchier and Trouw, 2005). In this paper the deformation history and metamorphic mineral growth in the BIF of the poly deformed and metamorphosed Maru schist belt of NW Nigeria is deciphered using evidence derived from garnet growth within grunerite matrix.

#### REGIONAL SETTING

The Nigerian Basement Complex (Dahomeyan Shield) rocks form part of the rejuvenated rocks between the West African and Congo Cratons and belongs to the pre-drift Pan African mobile belt that has been linked to the Boborema province of Brazil (Dada, 2008; Goki *et al.*, 2010). A continental collision plate tectonic model (Burke and Dewey, 1972; Black *et al.*, 1979) has been accepted to be responsible for the reactivation of the Dahomeyan shield east of the Ghana-Togo-Benin suture zone (Fig.1).

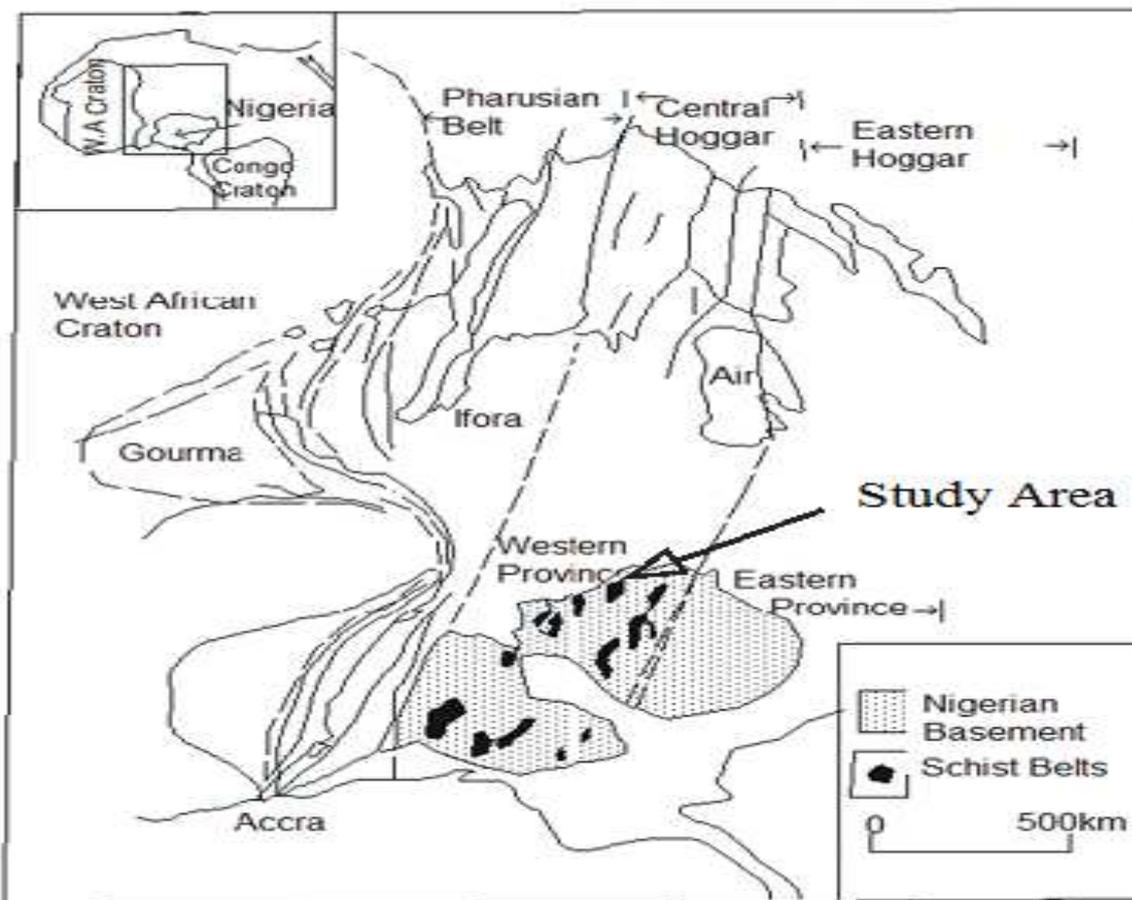


Fig. 1. Location of Nigeria within the African Continent, and in West Africa relative to the West African Craton (inset); the regional setting of Nigerian shield in major structural units of West Africa showing the area of study.

The Nigerian Basement Complex has been differentiated into three broad lithostratigraphical groups:

i.) The Migmatite-Gneiss Complex or Basement Complex (*sensu strictu*) is composed of gneisses and migmatites with entrained supracrustal relics whose metamorphism is generally in the amphibolites facies grade. Other but relatively minor, rocks are amphibolites, calcareous rocks, and pegmatites (Wright *et al.*, 1985; Dada, 1999). Rock age range from Archaean to Upper

Proterozoic, generally overprinted by the Pan-African event (750-450 Ma).

ii.) The schist belts occur in a 300 to 400 km wide zone, predominantly west of longitude 8°E, trending NNE, and can be traced along a strike for about 800 km. They are apparently folded into the Migmatite-Gneiss Complex. Lithologically, the schist belts are composed predominantly of pelitic and semi-pelitic schists, with intercalated quartzites, Banded Iron Formation (BIF), calc-silicate rocks and marbles as well as basic to acid meta-volcanics.

Basement-cover relationship is still disputed, and even the distinction from the basement *sensu strictu* is not always clear (Trompette, 1994). Radiometric dates strongly testify to penetrative Pan-African event, but some of the schist belts may be of Birrimian age (Paleoproterozoic) or older. (Turner, 1983; Fitches *et al.*, 1985; Ajibade *et al.*, 1987; Trompette, 1994; Adekoya, 1996; Dada, 1999).

iii.) The Older Granites of Nigeria occur in all parts of the Nigerian basement (Ajibade *et al.*, 1987). They intruded into both the gneiss-migmatite (Dahomeyan?) and the schist belts by stopping and diapiric processes (Fitches *et al.*, 1985). They are generally regarded as syn - to post-tectonic with respect to the main deformation of the Pan-African tectonism.

The Maru Schist Belt (Fig. 2) consists predominantly of pelitic to semi-pelitic metasediments interlayered with psammities, BIF and metabasic rocks (Egbuniwe, 1982; Adekoya, 1998; Ibrahim, 2011). All the rocks strike approximately N - S, parallel to the structural pattern of the surrounding basement complex. The pelites are represented by phyllites and schist while the psammities and the semi-pelites are represented by quartzites and quartz schists. Metabasic rocks are amphibolites and

greenschist. The schist and phyllites predominantly consist of muscovite, garnet and quartz with subordinate chlorite, biotite, epidote and tourmaline. The schists may also contain graphite, magnetite and pyrite in several localities especially in the south east (Egbuniwe, 1982). The Maru belt is intruded by Pan - African granitoid plutons, the intrusion of which causes the developments of chiastolite and sillimanite schists by contact metamorphism.

The Maru belt, like other schist belts of Nigeria exhibits complex structural patterns, as a consequence of poly metamorphism. At least three deformational episodes have been identified in the Maru belt corresponding to D<sub>1</sub>, D<sub>2</sub> and D<sub>3</sub> structures (Egbuniwe, 1982). Table 1 is a summary of the sequence of events in the Maru Schist Belt modified after Egbuniwe, (1982). The BIF is exposed in a range of northeast - southwest trending metasedimentary ridges within the Maru formation; mostly the ridges are truncated by a sub circular granitoid intrusion (Fig. 2) and extend north and south of the intrusion for several kilometers. The iron formation consists of silicate facies with sporadic oxide facies and thin laminae of manganese oxide.

**Table 1: Sequence of main events in the Maru Belt (Modified after Egbuniwe, 1982).**

STEP	EVENT	AGE
10	Localised D <sub>4</sub> deformation of the Maru Formation under greenschist facies condition.	
9	Emplacement of Kanoma and Sabon Gida peralkaline-peraluminous plutons; Localised deformation and contact metamorphism of metasedimentary envelope.	<577 m.y
8	Localised deformation :D <sub>2</sub> in Gusau Granite Gneiss under greenschist facies conditions(retrograde) D <sub>3</sub> in Maru Formation under greenschist facies conditions (retrograde) D <sub>4</sub> in Gusau Migmatites under greenschist facies conditions (retrograde)	
7	Emplacement of Damaga and Riorji calc-alkaline plutons; localised contact metamorphism of the Maru Formation.	
6	Regional deformation: D <sub>1</sub> in Maiinchi batholith and Gusau Granite gneiss producing regional trends and structures under amphibolite facies conditions. D <sub>2</sub> in Maru Formation under greenschist facies conditions. D <sub>3</sub> in Gusau migmatites under amphibolite facies conditions.	678-577 m.y.
5	Emplacement of Gusau Granite gneiss and Maiinchi batholith.	
4	Regional deformation: D <sub>1</sub> in Maru Formation under greenschist to lower amphibolite facies conditions. D <sub>2</sub> Gusau migmatites under amphibolite facies conditions	1900 ± 250
3	Deposition of Maru Formation: contemporaneous subaqueous extrusion.	2500
2	Emplacement of basic dykes in gneissified rocks. D <sub>1</sub> deformation of Gusau migmatites under amphibolite facies conditions.	3100 - 2750
1	Formation of parental rocks of Gusau migmatites of igneous or sedimentary origin.	

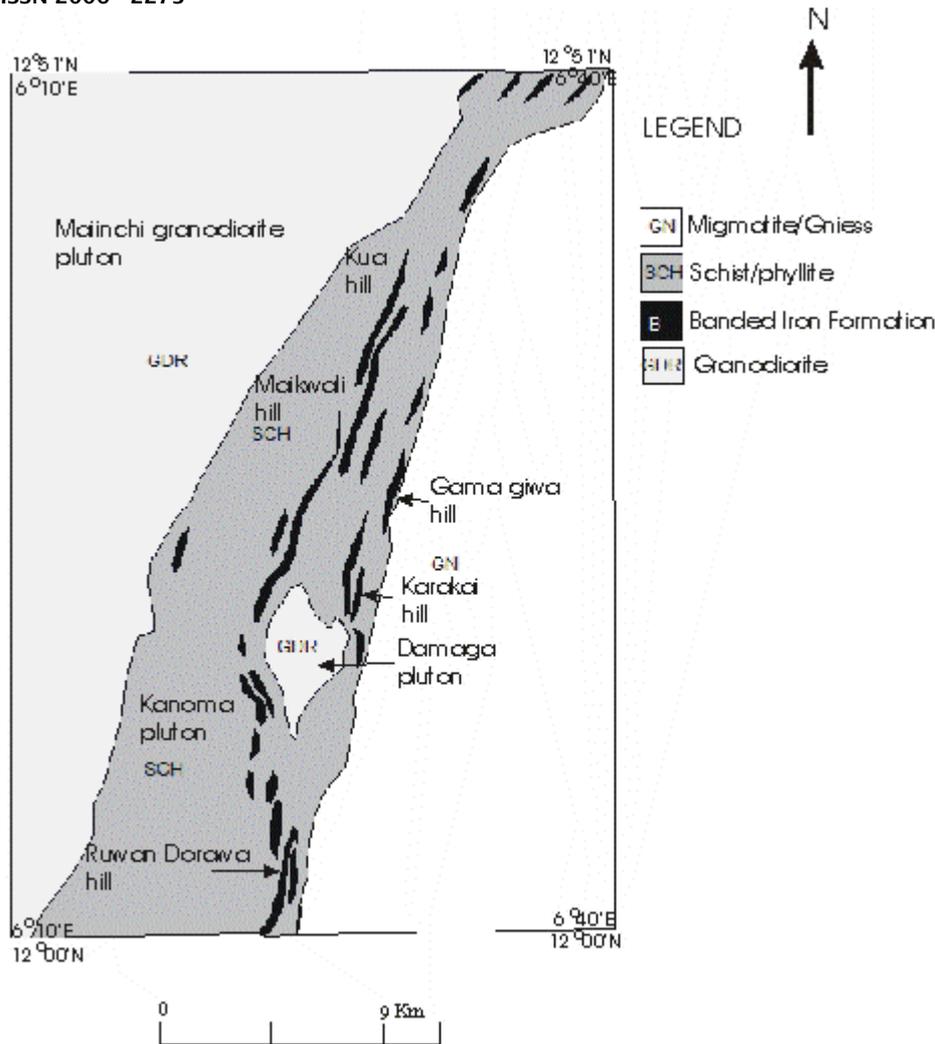


Fig. 2. Distribution of the main geological units the Maru Schist Belt.

### MATERIALS AND METHODS

Representative samples of the Banded Iron Formation (BIF) were collected from the eastern zone, defined by the Karakai hills; and the western zone, defined by the Baraba hills. Petrographic analyses, using reflected and transmitted light microscope were carried out. Chemical mapping using Scanning Electron Microscope (SEM) fitted with Energy Dispersion Spectrometer (EDS) was also carried out on the samples at the Department of Mineralogy, University of Silesia, Poland. Microprobe analysis was carried out in the Inter-Institute Analytical Complex for Minerals and Synthesis substances in Warsaw, Poland, using Cameca SX 100 with a Pirho-2 correction program.

### RESULTS

The dominant fabric preserved in the rocks of the Maru Schist are the flat-lying folds with N-S axes and related S1 schistosity, however most of these folds are obliterated by transposition.

These were later refolded on N-S trending steep axial planes, resulting in the major folds and the trends with north-northeast trending, steeply dipping foliation that is axial planar to variably plunging small-scale folds. This second phase of deformation can be found in these rocks and similarly related to the timing of metamorphic mineral growth. This deformation is characterized by NNE trending asymmetric Z-folds and localized dextral shear bands. These structures clearly post-date the earlier flat-lying folds and the associated foliation.

The BIF is a dark grey, banded rock with a rhythmic alternation of light grey silica rich and darker Fe-oxide rich bands. The compositional bands are variable in thickness ranging from thin laminations 0.5 - 1 cm thick to thicker bands 2cm - 5cm thick. Other varieties exhibit even thicker bands of contrasting rock types. These three types of banding represent the micro banding, meso banding and macro banding types respectively.

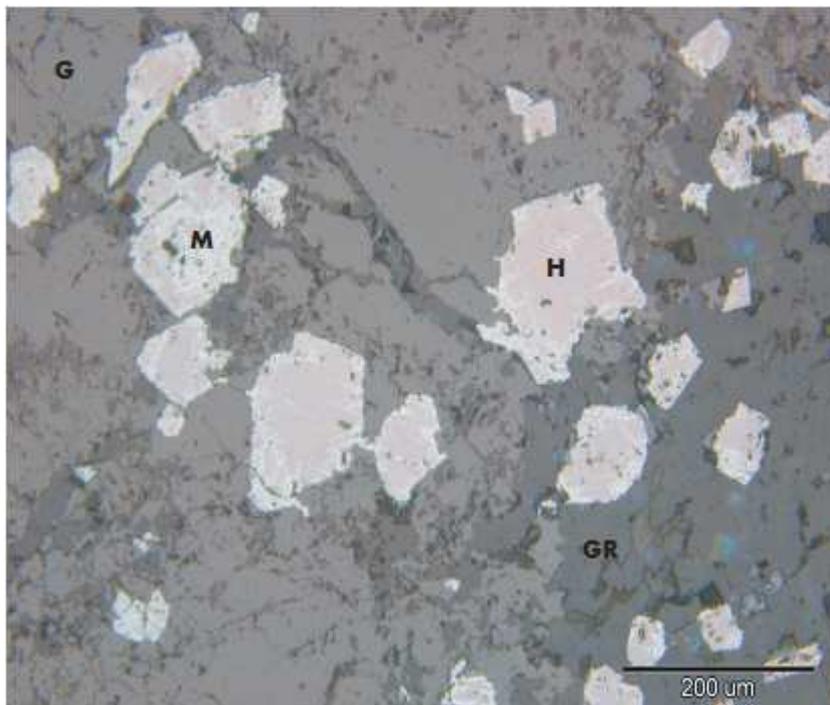
The BIF is generally granular in texture and the grain sizes are varied from fine to coarse. The microbanded BIF are composed of very fine-grained crystals of chert and other silicates in the light colored band and the dark band is composed of very fine-grained magnetite garnet, grunerite and other iron oxides, the atoll garnets are best developed in this band. The grain size is coarser in the mesobands. However, some of the mesobands are also locally micro banded, giving a microbanded mesoband appearance.

Generally, the BIF samples from Maru belt are composed of the following mineral composition:

- a) The Fe oxide (dark) band:  
Magnetite, Hematite, Quartz,  
Goethite, Almandine,  
Grunerite, Siderite,

- b) The Silicate (light) band:  
Grunerite,  
Almandine/Spessertite,  
Magnetite, Hematite, Quartz,  
Chamosite, Rhodochrosite,  
Siderite, Stilpnomelane,  
Greenalite, Olivine, Pyroxene.

Magnetite and hematite are the dominant minerals in the iron oxide band, hematite (martite) developed after magnetite, while goethite that occurs in considerable proportion as secondary mineral (Plate 1). Amphibole and garnet occur in considerable amounts, they are next in abundance to the hematite and magnetite.



**Plate 1.** Photomicrograph of the BIF: G - Garnet, H - Hematite, M - Magnetite Gr - Grunerite (Reflected light, ppl).

Amphibole and garnet occur in considerable amounts, they are next in abundance to the hematite and magnetite. Garnets in the BIF are mainly of almandine, spessartine and rarely grossularite composition (Fig. 3). They occur as idiomorphic to hypidiomorphic rounded porphyroblasts of varying grain sizes (1mm - 3mm) within microcrystalline Fe-rich bands. Microcrystalline grains of garnet ranging in size from <0.029mm - 0.29mm also occur within amphibole and as randomly oriented rounded

grains in the dark colored Fe-rich bands, especially in the Baraba hill samples. Garnets constitute about 10 - 15vol % of the BIF, and are mostly concentrated in the light-coloured silicate bands. The garnets enclosed by amphiboles within this band and the amphiboles may contain inclusions of magnetite or hematite, chamosite and siderite. The garnets are also altered in many places and appear bluish rather than brown in transmitted light.

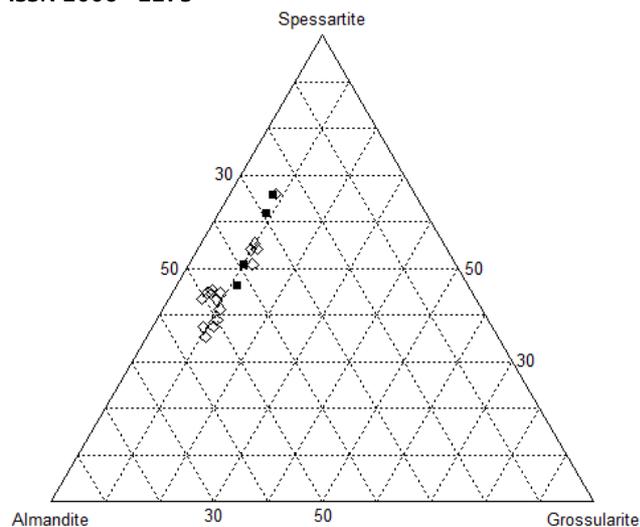


Fig. 3. Compositional plot of garnet in the BIF. open squares – atoll; black squares – non atoll)

Two generations of garnets are identified in the area. The early garnets are microcrystalline and rounded, which resemble sedimentary garnets. The late garnets occur as porphyroblasts and develop microstructures such as the atoll and peninsular forms.

#### Microstructures

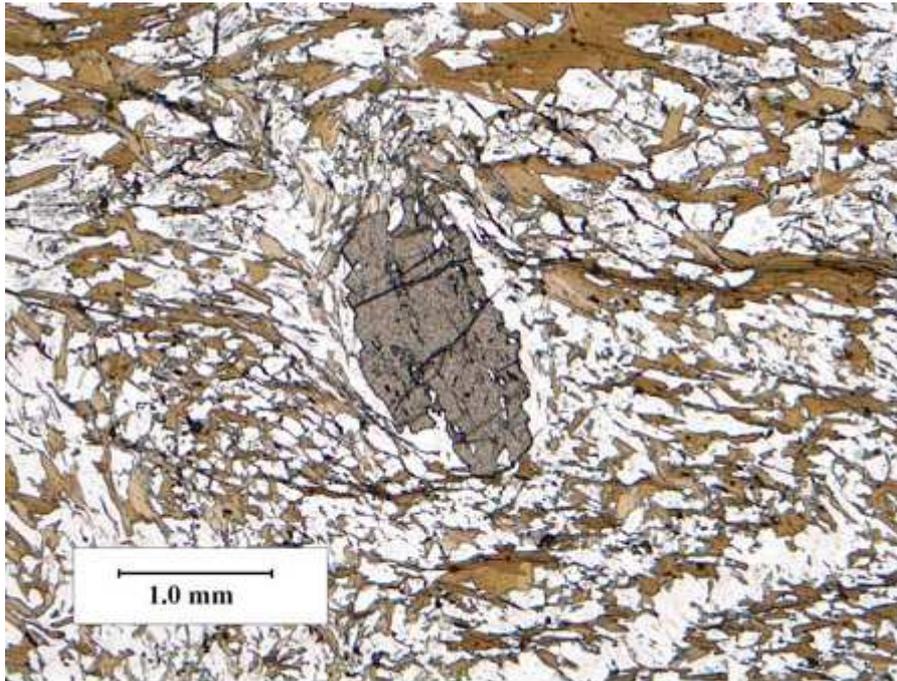
In order to understand the relationships between metamorphic mineral growth and deformation in the Maru Schist Belt, microstructural textures were analyzed focusing on porphyroblast-matrix relationships. Relationships between preserved internal fabrics within porphyroblasts and the matrix fabrics or external fabrics are used to infer the relationships between porphyroblast growth and deformation in the BIF of the belt.

A study of the relationships between porphyroblast growths relative to the deformational episodes provides information on the relative timing of metamorphism and deformation in the area.

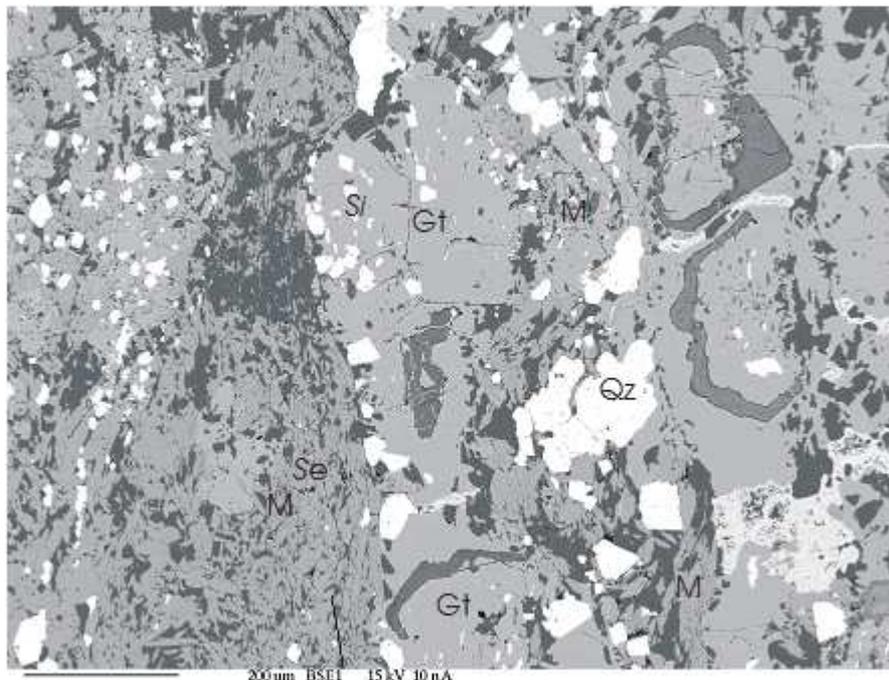
Microstructural features of garnets in the BIF of the study area suggest that there are different generations of garnet growth from pre- $D_2$  to post- $D_2$  events. The internal schistosity ( $S_i$ ) in garnet is correlated with regional first generation ( $S_1$ ) cleavage in the BIF and mica schists developed by the  $D_1$  deformation episode.

Two generations of garnet formation episodes can be inferred from the microstructures recorded in this study. The pre-tectonic (intertectonic) porphyroblasts of garnet are shown in Plate 2 and syn-tectonic porphyroblasts of garnet in Plate 3. Thus the timing of porphyroblast growth relative to the dominant matrix fabric in these rocks provides information on the timing of metamorphism relative to the major folding and foliation producing event in the belt.

The most compelling evidence for episode of metamorphic mineral growth prior to the Pan African orogeny that causes the  $D_2$  deformation responsible for the NNE-SSW folding comes from garnet porphyroblasts. Many of the small garnet porphyroblasts show internal foliations that are generally discontinuous with the external fabric (Plate 2). These foliated inclusion trails within many of the garnet porphyroblasts in the BIF are generally discordant with the external fabric. These relationships strongly suggest that an episode of garnet growth occurred prior to NNE-SSW folding and the development of the associated axial planar foliation. Whether this deformation is related to the early stages of the Pan African orogeny or an earlier unrelated deformational episode is unclear.



**Plate 2.** Photomicrograph of a garnet porphyroblast displacing matrix foliation within the silicate band. The NW-SE internal foliation preserved within the garnet porphyroblast is discordant to the external matrix foliation. Plane polarised light, viewed perpendicular to the external foliation.



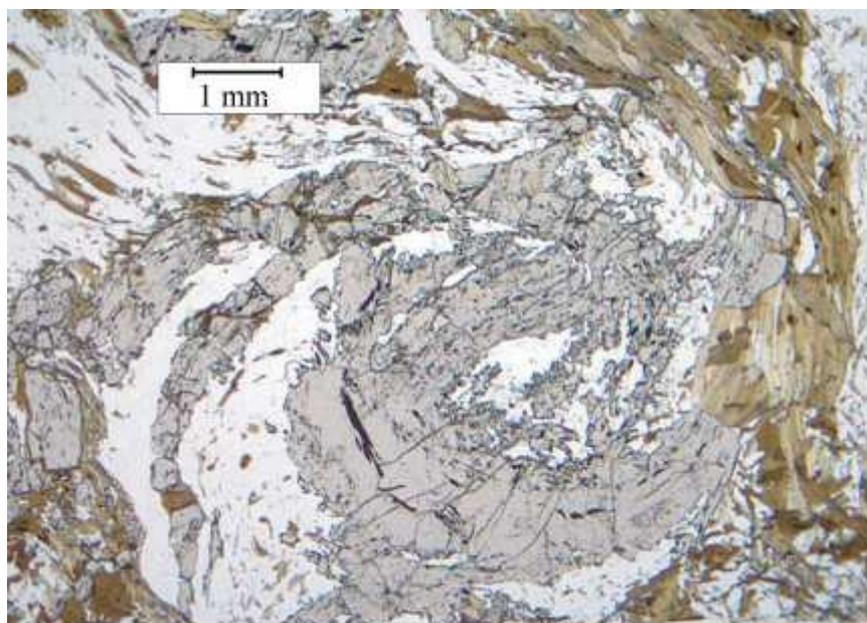
**Plate 2b.** BSE image of the silicate zone of the BIF showing the garnet porphyroblasts (Gt) deflecting the  $S_2$  foliation of the amphibole (M) as pre-tectonic porphyroblast, while the  $S_1$  foliation is preserved.

Evidence for syn-tectonic mineral growth in the BIF is reflected in the porphyroblast-matrix structures involving garnet growth during the development of the dominant foliation in the BIF. Syn-tectonic mineral growth is the most difficult relationship to unequivocally distinguish, but is also the most common in orogenic belts as it

reflects mineral growth during a deformational episode. A spectacular example of the syn-tectonic growth is shown in Plate 3, showing a snowball garnet. The swirling pattern of the sections of garnet is suggestive of syn-tectonic growth.

The Pan African orogeny is taken to be the last orogenic cycle that affected rocks in this region and has a dominant NNE-SSW structural style. The obliterating effect of this orogenic cycle on

pre existing structures in this region makes it difficult to unequivocally distinguish previous structural trends.



**Plate 3.** Photomicrograph of a garnet crystal with a swirling structure, suggestive of syn-tectonic growth. The external foliation ( $S_e$ ) is deflected by the deformed garnet crystal with internal foliation ( $S_i$ ); PPL view perpendicular to the foliation in a down-dip direction.

### DISCUSSIONS

The pre-tectonic porphyroblasts might have been developed during an earlier rock forming episode prior to the Pan African (possibly the Eburnean or Liberian) during the  $D_1$  deformation event in the Maru formation. This corresponds to the peak of metamorphic condition that saw the growth of garnet, amphibole and iron oxide minerals in the BIF and the pelitic schist in the belt.  $S_1$  schistosity was crenulated and folds were mostly obliterated by transposition of beds in the subsequent  $D_2$  deformation. In Plate 2, the external foliation  $S_e$  is represented by the foliation of the matrix. The rigid garnet porphyroblast deflects the schistosity of the matrix around it, indicating the pre-existence of the garnet crystal prior to the deformation causing the development of the matrix foliation.

The syn-tectonic porphyroblast could have developed at the onset of the main phase of the Pan-African orogeny which is synchronous to regional deformation and mineral formation corresponding to  $D_2$  deformation in the Maru formation. It is here envisaged that temperatures, during the Pan-African might have risen locally to high grades (possibly reaching up to the garnet zone) within contact aureoles of intrusive bodies. These local temperature increases might have allowed for the interstitial recrystallization of

garnets. The garnet porphyroblasts might have grown together with fabric development as a result of  $D_1$  deformation in the Maru formation. In Plate 2, the garnet porphyroblast grew enclosing crystals that are foliated. This internal foliation  $S_i$  might have developed prior to the  $D_1$  episode, or the garnet crystal developed as an inter-tectonic porphyroblast, and thus passively grew enclosing the pre-existing matrix foliation and became preserved within the garnet crystal and protected from the subsequent  $D_2$  deformation of the Pan-African orogeny.

### CONCLUSION

It is inferred that at least two cycles of deformation corresponding to  $D_1$  and  $D_2$  in the Maru developed two sets of foliations corresponding to  $S_1$  and  $S_2$  schistosities. The initial  $S_1$  schistosity might have been developed during the Eburnean. The subsequent  $S_2$  schistosity might have been developed during the main phase of the Pan African orogeny.

### Acknowledgement

Contributions from colleagues at both the Department of Geology A.B.U. Zaria and at University of Silesia, Poland, are gratefully acknowledged.

REFERENCES

- Adekoya, J.A. (1998). The geology and geochemistry of the Maru Banded Iron-Formation, northwestern Nigeria. *Journal of African Earth Science*, 27 (2), pp. 241-257.
- Adekoya, J. A. (1996). The Nigerian Schist belts: Age and depositional environment implications from associated banded iron-formations. *Journal Mining and Geology*, 32: pp. 27-46
- Ajibade, A. C., Woakes, M. and Rahaman, M. A. (1987). Proterozoic crustal development in the Pan - African regime of Nigeria. *American Geophysical Journal*, pp. 259 - 271.
- Black, R., Caby, R., Monssine Pouchkin, A., Bayer, R., Bertrand, J. M., Bourllier, A. M., Fabri, J. and Lesquer, A. (1979). Evidence for Late Precambrian plate tectonics in West Africa. *Nature*, pp. 278: 233-237.
- Barker A. J. (1994). Interpretation of porphyroblast inclusion trails: limitations imposed by growth kinetics and strain rates; *Journal Metamorph. Geol.* (12) 681- 694.
- Barker A. J. (1998). *Introduction to metamorphic textures and microstructures*; 2nd edn., Blackie, Glasgow.
- Bell T. H. (1985). Deformation partitioning and porphyroblast rotation in metamorphic rocks: aradical reinterpretation; *Journal Metamorph. Geol.* (3) 109-118.
- Bell T. H. and Rubenach M. J. (1983). Sequential porphyroblast growth and crenulation cleavage development during progressive deformation; *Tectonophys.* (92) 171- 194.
- Burke, K.C., Dewey, J.F. (1972). Orogeny in Africa. In: *African Geology*: Dessauvagine, T.J.F., Whiteman, A.J. (Eds.), University Press, Ibadan. pp. 583-608.
- Busa M D and Grey N. H. (1992). Rotated staurolite porphyroblasts in the Littleton Schist at Bolton, Connecticut, USA; *Journal Metamorph. Geol.* (10) 627-636.
- Chattopadhyay , A. And Ghosh, N. (2007). Polyphase deformation and garnet growth in pelitic schist of Sausar Group in Ramtek area, Maharashtra, India: A study of Phorphyroblast-matrix relationship. *Earth Syst. Sci.* (116), No. 5 pp 423-432.
- Dada, S.S. (2008). Proterzoic evolution of the Nigeria-Boborema province, *Geological Society London Special publication.* (294): pp. 121-136.
- Dada, S.S. (1999). Geochemistry and petrogenesis of the reworked gneiss complex of North Central Nigeria: Major and trace elements studies on Kaduna amphibolites and migmatite gneisses. *Global Journal of Pure and Applied Sciences*, 5 (4): pp. 535-543
- Egbuniwe I. G. (1982). Geotectonic Evolution of the Maru belt, northwestern Nigeria. Ph.D thesis, University of Wales, Aberystwyth, U.K.
- Fitches, W. R., Ajibade, A. C., Egbuniwe, I. G., Holt, R. W., and Wright J. B. (1985). Late Proterozoic Schist belts and plutonism in NM Nigeria. *Journal of Geological Society of London*, pp. 142: 319-337.
- Goki, N.G, Dada, S.S, Oha, A.I. and Moumouni A. (2010). An interpretation of tectonic elements of the Kanke Basement Complex, Central Nigeria. *Online Journal of Earth Sciences*, 4(2): pp. 89-94
- Ibrahim A. A. (2011). Banded Iron Formation: *Petrology, geochemistry and genesis, case study of the of Maru Schist belt, Nigeria*. LAP LAMBERT Academic Publishing, GmbH & Co. KG, Germany
- Passchier C W and Trouw R. A. J. (2005). *Microtectonics*. Springer-Verlag.
- Powell D and Treagus J.E. (1970) Rotational fabrics in metamorphic minerals; *Mineralogical Magazine* (37) 801-814.
- Trompette, R. (1994). Geology of West Gondwana (2000-500 Ma). *Pan-African Brasiliano aggregation of South America and Africa*. Balkem, Rotterdam - Brookfield.
- Turner, D. C. (1983). Upper Proterozoic Schist belts in the Nigerian sector of the Pan - African Province of West Africa. *Precambrian Research* (21): pp. 55-79.
- Vernon R. H. (1976). *Metamorphic processes*. Allen and Unwin, London.
- Vernon R. H. (1975). Deformation and recrystallisation of a plagioclase grain; *American Mineralogist* (60) 884-888.
- Wright, J. B., Hastings, D. A., Jones, W. B. and Williams, H. R., (1985). *Geology and Mineral Resources of West Africa*. Allen and Unwin. London.
- Yardley B. W. D (1989). *An introduction to metamorphic petrology*. Longman Earth Science Series, Wiley, New York.
- Zwart H. J. (1962). On the determination of polymetamorphic mineral associations, and its application to the Bosost area (central Pyrenees); *Geol. Rdsch* 52 38-65.