Formation of Atoll Garnets in the Banded Iron Formation of Maru Schist Belt

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Abstract

Petrographic and microprobe analyses from the banded iron formations (BIF) of the Maru Schist Belt shows that the BIF contain occurrences of atoll-like garnets. The formation of the atoll garnet is discussed using textural, chemical and Backscatter Electron image (BSE) characteristics. The garnets are of almandine (Alm - 45) composition in the outer rims, with increased amount of spessartine (Spst - 40) in the central rims, and a low amount of grossularite and pyrope. The garnet replaced by chlorite (chamosite), with magnetite inclusions are contained in silicate facies BIF. Textural evidence reveals incipient garnet replacement by chamosite along the Fe - rich rims. Based on the microprobe analysis and BSE data it is supposed that atoll-like forms of the garnets in the BIF developed by replacement of the preexisting garnets mainly by chamosite, hematite, and ilmenite under varying temperature pressure conditions (from high grade - garnet zone, to low grade - chlorite zone) typical of polymetamorphic regions.

1.0 Introduction

Some metamorphic garnets display microstructures such as coronas, symplectite texture, fishnet texture, atoll structure and patchy growth fabrics, the particularly intriguing atoll microstructures are thought to be a special variety of corona texture consisting of a garnet ring surrounding a mixture of several other phases and/or island-shaped garnet fractions. Atoll garnets commonly consists of a complete or almost complete rim of garnet with an interior filled with any combination of biotite, muscovite, feldspar, quartz and iron oxide (Semellie, 1974). In several cases garnet islands can be seen inside the rims (Homam, 2003). Generally, all atoll garnets show some breaching of their characteristic idioblastic outline. Atoll – like garnets represent a specific type of garnets whose genesis has not been unambiguously resolved yet. Previous works emphasized the replacement of the core of what used to be a complete garnet as the mechanism for the atoll texture. However, recent studies suggest that prograde breakdown of garnet due to clockwise P-T path is responsible for the formation of atoll garnet in regional metamorphosed pelitic rocks (Gibson, 1992; Casco and Roldan, 1996).

The atoll garnets occur in a variety of medium – high grade metamorphic complexes. There are known occurrences of atoll-like garnets from Ireland, (Homam, 2003); the Bohemian Massif (Spisiak and Hovorka, 2003); China (O'brien and Carswell, 2006). They are found to be associated with contact metamorphosed pelitic rocks in the British Isles (Atherton and Edmonds, 1966); Regional metamorphosed pelitic rocks at Canigou Massif of the Pyrenees (Gibson, 1992); Barrovian type quartzofeldspathic gneiss in New Zealand (Cooper, 1972) and with eclogites in the Armorican Massif in France (Godard, 1988). The atoll garnet texture is also recognized in the Banded Iron Formations (BIF) of Maru Schist Belt, Northwestern Nigeria which is discussed in this work.

2.0 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 have been linked to the Boborema province of Brazil (Dada, 2008 and 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 (Figure 1).

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 ages ranges 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^{o}E, trending NNE, and can be traced along strike for about 800 km. They are apparently infolded 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 (Figure 2) consists predominantly of pelitic to semi-pelitic metasediments interlayered with psammites, BIF and metabasic rocks (Egbuniwe, 1982; Adekoya, 1998; Ibrahim, 2010). 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 psammatites 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_1, D_2 and D_3 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 (Figure 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.

3.0 Materials and Methods

Representative samples of the 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 Phirho–2 correction program.

4.0 Results

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 – 1cm 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, Plate 1.

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:

1) The Fe oxide (dark) band:

Magnetite + Hematite + Quartz + Garnet + Grunerite + Siderite, other minerals are: Stilpnomelane, Greenalite, Minnesotaite, Chalcopyrite, and Goethite.

2) The Silicate (light) band:

Grunerite + Garnet + Magnetite + Hematite + Quartz + Chamosite + Rhodochrosite + Siderite + Olivine + Pyroxene

Magnetite and hematite are the dominant minerals in the iron oxide band, hematite (martite) developed after magnetite. Amphibole and garnet occur in considerable amounts, they are next in abundance to the hematite and magnetite. Stilpnomelane, minnesotaite and greenalite represent the primary minerals while goethite that occurs in considerable proportion and chalcopyrite as secondary mineral (Plate 2).

Garnets occur as subhedral to anhedral crystals within the bands of the BIF. Normal, atoll and peninsular shaped garnets occur in the BIF units located near plutons in the Maru Schist Belt. The garnet crystals exhibit compositional variability. Figure 4 show variations in Mn, Fe, Mg, Ca, along the line of traverse O – P. Both the Normal (non atoll) and the atoll shaped garnet show compositional zoning characterized by increasing Fe and decreasing Mn from the core (Table 2, Plate 3, 4, 5, Figure 3 and 4). Variations in all these elements are very symmetrical across the garnet porphyroblast. The garnet is relatively low (<5wt %) in both calcium and magnesium. Magnesium shows little to no variation across the porphyroblast, while calcium shows slight enrichment towards the rims, followed by a slight drop at the edges of the porphyroblast. Manganese is characteristically high in the core and this concentration systematically decreases towards the rim where near the edges of the porphyroblast, it rises noticeably. Iron behaves in an opposite fashion to manganese as it is low in the core, rises steadily towards the rim, and then drops slightly at the mineral edges. In many instances the outer rim is Fe-rich and the center is Mn-rich.

The normal garnets in the samples contain inclusions of hematite and ilmenite (Plate 5). The atoll shaped garnets consist of garnet surrounded by a ring of chlorite, and inside the ring are the hematite and ilmenite replacements. The peninsula shaped garnets consist of garnet partially surrounded by chlorite (Plate 3).

Chlorite rims replaces the almandine-rich sections of the garnet crystals sorrounding the Mn rich cores. Lines of microprobe traverse O – P, R – S gives results that indicate differences in composition within the garnets, the inner sections are spessartine (Mn) rich, while the outer portions are almandine (Fe) rich (Plate 6).

5.0 Discussions

It is difficult to draw definite conclusion for mechanism of atoll formation using textural evidence alone, hence in this study, microprobe data is used to compliment petrographic evidence to explain the formation of atoll structures in garnets from the Maru Schist Belt. This schist belt is similar in setting and evolution to that in the Donegal region of the Republic of Ireland where the Dalradian metasedimentary rocks have been reported to contain atoll garnets within Ardara aureole in the pelitic rocks (Homam, 2003).

Although, the presence of cloudy cores in many small and porphyroblastic garnets suggest the possibility of incipient garnet replacement from the core (Semellie, 1974), in this study the replacement of garnet by chlorite is observed to be from the outer rims (Plate 6). Chemical mapping across garnet crystals (Plate 5 and 6; Table 2 and 3) shows regular difference in composition. Mn shows continuous decrease towards the rim, whereas Fe shows constant increase towards the rim. Ca is fairly constant across the traverse. The chlorite that develops in a circular to sub circular pattern follows the Fe-rich outer portions of the garnets replacing the almandine. It is evident from the petrographic data that the garnets and the chlorite replacements were formed during different mineral formation episodes. Considering the polymetamorphic nature of this belt it can be said that the garnets were formed by an earlier high grade metamorphic event and became involved subsequently in low grade metamorphic cycle that led to retrograde replacement of the garnets by chamosite.

The central parts of such crystals which are normally rich in spessartine contain inclusions of ilmenite, hematite and or pyrite that develop as the P – T conditions became elevated by replacement. From the microprobe analysis, it is evident that the genesis of the atoll like forms is by replacement of the initial normal garnet about a path that is rich in Fe by chlorite rather than by separate nucleation.

This is further strengthened by the lack evidence of fluid infiltration into the garnets. A similar conclusion was arrived at by Speiss *et al.*, (2000). The peninsular form developed in other areas lends support to this observation, as the peninsular (incomplete rings) developed within normal garnets following path defined by compositional differences rather than structural patterns. The central portions are selectively replaced by hematite and ilmenite that developed probably as pseudomorphs after garnet. This development of atoll garnets within the BIF sequence of the Maru Schist Belt shows that the BIF and the associated metasediments suffered at least two cycles of mineral formation episodes. The initial, lead to the formation of the garnet crystals, this may correspond to the Eburnean thermotectonic event. This is because BIF are reported to be confined to certain geologic ages, and that the BIF of Maru Schist Belt have been shown to belong to the Algoma type (Mucke *et al.*, 1996), or Lake Superior type (Ibrahim, 2010; Egbuniwe, 1982), in either case, the BIF is indicated to be older than the Mesoproterozoic. Therefore, since the BIF is syngenetic with the associated rocks, (Klien, 2005; Mucke *et al.*, 1996) the initial deformation of the Maru formation could not have occurred during the Kibaran (1100 Ma) as indicated by Egbuniwe, (1982) and Fitches *et al.*, (1985), since this age bracket does not fall within the metallogenetic epoch of BIF as shown by Gole and Klein, (1981); Walker *et al.*, (1983); Trendall *et al*,. (2004); Klein, (2005).

This development of atoll garnets in the BIF therefore supports the proposal of Dada, (1998) that the metasedimentary belts of Nigeria belongs to the Paleoproterozoic which is contrary to the views of Ajibade *et al* (1987) which supposes that the schist belts of Nigeria to be Pan African (600±150 Ma). The difficulty in determining the age of the metasedimentary rocks of Nigeria is related to the obliterating effect caused by the Pan African which led to the resetting of mineral ages, thus making it a challenging task. However, the Pan African is regarded by many workers to have mildly affected the northwestern Nigeria basement complex. Large scale plutonism was however shown to be associated with the Pan African (McCurry, 1976; Ajibade *et al.*, 1987) this Pan African plutonism led to the emplacement of the Damaga, Kanoma and Maiinch plutons (Figure 2). It is envisaged that these plutons might have affected the Maru formation causing localized metasomatic changes to the rocks within the contact aureole. These changes are recorded in the BIF in form of martitization of magnetite (Ibrahim, 2010; Mucke, 2005); and the development of atoll garnets due to replacement by chlorite (chamosite).

The atoll garnets are associated with both the silicate and oxide facies BIF in this belt. The silicate facies is the dominant type of occurrence in the area. While the oxide facies is represented in the Baraba, Karakai and Gamagiwa BIF as minor occurrences. This is the first reported occurrence of atoll garnets in the Nigerian schist belts.

7.0 Conclusions

From petrographic evidence, microprobe and BSE image data it can be concluded that atoll garnets in the Banded Iron formations of the Maru Schist Belt developed by the replacement of garnets by chlorite, hematite, pyrite and in some places ilmenite. The presence of incomplete diffusional modification (peninsular) as the initial stage of garnet replacement process matches well the development of atoll textures, as dissolution replacement is supposed to have progressed faster upon those parts of garnet that had failed to change their composition this is also in accordance with (Homam, 2003). The garnets crystals were probably formed during the Eburnean thermotectonic event, while the replacement might have been triggered off by a subsequent metamorphic activity caused by the plutonism associated with the Pan – African thermotectonic event. Therefore, the occurrence of atoll garnet within BIF that have metallogenetic epochs serves as petrographic evidence for the Paleoproterozoic age of the schist belts of Nigeria.

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

STEP	EVENT	AGE
10	Localised D_4 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_2 in Gusau Granite Gneiss under greenschist facies conditions(retrograde) D_3 in Maru Formation under greenschist facies conditions (retrograde) D_4 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_1 in Maiinchi batholith and Gusau Granite gneiss producing regional trends and structures under amphibolite facies conditions. D_2 in Maru Formation under greenschist facies conditions. D_3 in Gusau migmatites under amphibolite facies conditions.	678-577 m.y.
5	Emplacement of Gusau Granite gneiss and Maiinchi batholith.	1900 ± 250
4	Regional deformation: D_1 in Maru Formation under greenschist to lower amphibolite facies conditions. D_2 Gusau migmatites under amphibolite facies conditions	
3	Deposition of Maru Formation: contemporaneous subaqueous extrusion.	2500
2	Emplacement of basic dykes in gneissified rocks. D_1 deformation of Gusau migmatites under amphibolite facies conditions.	3100 – 2750
1	Formation of parental rocks of Gusau migmatites of igneous or sedimentary origin.	

Table 2: Microprobe results for traverse analysis across a garnet crystal in Plate 5a

Oxide	Point 1	Point 2	Point 3	Point 4	Point 5	Point6	Point7	Point8
SiO2	36.532	36.398	36.777	36.635	35.970	36.462	36.590	36.316
TiO2	0.203	0.208	0.156	0.100	0.046	0.049	0.094	0.111
Al2O3	19.962	20.060	20.310	20.339	20.473	20.422	20.552	20.659
Cr2O3	0.007	0.005	0.015	0.012	0.049	0.000	0.022	0.000
Fe2O3	1.065	0.935	0.652	0.707	0.148	0.447	0.408	0.078
MgO	0.260	0.262	0.229	0.165	0.248	0.228	0.250	0.274
CaO	3.844	4.221	4.290	4.390	3.578	3.950	3.634	3.123
MnO	26.426	24.928	23.113	22.176	18.353	19.147	20.751	22.049
FeO	11.963	13.262	14.701	16.004	20.594	19.209	18.375	17.601
NiO	0.033	0.000	0.000	0.013	0.000	0.012	0.067	0.000
Na2O	0.000	0.001	0.035	0.000	0.000	0.000	0.000	0.001
K2O	0.003	0.000	0.014	0.000	0.000	0.000	0.000	0.000
	100.298	100.280	100.292	100.541	99.459	99.926	100.743	100.212

Oxide	Point 9	Point 10	Point 11	Point 12	Point 13	Point 14	Point 15	Point 16
SiO2	36.477	36.431	36.209	36.437	36.383	36.667	36.770	36.547
TiO2	0.139	0.174	0.232	0.195	0.151	0.166	0.087	0.069
Al2O3	20.651	20.238	20.503	20.584	20.461	20.523	20.495	20.319
Cr2O3	0.002	0.012	0.039	0.037	0.046	0.045	0.050	0.005
Fe2O3	0.187	0.503	0.152	0.195	0.344	0.309	0.500	0.663
MgO	0.274	0.250	0.247	0.267	0.245	0.257	0.236	0.305
CaO	3.069	3.302	3.008	3.718	4.322	3.837	3.421	3.949
MnO	21.638	21.081	21.397	20.225	20.247	20.039	20.069	18.812
FeO	18.241	17.804	18.551	18.894	17.922	18.602	19.266	19.494
NiO	0.000	0.000	0.000	0.000	0.000	0.053	0.003	0.029
Na2O	0.000	0.012	0.006	0.000	0.001	0.004	0.004	0.008
K2O	0.000	0.000	0.000	0.000	0.041	0.000	0.000	0.000
	100.678	99.807	100.344	100.552	100.163	100.502	100.901	100.200

Table 3: Microprobe results for traverse analysis across O – P in Plate 6

OxidePoint	O#101	#102	#103	#104	#105	#106	#107	#108
SiO2	39.002	36.750	36.425	36.292	35.557	36.490	36.196	36.420
TiO2	0.155	0.142	0.142	0.327	0.425	0.382	0.323	0.218
Al2O3	21.822	20.106	20.101	20.079	19.311	20.077	20.131	20.098
Cr2O3	0.011	0.000	0.036	0.000	0.000	0.000	0.004	0.007
Fe2O3	0.000	1.172	0.834	0.737	1.433	0.812	0.717	0.854
MgO	0.262	0.154	0.165	0.155	0.122	0.117	0.119	0.150
CaO	5.511	5.864	5.376	6.715	6.807	5.744	5.434	5.419
MnO	13.915	18.562	19.389	19.533	21.173	22.729	23.463	23.443
FeO	20.659	17.972	17.329	15.686	13.725	13.873	13.710	13.386
NiO	0.061	0.039	0.017	0.000	0.000	0.000	0.000	0.000
Na2O	0.015	0.005	0.000	0.001	0.016	0.005	0.000	0.000
K2O	0.000	0.000	0.000	0.008	0.000	0.000	0.000	0.000
	101.413	100.766	99.814	99.533	98.569	100.229	100.097	99.995

OxidePoint	#109	#110	#111	#112	#113	#114	#115	P#116
SiO2	36.445	36.522	36.591	36.429	36.411	36.359	36.454	36.135
TiO2	0.349	0.317	0.248	0.325	0.322	0.214	0.143	0.216
Al2O3	19.179	19.987	20.231	19.916	20.061	19.958	19.930	19.792
Cr2O3	0.000	0.017	0.010	0.051	0.039	0.000	0.010	0.024
Fe2O3	2.034	0.963	0.655	0.885	0.770	1.273	1.213	1.201
MgO	0.218	0.131	0.114	0.099	0.122	0.157	0.159	0.215
CaO	5.090	5.176	5.253	5.786	6.299	5.469	5.787	6.119
MnO	22.731	23.168	22.688	22.088	20.947	19.804	18.020	15.550
FeO	13.994	13.998	14.274	14.093	14.829	17.557	18.405	20.391
NiO	0.000	0.000	0.008	0.000	0.000	0.000	0.000	0.000
Na2O	0.005	0.003	0.023	0.000	0.000	0.007	0.004	0.000
K2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	100.045	100.282	100.095	99.672	99.800	100.798	100.125	99.643

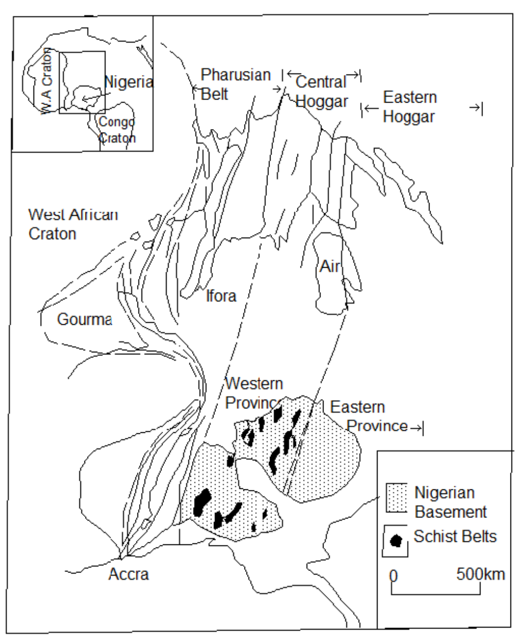


Figure 1. Location of the Nigerian shield in the major structural units of West Africa and the Brazilian belt following the pre-Mesozoic reconstruction of Caby (1989).

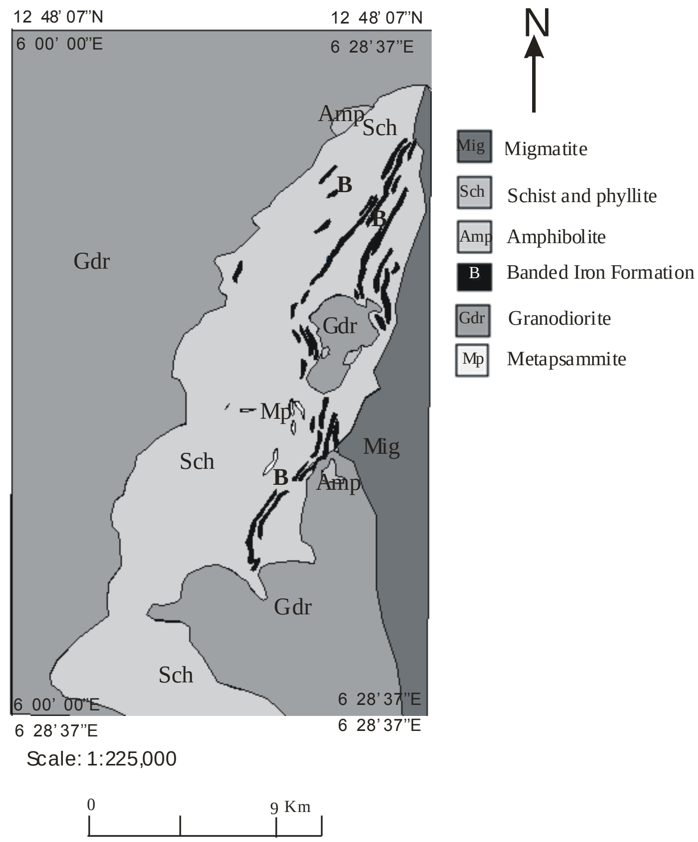


Figure 2. Geological map of Maru Schist Belt

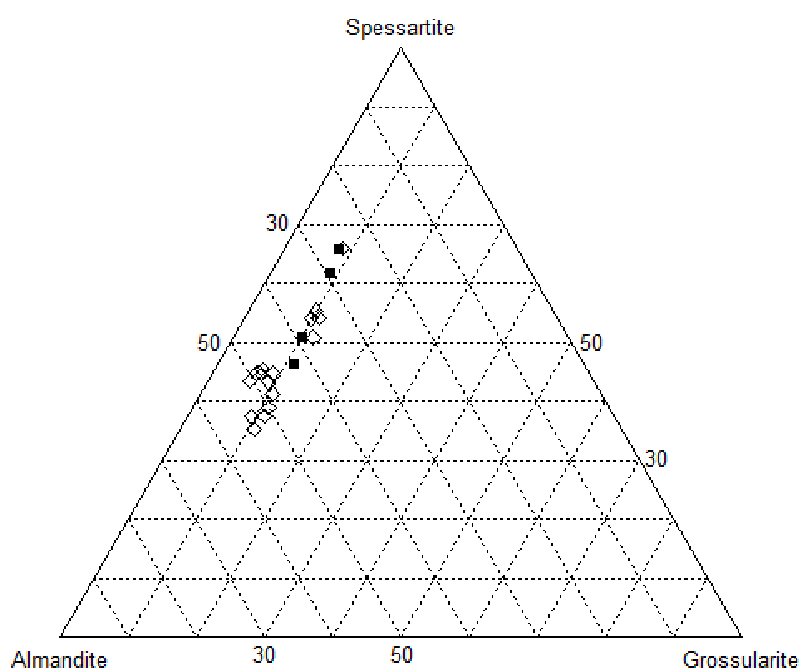


Figure 3. In the triangular diagram the garnets in the BIF show compositional characteristics midway between spessartite and almandine garnets.

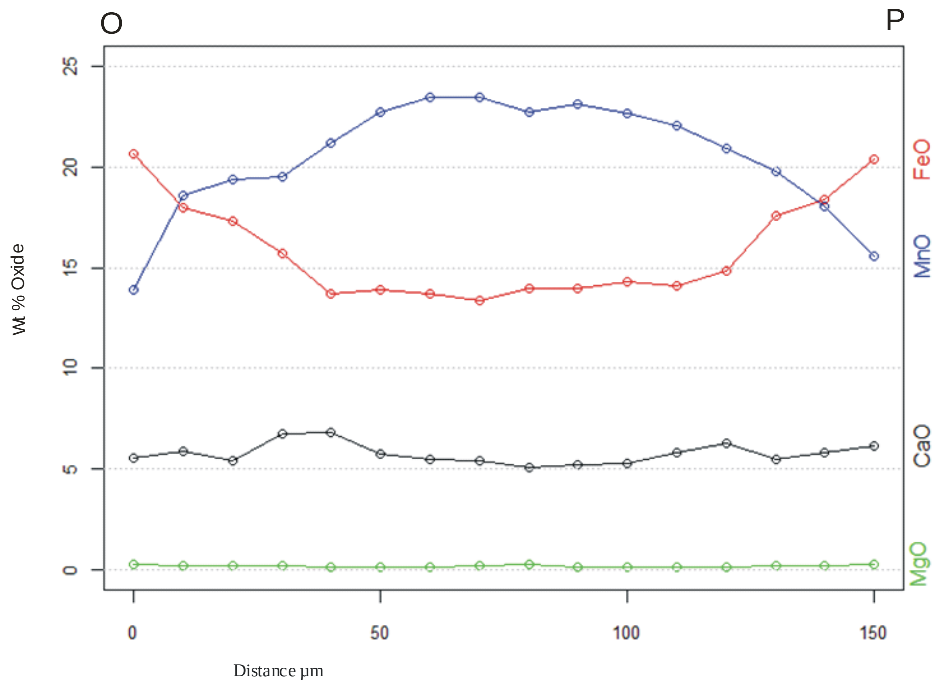
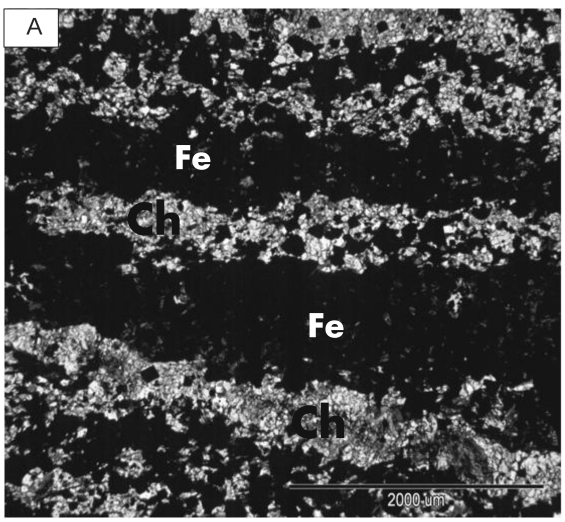


Figure 4. Plot of variations in elements Fe, Mn, Mg, and Ca across garnet porphyroblast. Analysis done in a line transect O – P, of 16 equidistant spot analyses.



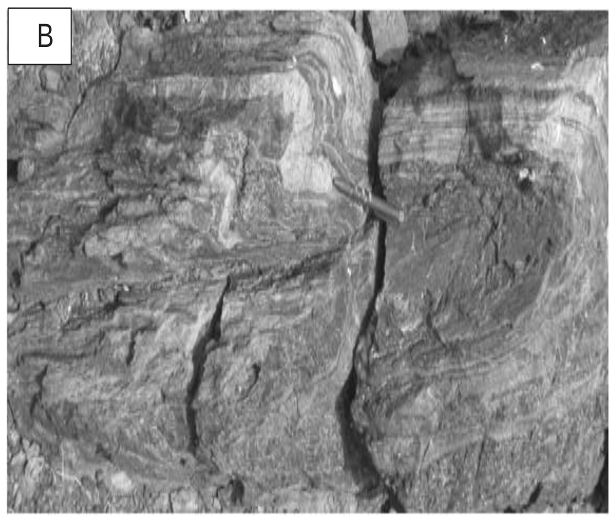


Plate 1. a) Photomicrograph showing microbanding in the BIF in transmitted plane polarized light, the iron-rich band (Fe) alternates with chert rich band (Ch); b) Field photograph of the BIF with meso- and macro-banding types represented.

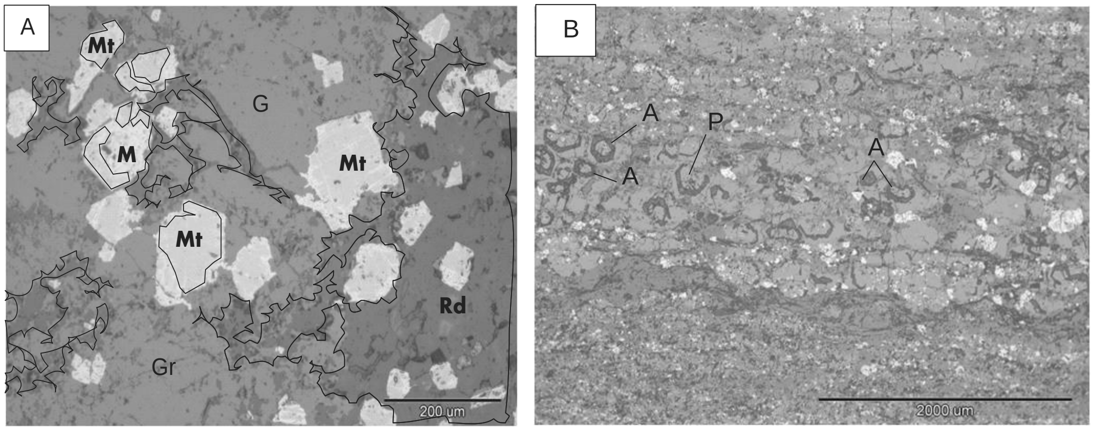


Plate 2. a) Martite – Mt develops after magnetite – M as replacement mineral in the BIF. The Fe – oxide minerals are associated with garnet – G, grunerite – Gr and rhodochrosite – Rd. b) Garnet crystals exhibiting replacement structures resembling atolls – A and peninsular – P shapes within the Fe – oxide band. Reflected light, plane polarized

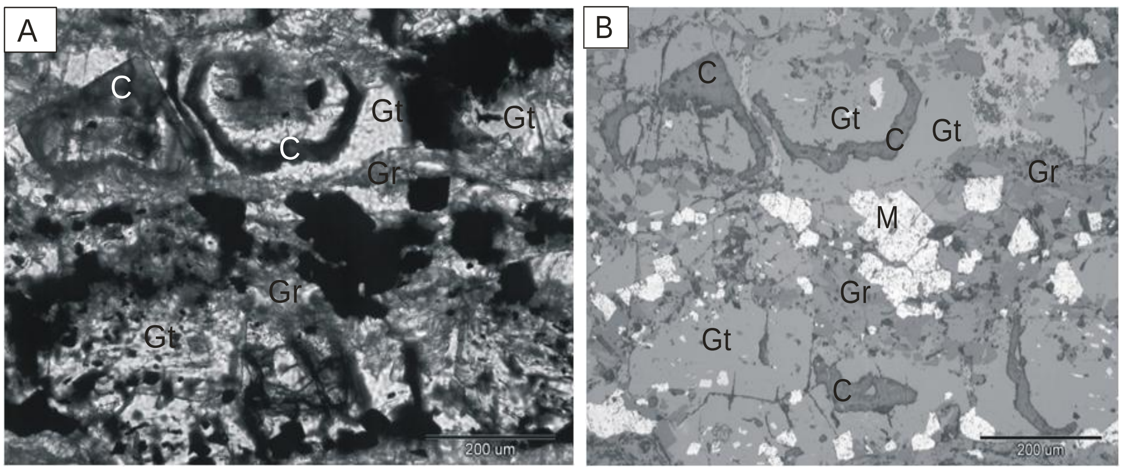


Plate 3. . a) Transmitted light photomicrograph showing chamosite – C replacements in garnets – Gt intergrown with grunerite – Gr; in reflected light (b), the garnet crystals are obviously distinguishable from the coexisting grunerite – Gr and the highly reflecting magnetite – M.

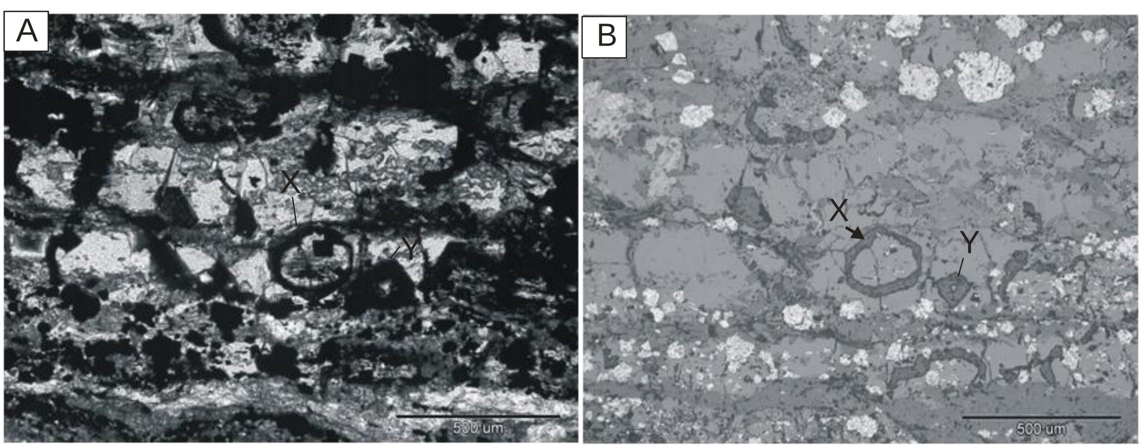


Plate 4. a) Differences in the degree of replacement in the garnets varies and proceeds towards the centre of the crystal as shown in crystals X and Y, in both transmitted and reflected light as in A and B.

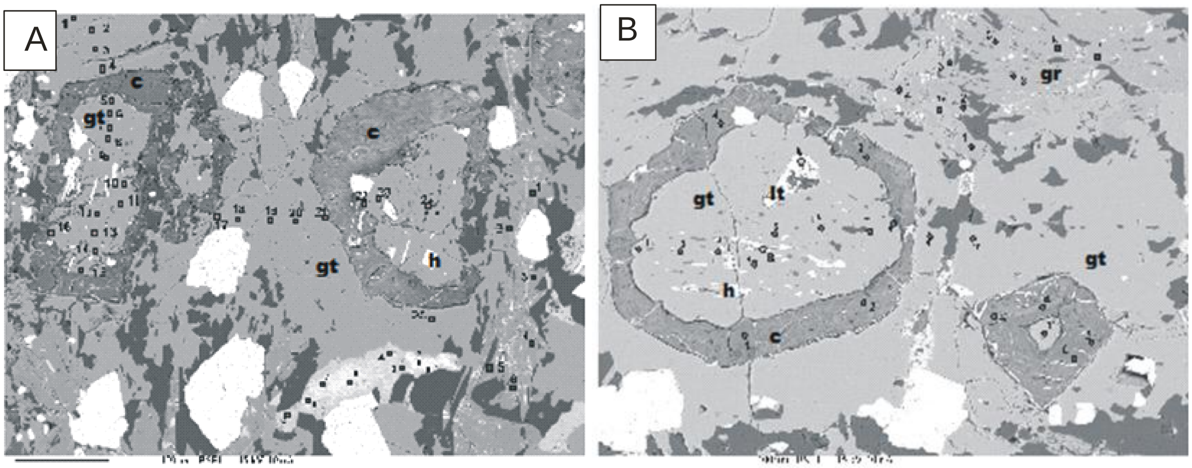


Plate 5. BSE image of the oxide band of the BIF with atoll like textures on garnets – gt intergrown with grunerite - gr. Analysis points along a traverse lines through the garnet crystal are indicated in (a); inclusions of ilmenite - lt, and hematite – h are represented in (b).

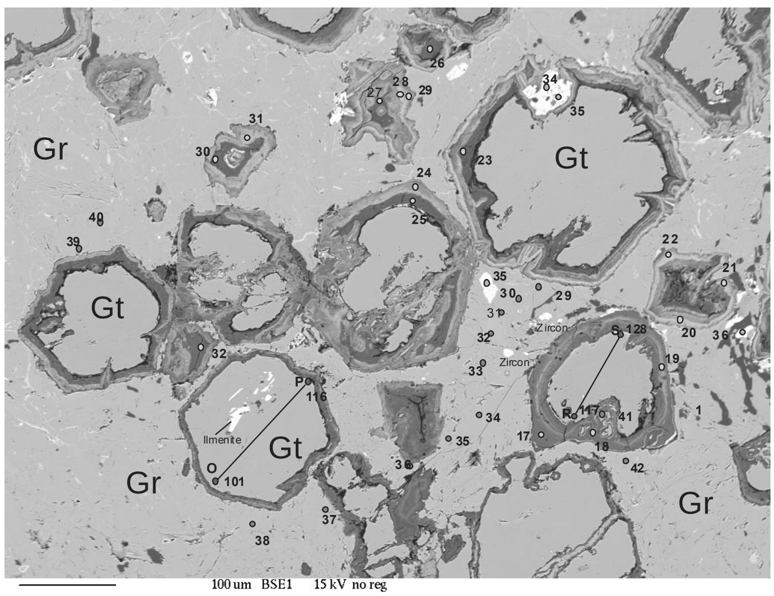


Plate 6. BSE image of the BIF showing crystals of garnet – Gt within fine-grained grunerite – Gr , with the garnets exhibiting various degrees of alteration. Microprobe analysis traverse lines are indicated on the crystals.