

Full Length Research Paper

Migmatization process and the nature of transition from amphibolite to granulite facies metamorphism in Ikare area Southwestern Nigeria

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The Ikare area is underlain by rocks of the migmatite-gneiss-quartzite complex and older granite lithologic groups and charnockites. Categorization of these rocks in the literature and published map is generalized and the rocks are undifferentiated. Though reported in few literature as an area with rocks composed of granulite facie grade, the nature of transition is not well documented. Field and petrographic studies were carried out to properly characterize the different rock types, evaluate the migmatization processes and elucidate the nature of amphibolite to granulite facie transition. Major rock types recognized and mapped includes grey gneiss, charnockitic gneiss, granite gneiss, pelitic gneiss, porphyritic granite and quartzite. Minor rock types are the mafic and ultramafic components which are made up of basic schist and amphibolites. The area suffered at least four episodes of deformation (D₁, D₂, D₃ and D₄) and at least three episodes of metamorphism (M₁, M₂ and M₃). Petrographic studies further show that the mineral assemblage within the quartzo-feldspathic rocks changed from hydrous to anhydrous phases as one traverses from the southern part of the study area to the northern part. Reaction textures indicate that the transition zone between the amphibolite and granulite facie rocks is achieved by a prograde dehydration reaction while rehydration reactions took place during the waning retrograde stage. Anatexis and metamorphic differentiation were mainly responsible for the migmatization process in Ikare area while the charnockitization process was a product of dehydration reactions aided by reduction in water fugacity due to influx of CO₂.

Key words: Structure, migmatites, granulite facies, deformational episodes, metamorphism, charnockitic gneiss.

INTRODUCTION

High grade metamorphic terrains in most parts of the world are made up of migmatitic rocks and associated

charnockitic rocks. Migmatitic rocks are the least studied as they are mostly devoid of mineralized components to

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arouse economic interest. In spite of the lack of economic importance, embedded in migmatites are clues and evidences for better understanding of past thermal regimes and structural evolution of the continental crust (Lee and Cho, 2003). Determination of previous P-T conditions of such rocks gives some insights on the associated tectonic processes (Thompson and Ridley, 1987; Harley, 1989). Exposed granulite-facies terrains are often regarded as windows into the middle to lower continental crust (Fountain and Salisbury, 1981; Percival et al., 1992). Thus, in-depth analysis of the pressure-temperature paths of granulites enables evaluation of the deep crustal processes responsible for the formation and stabilization of the continental crusts.

The study area is underlain by rocks of the migmatite-gneiss quartzite complex. Other important groups of rocks that were encountered include the Older Granites and the Charnockites. Areas of migmatitic rocks make up much of the basement complex in Archean provinces worldwide and an understanding of their petrogenesis provides important insights into early crust-forming processes. The processes of migmatite formation vary and it can be divided into those that involve melt and those that do not involve melt. These processes are not mutually exclusive (Merhnet, 1968).

A substantial portion of the study area is composed of high grade metamorphic rocks, mainly migmatitic gneisses, grey gneisses and charnockitic gneisses of granulite facies grade. Categorization of these rocks in the literature and published map is generalized and the rocks are undifferentiated. The processes that led to migmatization are not well defined and the nature of transition from amphibolite to granulite facies rocks is not well understood. The exposure of these important rock groups within the Basement Complex of Nigeria represents an important opportunity to unravel the field relations, geochemistry and petrogenesis of migmatites towards a better understanding of the geology of the area. The present work reports on the field and petrographic analysis of rock samples from the area with a view to carry out a detailed geologic mapping of the area; map the major and minor structures present in the migmatites to determine the structural evolution of the area; identify and describe the different types of migmatites; and finally determine the nature of transition from amphibolite – to granulite facies metamorphism in the area.

METHODOLOGY

Detailed geologic mapping of the area on the scale of 1:25,000 was carried out over a period of 3 years. The Geographic Positioning Receiver System (Garmin, GPSMAP 78s) was used to correctly plot positions of outcrops on the base map. During the mapping, lithologic and small-scale geologic structural units were identified and described. The different types of migmatites were also described. Representative fresh rock samples were collected for laboratory thin section analyses. About fifty different rock samples were selected for thin section analysis. Thin sections were prepared

in the Department of Geology, Obafemi Awolowo University, Ile-Ife. These were studied under the petrographic microscope in order to describe texture and mineral assemblages and determine the metamorphic grade. Relevant photomicrographs were also taken to illustrate the mineral assemblages, textural relationships and possible mineral reactions.

Geology / petrography

The following major rock types were recognized and mapped in the area of study: grey gneiss, charnockitic gneiss, granite gneiss, pelitic gneiss, porphyritic granite and quartzite. Minor rock types in the study area are the mafic and ultramafic components which are made up of basic schist and amphibolites. The distribution of the various units mapped in the study area is presented in Figure 1.

Grey gneiss

Grey gneiss is the most dominant rock type in the study area and it underlies about 70 % of the total surface area. On the basis of field characteristic and petrography, three types of grey gneisses were recognized: (i) early gneiss, (ii) grey gneiss with charnockitic spots and (iii) charnockitic gneiss.

Early gneiss

The first type of grey gneiss occurs in the South-western part of the study area around Supare, north-central and south of Ikare especially around Aiyegunle. The grey gneiss underlies about 45% of the total surface area of the study area (Figure 1). It occurs as low lying outcrops as well as ridges and inselbergs of moderate heights which range from 20 m to 500 m above mean sea level. North of Ikare, the early gneiss is closely associated with the charnockitic gneisses. The early gneisses are medium- to coarse-grained, light grey to dark grey and strongly foliated rock. The foliation is defined by a mineralogical banding in which light coloured bands composed of grey feldspar and quartz about 3 mm thick alternate with dark coloured bands made up of biotite and other ferromagnesian minerals (Figure 2a). The dark coloured bands often tend to be discontinuous, frequently showing pinch and swell structures. Under the microscope, the foliation seen on outcrop is apparent. It is defined by mineralogical banding in which bands rich in biotite and amphibole alternate with bands rich in plagioclase, alkali feldspar and quartz (Figure 2b). In some of the thin sections studied, the long axes of the biotite grains have a preferred alignment parallel to the foliation marked by mineralogical banding. However, in other thin sections, a new generation of biotite was recognized. This new generation of biotite exhibits a preferred alignment of their long axes oblique to the foliation described above which defines another foliation. This second generation of biotite grows across plagioclase grains (Figure 2c).

Mineralogically, early gneiss is composed of quartz, plagioclase, biotite, amphibole and alkali feldspar. Accessory minerals identified are apatite, sphene allanite, zircon and opaques (probably ilmenite).

Grey gneiss with charnockitic spots

Grey gneiss with charnockitic spots is exposed towards the northern part of the studied area. It occurs in isolated locations in Akungba, for example, the road almost opposite Adekunle Ajasin University. It also outcrops within and around Ikare (Victory College). Between Akungba and Ikare, and especially in and around the premises of Victory College, Ikare, the following

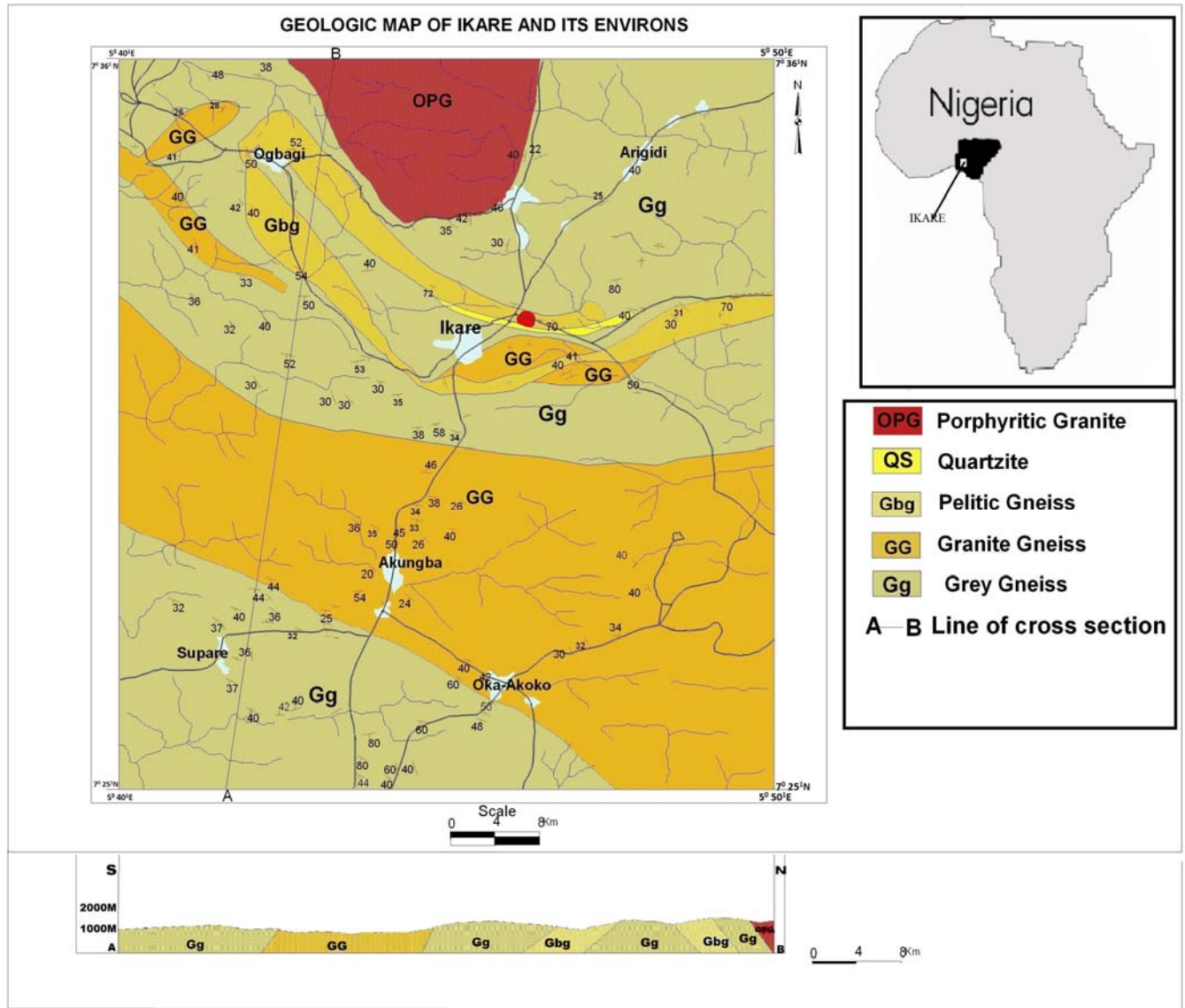


Figure 1. Geologic map of Ikare area.

changes were observed in the early gneiss: (i) appearance of black minerals probably ilmenite and (ii) greenish spots with almost circular to ovoid shapes of about 2-3 cm across. These changes give the early gneiss a spotted appearance similar to those described by Pichamuthu (1960) in southern India and interpreted as charnockite in arrested state of development (Figure 3).

The main rock is characterized by strongly developed foliation defined by mineralogical banding in which light coloured bands rich in quartz and feldspar alternate with dark coloured bands. The mafic bands are very thin (0.1- 0.5 cm) and sometimes discontinuous while the light coloured bands are thicker being 0.5 cm to 1 cm or more, and are continuous. Under the microscope, the foliation seen at the outcrops is apparent. The foliation is defined by preferred alignment of long axes of the mafic minerals. Mineralogical banding in which dark coloured bands rich in biotite, amphibole, orthopyroxene ± clinopyroxene alternate with light coloured bands rich in plagioclase, quartz and alkali feldspar is developed (Figure 4). Mineralogically, the gneiss is composed of

quartz, amphibole, biotite, plagioclase, alkali feldspar, orthopyroxene ± clinopyroxene + accessory minerals (opaques and apatite).

Charnockitic gneiss

This variety of gneiss occurs within Ikare town, Arigidi and Ogbagi in the northern part of the study area. They occur as low lying units to fairly elevated (20 m) outcrops in and around Ikare town. At Ogbagi, and towards Irun in the North-western part of the mapped area, the charnockitic gneiss occurs as bands of about 50 m alternating with the bands pelitic gneisses.

Charnockitic gneiss is coarse-grained, grey to greenish in colour and is weakly foliated. The foliation is defined by a mineralogical banding in which bands rich in ferromagnesian minerals alternate with bands rich in quartz and feldspar. The greenish colouration is due to the fact that the feldspar is green. The rock is composed of

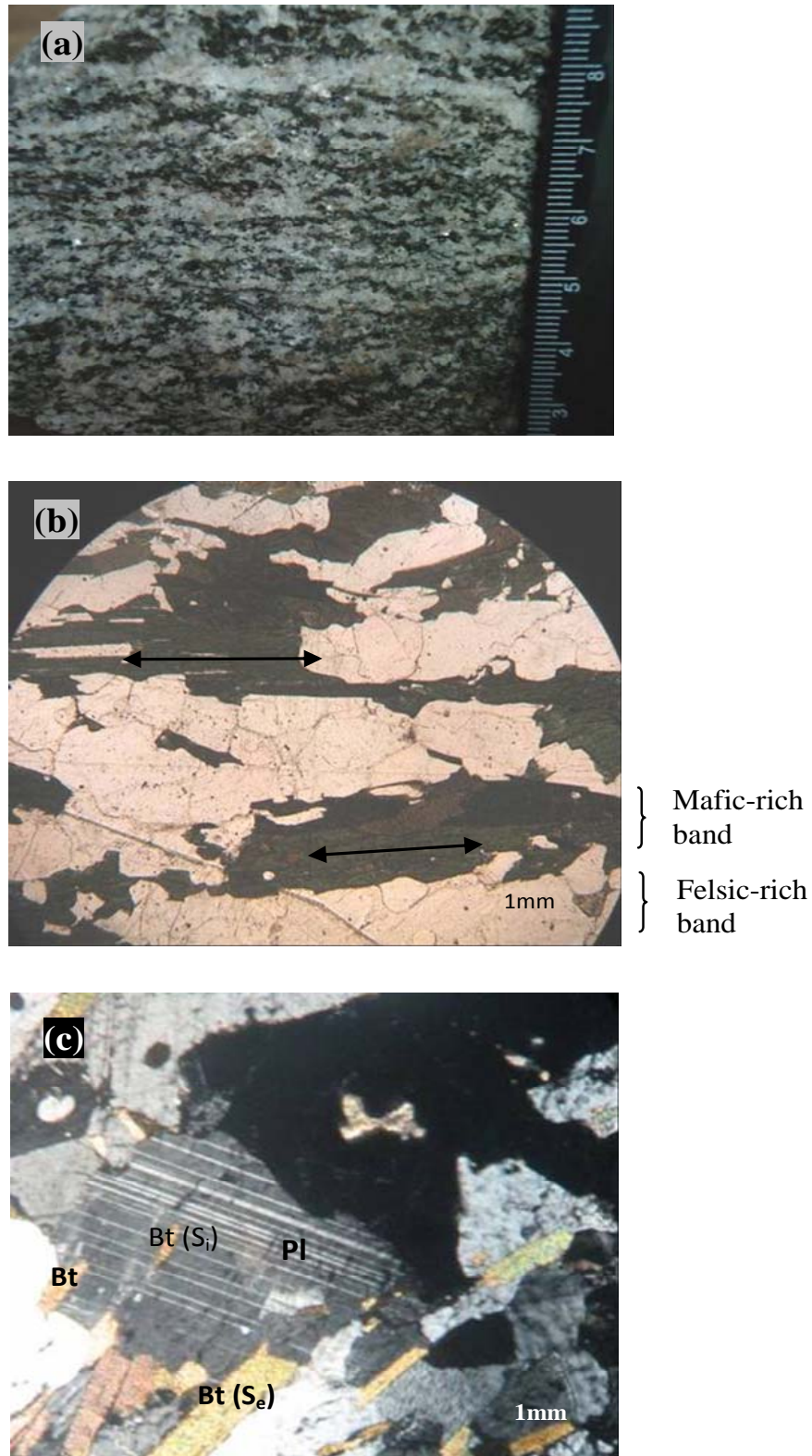


Figure 2. Representative Field photograph and microstructure of early gneiss. (a) Hand specimen from Iwaro-oka showing mineralogical banding. Note the discontinuous nature of the dark coloured bands. (b) Foliation defined by mineralogical banding and preferred alignment of long axes of mafic minerals. (c). Photomicrograph showing a generations of biotite (Bt) flakes with a preferred alignment of their long axes growing across a plagioclase (Pl) grain.



Figure 3. Hand specimen of early gneiss with charnockitic spots. Arrows indicate the charnockitic spots.

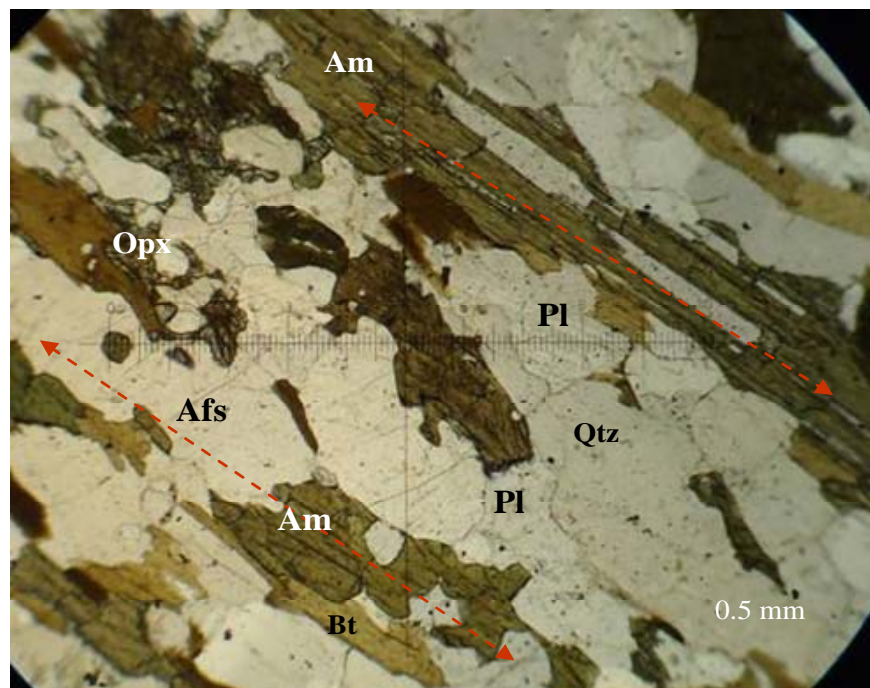


Figure 4. Foliation in early gneiss with charnockitic spot marked by preferred alignment of the long axes of amphibole and biotite flakes in charnockitic gneiss with spots.

biotite, orthopyroxene (opx), clinopyroxene (cpx), plagioclase, quartz and alkali feldspar. Accessory minerals are apatite, amphibole and late chlorite.

Granite gneiss

Within Ikare and the environs, granite gneiss underlies about (45 - 50%) of the surface area. The bulk of the granitic gneiss outcrops in the Southern part around Iwaro - Oka, Akungba, and a small proportion in the northern part around Ikare towards Ogbagi along Arigidi - Ogbagi road. Based on grain size/texture, mineralogical composition and mode of occurrence, several types of granite gneiss can be distinguished.

The first variety encountered in the area mapped occurs mainly as concordant to semi-concordant bands within grey gneisses as part of the "felsic component" within the migmatite. This variety can be found within Iwaro - Oka, Supare and Oka-Akoko town. Granite gneiss is usually light grey to slightly pinkish in colour; medium-to coarse-grained and strongly foliated. The foliation is defined by millimetric to centimetric mineralogical banding in which light coloured bands rich in pinkish feldspar and quartz alternate with dark coloured bands rich in biotite and other ferromagnesian minerals. Occasionally, small oval shaped porphyroblasts of alkali feldspar are present. Under the microscope, foliation is fairly developed and defined by alignment of thin discontinuous biotite band alternating with thicker 0.5 - 2 mm bands rich in quartz and feldspars (Figure 5). Within the quartzo-feldspathic band, the grain boundaries between plagioclase and quartz are embayed suggesting that the rock must have undergone some deformation after crystallization. Mineralogically, the granite gneiss is made up of plagioclase, alkali feldspar, quartz, and biotite. Accessory minerals include sphene, apatite, zircon and opaques.

The second variety also occurs as mapable, semi-concordant bodies and the best examples occur as E-W trending band passing through Akungba, especially within and around the premises of Adekunle Ajasin University, Akungba. These are light grey to pink coloured strongly foliated rocks. The most distinctive feature in this variety is that the granite gneiss contains abundant lens-shaped alkali feldspar porphyroclasts (0.5 cm × 1.5 cm) giving them a distinctive augen structure and so can be referred to as augen gneiss. Two sub-types of augen gneisses were recognized. The first type at Ikare contains large porphyroblasts of garnet while the other type at Akungba does not contain garnet. In many of the localities, for example, within Ikare town, xenoliths of mafic components are seen in the granite gneiss while in other localities, sharp contact relationship can be established with the granite crosscutting the foliation plane of the grey gneiss. Under the microscope, the foliation is defined by the preferred alignment of the long axes of biotite and alternate bands of layers rich in mica and layers rich in quartz and feldspars. Within the quartzo-feldspathic bands, the rock is essentially equigranular with occasional porphyroclast of feldspar giving it a blastoporphyratic texture. This suggests that the granite gneiss was earlier porphyritic granite that has now been deformed and metamorphosed (Figure 6).

Mineralogically, the granite gneiss in Ikare area is composed of alkali feldspar, plagioclase, biotite, quartz and garnet with opaque and apatite as accessory minerals. Granite gneiss from Ikare area differ from the granite gneiss from Akungba, south of the study area by the absence of sphene and the presence of garnet in the mineral assemblage.

Pelitic (Garnetiferous) Gneiss

This rock unit underlies a relatively small proportion of the area mapped. It occurs as a continuous east-west trending band from

Boropa in the east, through Ugbe, Ikare and Ogbagi to the west. The band is between 400 m and 1500 m wide while the total length is about 12 km. On the map scale, the pelitic gneiss shows a folded structure with the fold closure at Ogbagi (Figure 1).

Most exposures of the pelitic gneiss studied are highly migmatitic with the leucosome constituting about 30 to 60% of the exposures. In a few places, for example at Ogbagi, the leucosome makes up more than 70% of the exposures. The leucosome is whitish to pinkish in colour, medium- to coarse-grained (>2 cm), to pegmatitic. They occur as discontinuous bands (about 2 - 3 cm in thickness) within the restite (Figure 7). The restite is light grey to dark grey colour and is strongly foliated. The foliation is defined by millimetric mineralogical banding in which dark coloured bands rich in biotite alternate with bands rich in quartz and sillimanite. One characteristic feature of the pelitic gneiss is the occurrence of abundant garnets. Some of the garnet forms porphyroblasts both in the restite and especially at Ogbagi in the leucosomes.

Under the microscope, most sections show foliation defined by mineralogical banding in which bands rich in biotite, garnet, cordierite, opaque ore and sillimanite alternate with bands rich in quartz and feldspar. The most distinctive feature is the presence of numerous porphyroblasts of reddish brown garnets (0.5 - 2 mm) embedded in a coarse-grained matrix comprising quartz, biotite, plagioclase and sillimanite giving the rock a distinctively porphyroblastic texture. In many of the thin sections studied, the banding is folded but the minerals especially the mica just mimic the fold and the individual flakes are not folded. This suggests that there was complete re-crystallization after the folding episode (Figure 8). Mineralogically, the pelitic gneiss consists of quartz, plagioclase feldspar, biotite, sillimanite, cordierite and garnet.

Mafic - ultramafic components

The amphibolites occur mainly as xenoliths within other rock types especially within the granite gneiss (Figure 9). They occur as boudinaged fragments within the grey gneisses in some localities, for example, within St Stephen Primary School, Iwaro Oka. In other localities, for example, within Supare town they are intricately in-folded within the host rock, indicating that they were also affected by the same deformation that affected the host rock. These components are typically fine to medium-grained and generally dark grey to almost black in colour. They exhibit a well-developed foliation defined by alignment of long axes of mafic minerals (probably hornblende). Mineralogical banding is however poorly developed. Due to the nature of their occurrence, they are often difficult to sample.

Under the microscope, the foliation observed in hand specimen is also visible and the foliation is defined by weakly developed mineralogical banding. Dark coloured bands made up essentially of green amphibole and biotite alternate with light coloured bands rich in plagioclase and quartz. The light coloured bands have a granoblastic texture while the dark coloured bands show preferred alignment of the long axes of the amphibole grains. Mineralogically, amphibolite consists of hornblende, plagioclase, biotite, quartz, sphene and opaques minerals.

Structural geology

Major structures

The published geologic map of the study area, Akure Sheet 61 on a scale of 1:250,000 (Dempster, 1966) shows major E-W lineaments. From previous study (Oyawale et al., 2020), the result of regional digital interpretation of the satellite image suggests that the area was affected by at least two episodes of deformation (Figure 10).

Early deformational episode (D₁) produces the NW-SE tight to

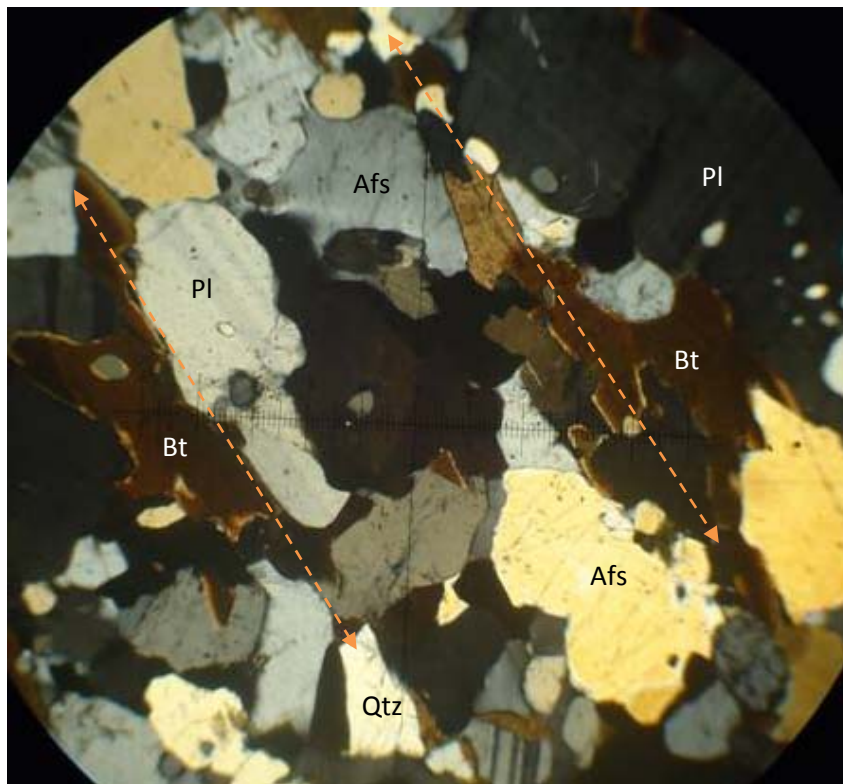


Figure 5. Foliation defined by the alignment of the long axes of biotite flakes in granite gneiss.

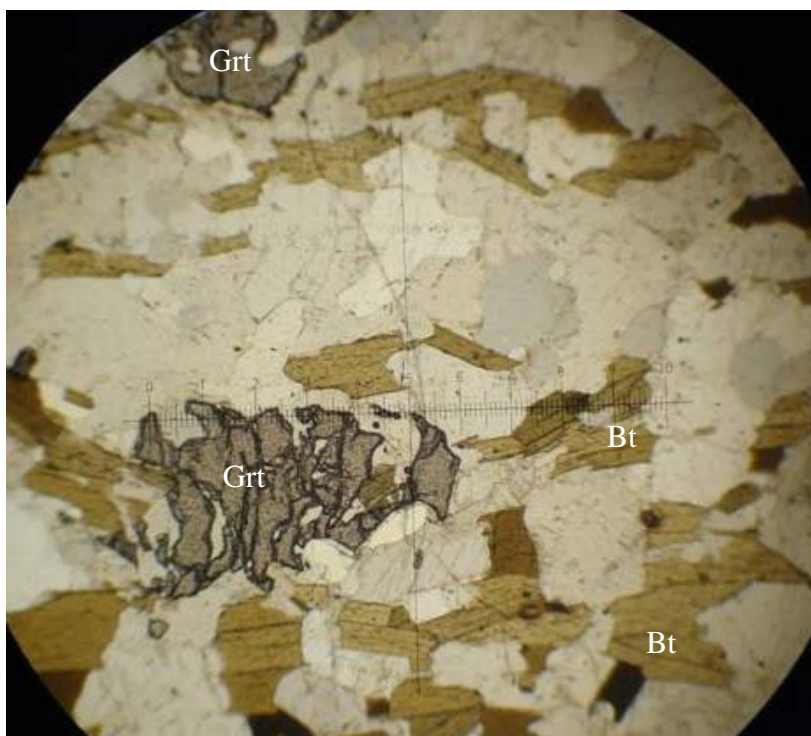


Figure 6. Foliation defined by mineralogic banding and preferred alignment of long axes of biotite. Note xenoblastic garnet in the lower left half of the photomicrograph. Granite gneiss from Ikare (General Hospital).



Figure 7. Photograph of pelitic gneiss showing leucosome (Newly formed portion of the Migmatite) and the restite which is the remnant of the protolith from which a substantial amount of the more mobile component have been extracted.

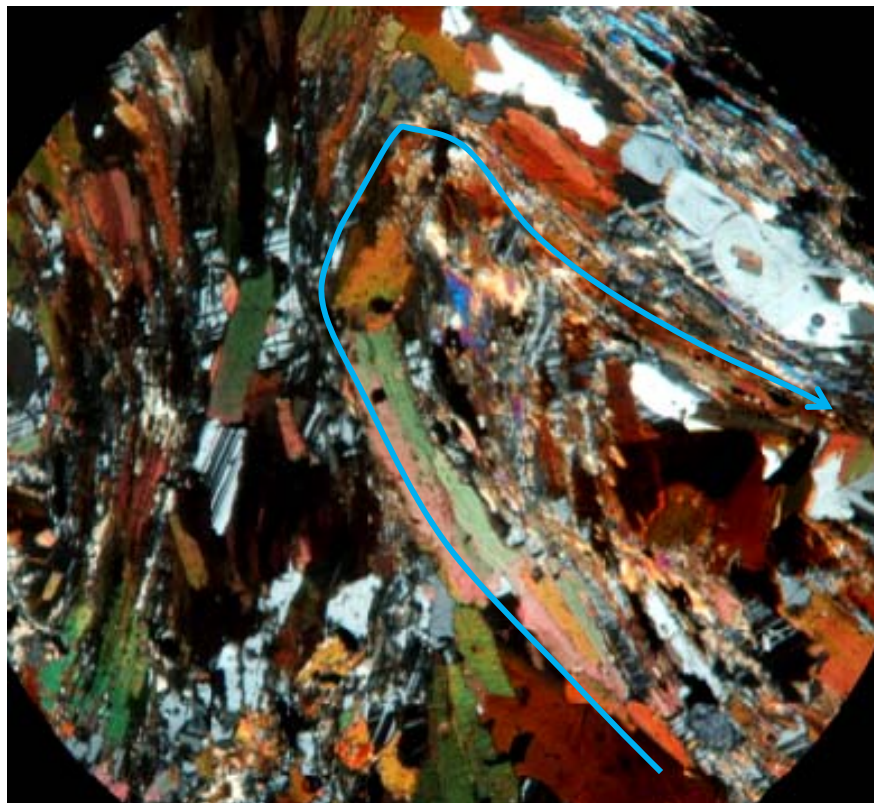


Figure 8. Pelitic gneiss showing folded foliation.



Figure 9. Xenolith of amphibolite (white arrow) within granite gneiss.

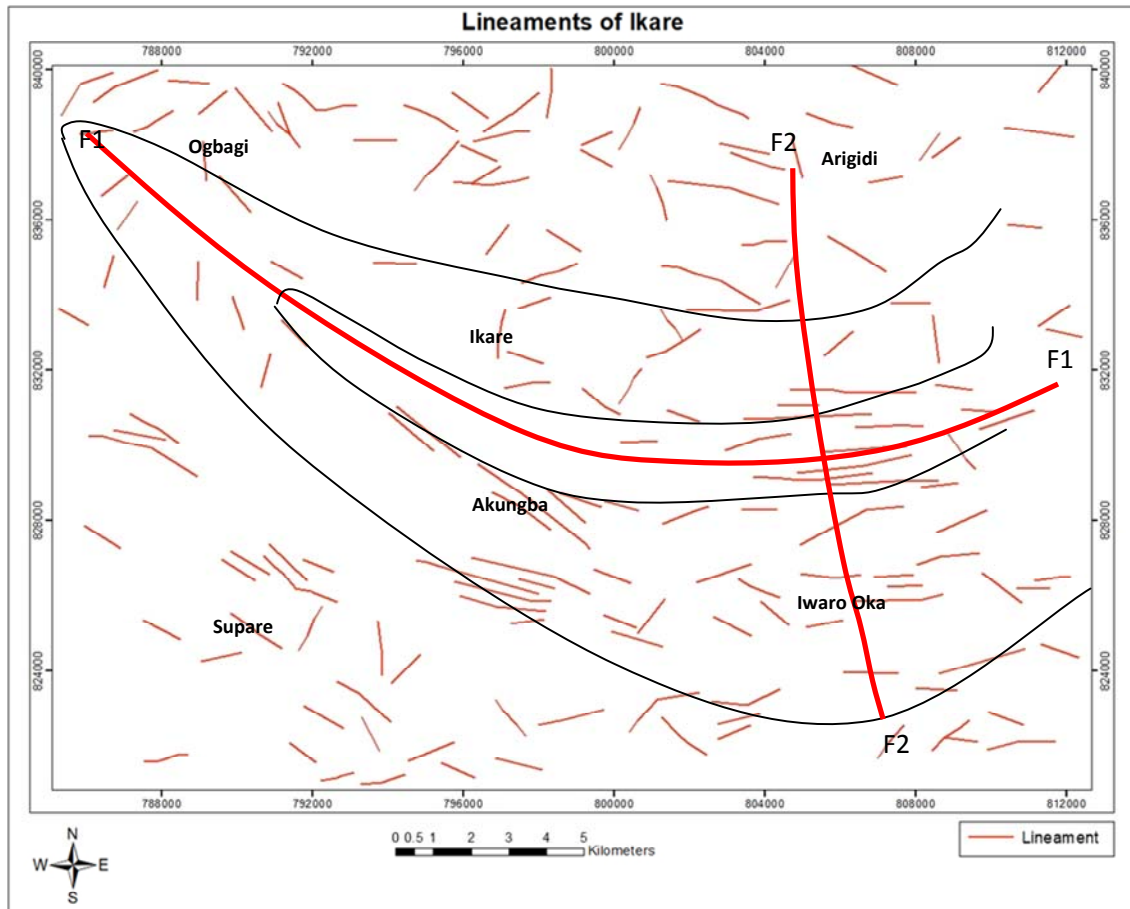


Figure 10. Regional structural map of Ikare and environs showing traces of axial planes of F1 and F2 folds and approximate locations of surrounding Towns.

isoclinal fold in style (F_1). The major E-W trending prominent ridges in the area form the limbs of this fold. D_1 was followed by a second deformation event, (D_2) which affected the axial trace of the first episode producing an open to gentle fold (F_2). This structural style conforms to the widely accepted theory of the tectonic history of the Basement Complex of Nigeria that the earliest structures are in the E-W direction and perhaps, this area is one of the few areas in South-western Nigeria that it is well exposed.

Minor structures

Observations of small-scale structures on outcrops in this study suggest that the study area was affected by at least four episodes of ductile deformation D_1 - D_4 and a later episode of brittle deformation producing joints and other fractures. Field evidence suggests that the earliest structural element recognized is the foliation defined by millimetric to centimetric mineralogical banding in all the rock groups studied. This was probably produced during the earliest episode of deformation (D_1). Evidence for the exact nature of deformation that produced this banding was not observed in the field. The second episode of deformation (D_2) present in nearly all the outcrops studied is the E-W centimetric to metric isoclinal folds (F_1) (Figure 11). This fold reorients S_1 producing the dominant foliation (S_2) in this area. The orientation of these folds is parallel to that shown in Figure 1. Examples of these isoclinal folds can be found at an outcrop opposite Otolomi Hotel at Ikare; along the road to Iwaro Dam from Ikare and at various outcrops along Ikare-Ogbagi Road. The third episode of deformation (D_3) produced gentle folds to open folds also seen on the map scale (Figure 1). This deformation refolded the axial trace of F_1 folds and the tectonic origin of this deformation is the F_2 fold. The axial surfaces of the F_2 folds have strikes approximately 140° and dip at angles of 40° W in most places. In most places careful observation shows that the fold produced an axial plane foliation defined by preferred alignment of mafic minerals. A mesoscopic example of this is shown in Figure 12. A lineation occasioned by the intersection of the S_1 and S_2 surfaces is well developed and is parallel to the fold axis.

In some areas, especially where the intensity of the deformation and folding is strong, such as at Ogbagi, refolding of F_1 by F_2 produced Type 1 (Dome and Basin), Type 2 (Mushroom structure) and Type 3 (Hook) patterns of fold interference after Ramsay's 1967 classification (Figures 13a-c). The fourth episode of deformation (D_4) recognizable in the area is associated with shearing events. This deformation episode is widespread in the area and affects almost all the different rock types studied. The sense of shear is both dextral and sinistral while displacement is in the order of few centimeters. The trend of the shear plane varies and the most commonly observed value for the dextral sense of movement is 120° while for the sinistral shear, the average value is 40° . In some cases, the intensity of shearing is so strong that a crenulation and a crenulation cleavage S_3 are produced. Probably, the last episode of deformation on the outcrop scale that affected the area resulted in brittle deformations as demonstrated by spaced parallel joints.

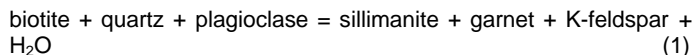
Metamorphism

The structure, texture and mineral assemblages described suggest the study area was affected by several episodes of deformation and metamorphism. The mineral assemblages and the relationship with recrystallization (metamorphism) in the different rock types are described below. Amongst the different rock types available in the study area, the pelitic rocks are the most suitable for the study of metamorphism.

Pelitic gneisses

The pelitic gneiss consists of quartz, plagioclase feldspar, biotite,

sillimanite, cordierite and garnet. Biotite is reddish brown in colour with strong pleochroism in shades of brown. The long axes of the flakes have a preferred orientation parallel to the foliation defined by alternation of bands rich in mafic mineral and bands rich in felsic minerals. Biotite also occurs as inclusions in the garnet and biotite itself contains numerous inclusions of radioactive mineral like zircon forming a pleochroic haloes within the biotite grain. Numerous needle shaped grains of sillimanite occur in close association with biotite suggesting that sillimanite is nucleating on biotite, probably growing at the expense of latter (Figure 14). This suggests that biotite is breaking down to form sillimanite and garnet, a reaction represented by the following equation:



Sillimanite (fibrolite) occurs as slender needles closely associated with biotite. Occasional prismatic grains are present in some of the thin sections. The long axes of the needle-shaped grains have a preferred orientation parallel to the foliation of the rock. This indicates that fibrolite formed during that deformation episode that produced the foliation (Figure 14). Garnet occurs mainly as xenoblastic porphyroblasts in a finer grained matrix. Some of the garnet porphyroblasts are wrapped round by the foliation marked by the preferred alignment of the long axes of biotite and sillimanite and characterized by pressure shadows (Figure 15). The existence of pressure shadow suggests that these porphyroblasts are pre-tectonic in relation to the deformation that produced the foliation.

Some of the garnet porphyroblasts contain numerous inclusions of sillimanite, quartz, opaques minerals and biotite. The long axes of these minerals have a preferred alignment defining an internal foliation (S_i). Based on these inclusion trails, two types of garnet can be distinguished. The first type of garnet shows curved inclusion trails within the garnet suggesting that this generation of garnet was syn-tectonic in relation to the episode that produced the foliation. In the second type of garnet, the long axes of these inclusions have a preferred alignment defining an internal fabric (S_i) that is parallel to the external fabric (S_e) defined by mineralogical banding outside the garnet porphyroblasts (Figure 16). This suggests that these garnet porphyroblasts are post-tectonic in relation to the deformation that produced the external fabric (S_e) and postdate them. The textural relationship suggests that there are probably three generations of garnets in these rocks: an early pre-tectonic garnet (G_1); a syn-tectonic garnet (G_2) and a late, post-tectonic garnet (G_3).

Cordierite occurs as irregular grains and is commonly associated with the bands rich in biotite, sillimanite and garnet. In some of the thin sections studied, cordierite occurs as reaction rims around biotite flakes and garnet porphyroblast. In the presence of sillimanite, similar textural observations were recognized in pelitic rocks in Finland (Markku and Pentti, 1999). This type of association has been interpreted to mean that the garnet grains are unstable and are breaking down according to the reaction represented by the following equations.



This reaction probably represents a major melt-producing process in these rocks. Plagioclase occurs as small idioblastic grains within the quartzo-feldspathic bands. It exhibits the characteristic polysynthetic albite twinning. Inclusions of sillimanite are common within it. Small idiomorphic grains of plagioclase are present as inclusions in K-feldspar grains. Along grain boundaries of alkali feldspar, myrmekite-like intergrowth is common. These textures are interpreted as indicating the presence of melt (Cenki et al., 2002).

Petrographic evidence, especially the S_i/S_e relationship within



Figure 11. Field photograph showing (F1) isoclinal fold in grey gneiss, opposite Otolomi hotel. Note compass needle in NS direction and the axial trace in almost E-W direction.

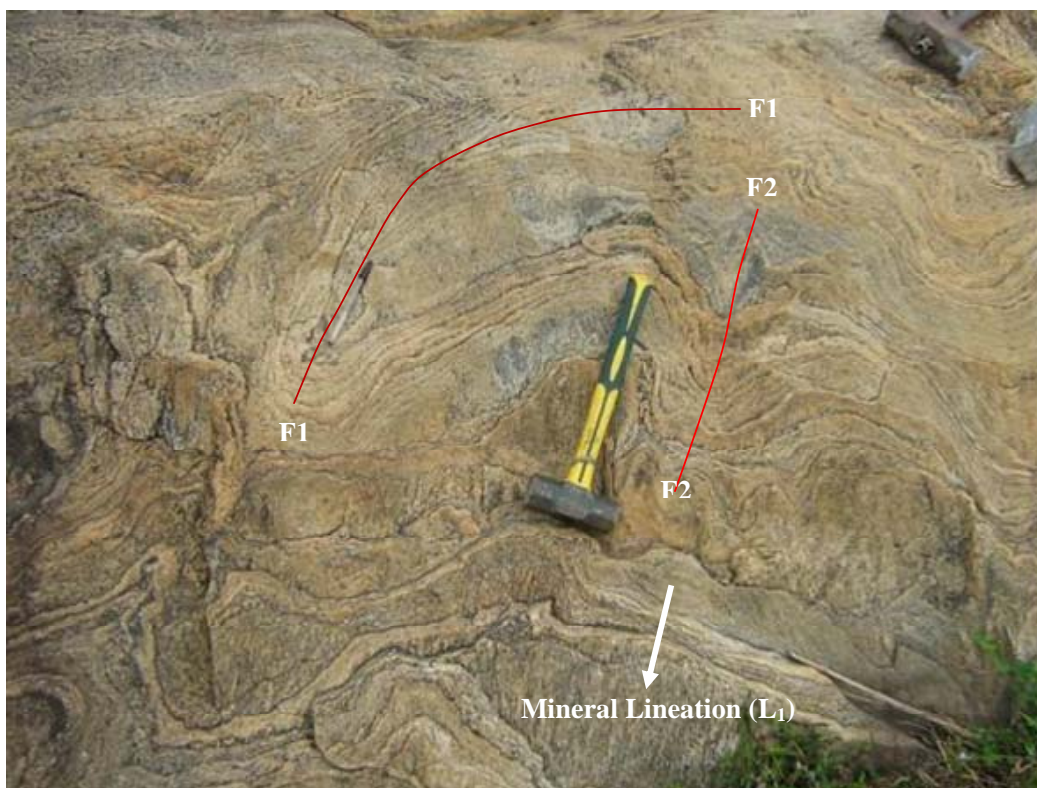


Figure 12. Field photograph showing axial trace of F1 and F2 folds. Prominent mineral intersection lineation (arrowed) on S2 Surface.

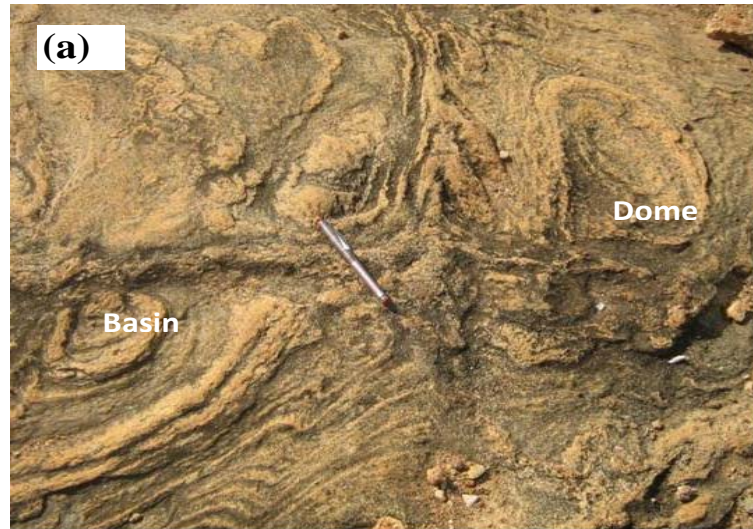


Figure 13. Field photographs showing (a) Type 1 fold interference pattern (Dome and Basin). (b) Type 2 fold interference pattern (mushroom). (c) Type 3 fold interference pattern (coaxial fold).

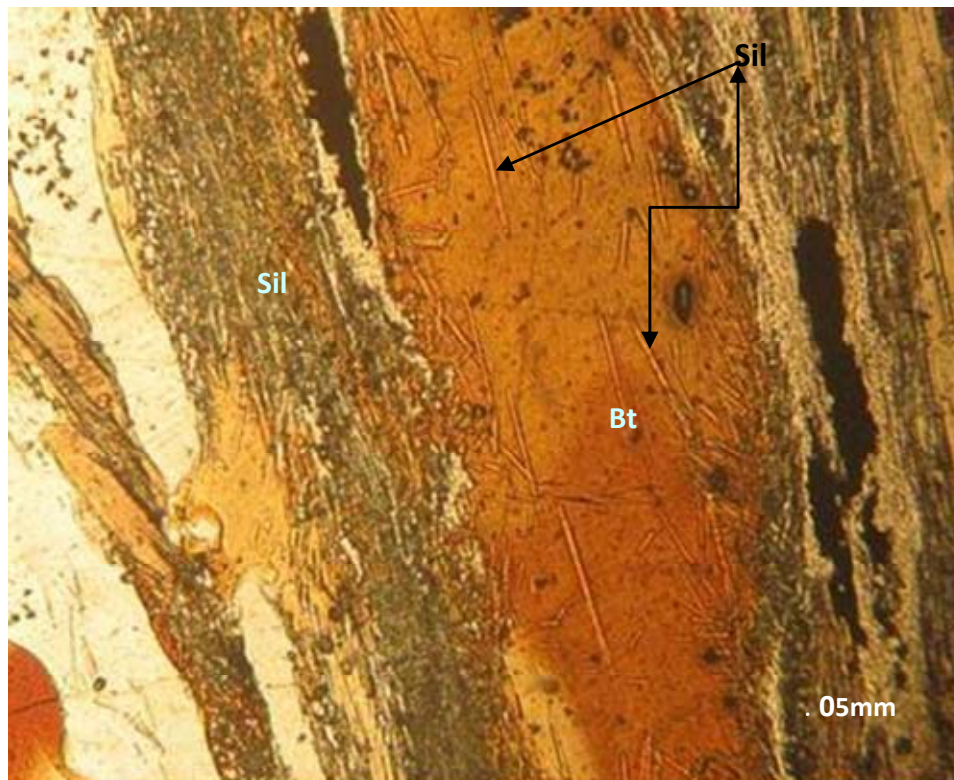


Figure 14. Pelitic gneiss showing sillimanite (Sil) and biotite (Bt) intergrowth in pelitic gneiss.

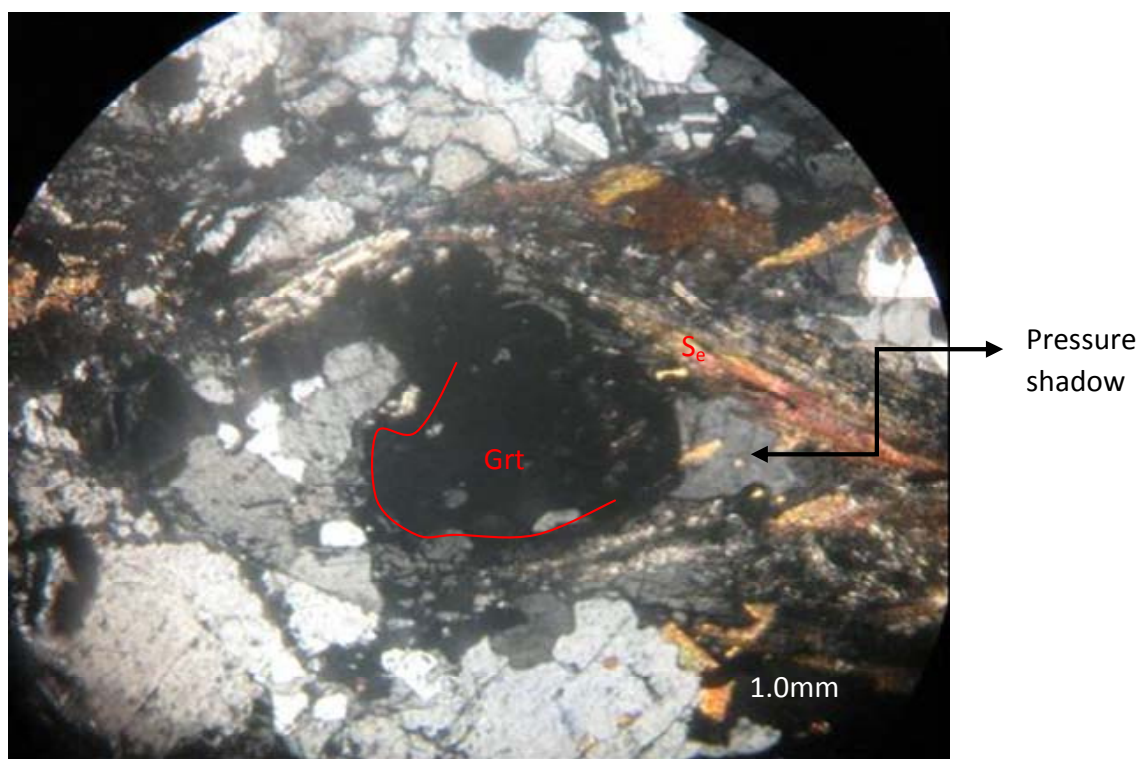


Figure 15. Pelitic gneiss showing foliation defined by the preferred alignment of long axes of biotite wrap around the garnet porphyroblasts.

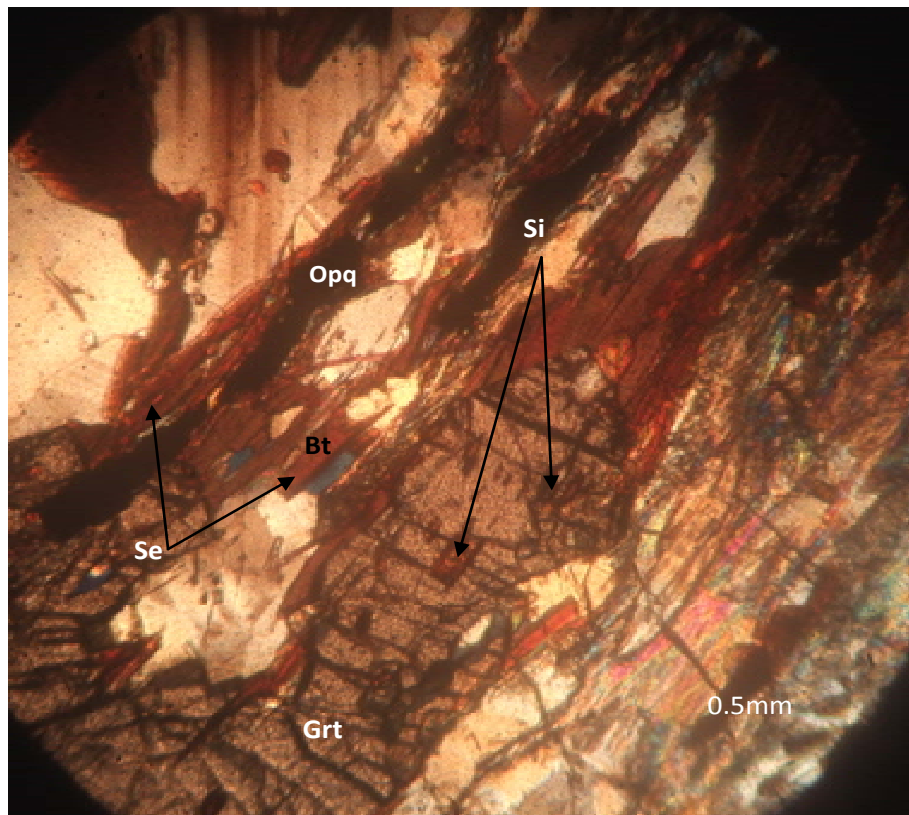


Figure 16. Garnet porphyroblast in pelitic gneiss with inclusions of biotite (Bt) grains defining internal fabric S_i which is concordant with the external fabric S_e .

and outside garnet porphyroblasts record at least three generations of garnet associated with at least three episodes of metamorphism. Based on microtextural relationships, the three types of garnet recognized in the pelitic rocks were: pre-tectonic, syn-tectonic and post-tectonic garnet. The first episode of deformation (D_1) is probably responsible for the development of the pervasive mineralogical banding that is recognizable both on mesoscopic and microscopic scale. D_1 is closely associated or contemporaneous with the first episode of metamorphism (M_1). Petrographic evidence suggests that (M_1) probably resulted in the development of the first generation of garnet during prograde metamorphism of medium pressure type.

The second episode of deformation (D_2), associated with the second episode of metamorphism (M_2) produced a new fabric that wraps around the pre-tectonic garnet. It was probably during this episode, that there was widespread breakdown of biotite to produce sillimanite. Contemporaneous with this episode of metamorphism is the production of syn-tectonic garnet (G_2). The third episode of metamorphism (M_3) is the development of post-tectonic garnet which overprints on existing foliation and enclosed earlier formed sillimanite. After the thermal peak period, the garnet became unstable, probably due to uplift or decompression to produce low pressure mineral such as cordierite. This later episode of metamorphism is related to the widespread production of melt (Censki et al., 2002).

Grey gneiss

The mineral assemblage in the typical early gneiss at Aiyetoro

consists of amphibole, plagioclase, biotite, quartz, K-feldspar and sphene in the southern part of the area mapped. Northward, towards Ikare town, orthopyroxene appears in the mineral assemblage of the early gneiss, suggesting that there is a transition from amphibolite to granulite facies grade of metamorphism. At the same time, transient charnockitization process also occurs so that at Ikare town, the early gneiss has been largely transformed to charnockitic gneiss. Petrographic evidence suggests that the orthopyroxene is late and was probably produced during the second episode of metamorphism (M_2). Within the charnockitic gneisses, there are pockets of outcrops of grey gneiss with charnockitic spots. The grey gneiss with charnockitic spots consists of low temperature minerals (e.g. chlorite) that are late as a result of rehydration reaction. This indicates that there is a second transition from the charnockitic gneiss to grey gneiss with charnockitic spots which is gradational. Chlorite seen in some of these gneisses was produced during the cooling stage and is contemporaneous with the third metamorphic episode (M_3).

Granite gneiss

Petrographic evidence in the mineral assemblages in the granite gneiss from the southern part differs from that in the northern part of the area studied. In the south, the granite gneiss consists of $qtz + k\text{-feld} + plag + bio + amp \pm sphene$, while in the north, towards Gboye Guest House, the mineral assemblages changed with the entrant of garnet and sillimanite. Also, there is a change of alkali feldspar from microcline to perthite. This suggests an increase in the grade of metamorphism from the south to the north of the area

mapped. In summary, the mineral assemblages within the different rock types show that there is a variation in the grade of metamorphism northwards from the south.

RESULTS AND DISCUSSION

Nature of transition from amphibolite - to - granulite facies

The results of the field mapping, as well as petrographic studies have corroborated earlier studies of Rahaman and Ocan (1988) who suggested that there exists in Ikare and its environs medium to high grade metamorphic rocks. Rahaman and Ocan (1988) stated that there is a transition from upper amphibolite facies to granulite facies, the nature of which was not addressed. Within the Ikare area, charnockitic rocks constitute one of the major rock types and they are important constituents of high grade terrain which could have developed either by igneous or metamorphic process (Newton, 1992a). Holland (1893, 1900) was the first to attribute plutonic origin to charnockites while Howie (1955) later emphasized the idea of plutonic metamorphism in which magma of charnockitic origin was emplaced at a lower crustal depth.

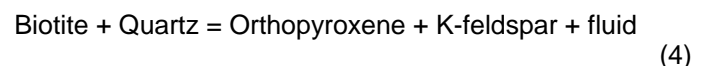
In Nigeria, both metamorphic and igneous charnockites have been described from various parts of the country (Olawaju, 1987; Ocan, 1991; Ferre and Caby, 2006). Pitchamutu (1960) first described 'patchy' charnockite within host amphibolites facies gneiss in India and interpreted it as arrested growth from the host. Subsequently, other workers have described it using various adjectives to qualify the origin petrographically such as 'charnockitization' (Janardhan et al., 1979; Newton, 1992b). Other workers even interpreted large bodies as product of 'progressive charnockitization' (Srikantappa et al., 1992; Janardhan et al., 1994). In Ikare area, charnockitic rocks of presumably metamorphic origin (Rahaman and Ocan, 1988) have been encountered. In the northern part of the study area, for example, within Ikare town, gneisses with patches of dark greenish spots outcrop as pockets within the grey gneisses. In some of the outcrops of charnockitic gneisses, the patches or spots were not visible any more.

The field relationships and petrography of the charnockites in the study area were used to establish the nature of transition in granulite facies rock. Eskola (1933) described granulite facies as being characterized by completely anhydrous mineral assemblages produced by the complete disappearance of amphibole and mica (biotite) in quartz-bearing rocks. Encountering a sharp transition from a completely hydrous assemblage to a completely anhydrous assemblage is rare in nature. Thus a wider region of transitional states occurs where many rocks show two pyroxene assemblages. Granulite facies can be divided into two groups to include all the transitional states: a low temperature and a high temperature subfacies.

The grey gneisses with charnockitic spots typify rocks of the lower temperature zone of the granulite rock as clinopyroxene is seen to nucleate on biotite in the presence of amphibole. The charnockitic gneisses contain both orthopyroxene and clinopyroxene with very little or no amphibole. The charnockitic gneisses show the development of pyroxene (ortho-pyroxene) from the breakdown of amphibole and/or biotite. In some of the thin sections, ortho and clino pyroxenes coexist with biotite and amphibole forming the core. As patches begin to form in the grey gneiss, the mineral assemblage becomes that of orthopyroxene with skeletal structures of biotite (Figure 17). The patchy variety of charnockite can be regarded as the transitional zone in which there is arrested growth or development of the patchy spots consisting of greenish feldspar and opaques in the grey gneiss. Thus, with increase in temperature, culminating into loss of more hydrous minerals like amphibole, higher grade of metamorphic facies can be attained.

Petrographic evidence suggests that mineral assemblages of the grey gneiss from Aiyetoro, Supare and Iwaro-Oka area, south of Akungba (biotite + amphibole + quartz + plagioclase feldspar (oligoclase) + sphene) are characteristic of amphibolite facies grade of metamorphism. Miyashiro (1994) stated that the boundary between the amphibolite and granulite facies is the temperature and pressure conditions under which orthopyroxene and clinopyroxene begin to coexist with amphiboles.

There is good evidence in the grey gneiss with charnockitic spots of breakdown of low/medium temperature mineral like amphibole to produce higher temperature minerals like pyroxene + K-feldspar and where there is no amphibole, biotite is seen to break down to produce pyroxene. The breakdown can be represented with the following equation:



The above reaction generates fluids which attest to the fact that charnockite formation is generally believed to be the product of sub-solidus dehydration. The dehydration reactions vis-a-vis charnockite paragenesis can only form through reduction in the activity of water which could be either internally or externally controlled (Hansek et al., 1984; Srikantappa et al., 1985). The assumption of external control in reducing water fugacity for the formation of charnockites is that sub-solidus dehydration of the gneiss assemblage was as a result of directed influx of CO₂ through a deep mantle source (Janardhan et al., 1982; Newton 1992b; Ravindra, 2004; Harlov et al., 2006). Alternatively, Srikantappa et al. (1985) postulate that incipient charnockitization (that is, dehydration) could result from a decrease of fluid pressure at the beginning of near-isothermal uplift following the peak stage of regional metamorphism. The rock association of Ikare area does not contain graphite, thus, the possibility of a

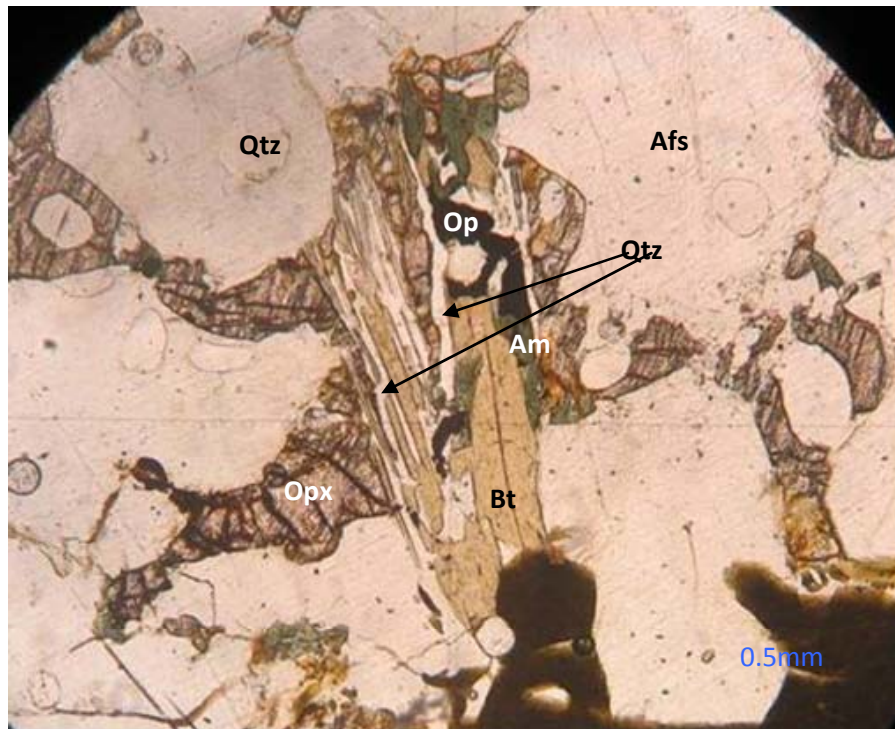


Figure 17. Symplectic intergrowth between biotite (Bt), pyroxene (Opx), opaque (Op), feldspar (Afs) and amphibole (Am). Note the wormlike quartz (arrowed).

CO₂ driven mechanism to generate charnockitic rocks is most unlikely. However, the idea of incipient charnockite along some structural weak zone could be compatible with the internally proposed mechanism of charnockite formation which is the reduction in the activity of water.

While the grade of metamorphism indicated by the mineral assemblages in the grey gneiss increases from south to the north, the amount of neosomes is more in the south than the north. This is contrary to what is expected as the amount of melt is expected to increase with higher grade (Sawyer, 2012). The transition from amphibolite to granulite facies is accompanied by a charnockitization process and a transition zone exists where there is a development of patchy charnockites. Similar developments described from India were attributed to influx of CO₂ thus reducing the activity of H₂O. This implies that dehydration reactions seen were probably the result of not only temperature increase but reduction in the activity of water in the area.

Reaction textures

In the charnockitic gneiss, within the granulite facies zone, biotite grains show corona texture and simplectic mineral intergrowth with pyroxene and opaques (Figures 17 and 18). These types of mineral intergrowth have been recognized as characteristic of granulite facies

rocks – particularly those that reached higher peak temperature (White and Powell, 2011). Reaction textures of this nature have been described as distinct spatial arrangements of minerals, typically comprising layers (coronae) and fine-grained mineral intergrowths (symplectites) that partially replace or separate coarser-grained minerals. Such textures can be inferred as evidence of change of mineral assemblage of a rock, occasioned by change in overprinted P–T conditions, or in some instances, externally controlled changes in chemical potentials as a result of some large-scale infiltration (Dunkley et al., 1999; Baldwin et al., 2005; White and Powell, 2010).

In Ikare area, the presence of these textural features in the charnockitic gneiss is in contrast with observed textures within the grey gneiss where relatively large idioblastic laths of biotite were observed to have sharp linear contacts with other minerals. The characteristic simplectic texture of biotite suggests that biotite is nucleating on pyroxene. Similar textural characteristic was shown to have occurred in some quarries of incipient charnockites from south India (Hanseck et al., 1984). Simplectic texture of this nature was described as a product of rehydration reaction in which water or fluid that was produced during the thermal peak is now reacting with the anhydrous mineral phases during cooling.

During prograde stage, as the temperature and pressure increases, hydrous phases such as biotite and

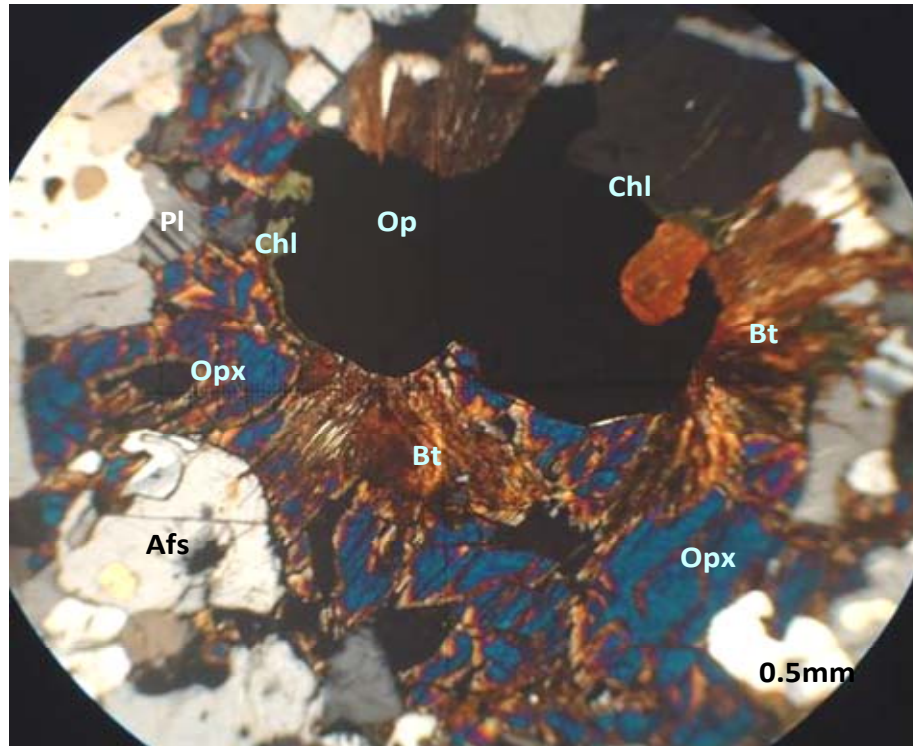


Figure 18. Corona texture in the patchy spot of grey gneiss with charnockite spots. Biotite (Bt), pyroxene (Opx), opaques (Op), plagioclase (Pl), alkali feldspar (Afs) and chlorite (Chl).

amphibole reacted to produce anhydrous phases (dehydration reaction). After reaching the thermal peak, during retrograde stage as the temperature dropped, remaining fluid that remains in the system or that percolate through some planes of weakness react with the anhydrous phases such as pyroxenes to produce hydrous phases (rehydration reaction).

Migmatization process

Winkler (1974) suggested that the production of melt of granite to granodioritic composition will most likely be accompanied by aluminosilicate formation such as sillimanite, cordierite and garnet. In the study area, the mineral paragenesis in the pelitic rock shows that the temperature of the rock was high enough to initiate partial melting and thus produce sillimanite, almandine garnet and cordierite. Thus, a viable mechanism for the production of migmatite in Ikare is through anatexis.

The pelitic rock outcrops as an east-west concordant band within the grey gneiss in the study area, the occurrence of which as an enclave, probably suggests that it is older than the quartzo-feldspathic gneiss and that the latter is igneous in origin. Pelitic gneiss indicates mineral assemblage made up of quartz + alkali feldspar + plagioclase feldspar + garnet + sillimanite + cordierite

+ opaque as observed in the paleosome and the neosome. This type of mineral assemblage indicates high temperature to medium pressure grade of metamorphism. Metamorphic reactions that characterize the transition from amphibolite facies to granulite facies in metapelites are commonly inferred to produce felsic partial melts in the crust (Thompson, 1982; Vielzeuf and Holloway, 1988; Brown, 1994; Brown et al., 1995; White et al., 2001, 2003). Such melting reactions represent a vital link between the P-T evolution of granulites and the melt production history of the middle to lower crust. This link is reflected in migmatite formation inferred to coincide with major mineral assemblage changes in high-grade rocks (White et al., 2004). For example, the breakdown of coexisting biotite and sillimanite to form garnet and cordierite will produce substantial volumes of melt as shown in equations 2 and 3 (Powell and Downes, 1990; Spear et al., 1999; White et al., 2001).

There are many examples in which there are complex textural relationships between the solid reactant and/or product of melt producing reactions and leucosomes (Waters and Whales, 1984; White et al., 2003). This textural relationship commonly involves a felsic segregation that hosts a ferromagnesian porphyroblasts such as garnet (Waters and Whales, 1984) and cordierite (Waters, 1988; Sawyer et al., 1999). The interpretation of textural signature of melting in migmatitic rocks is not

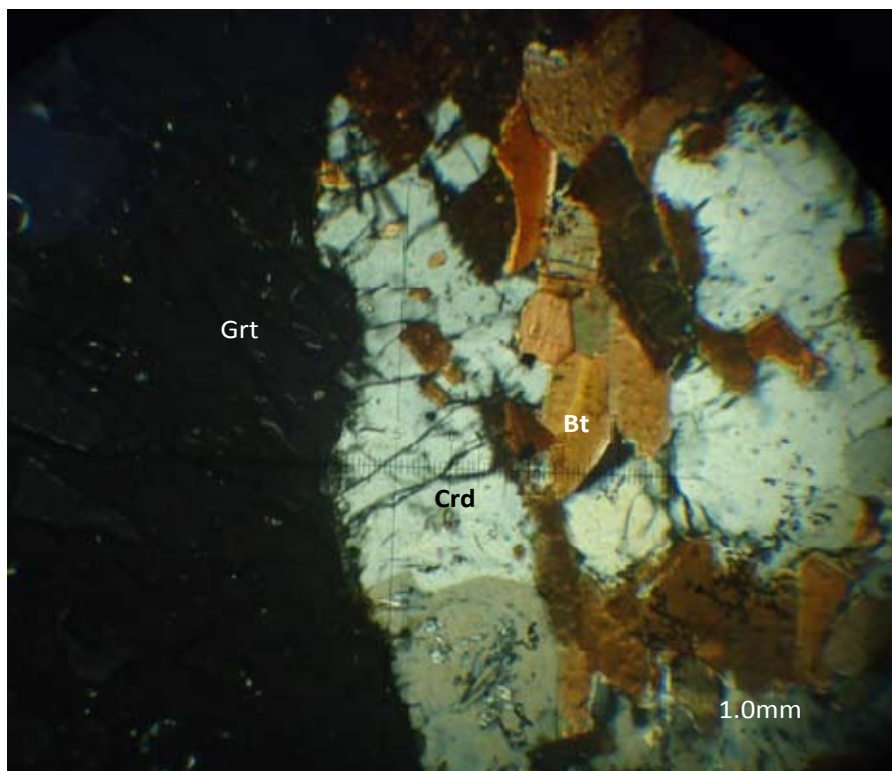
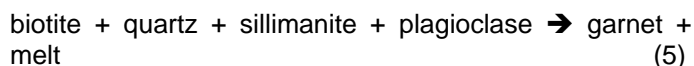
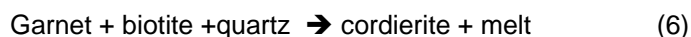


Figure 19. Rim of cordierite (Crd) around garnet (Grt)

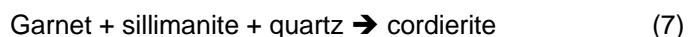
always straight forward (Sawyer, 1999) and the problem is greatest for widespread melting associated with regional metamorphism. In Ikare area, textural evidence in support of prograde anatexis is the reaction that produced garnet and probably the melts,



The above inference was drawn from inclusion of biotite, quartz, sillimanite and minute plagioclase in garnet. This was probably the first melt producing reaction, operating at moderately high pressure (Cenki et al., 2002). A possible second melt producing reaction is the coronas (rims) of cordierite around garnet (Figure 19). This probably took place at a lower pressure than the first melt producing reaction:



Scheuvs (2002) argued that the above reaction within resistive metapelites is not the result of back reaction as proposed by Spear et al. (1999) but are interpreted to result from the reaction,



Both reactions, Scheuvs (2002) argued are

characterized by a low pressure condition, pointing to persistent exhumation or uplift after deformation. The absence of orthopyroxene indicates that the conditions necessary for higher temperature orthopyroxene-producing dehydration melting reaction of biotite were not reached. The melt that was produced from both melt-producing reactions could either have migrated away from these sites or may have pooled there if the melt migration rate were substantially lower than the rate of melt production. Thus, rapid melt loss from the site of melt formation and melt accumulation at the site of melt formation may have occurred at the same time around different garnet grains. However, the high degree of preservation of the high-grade mineral assemblages is consistent with substantial loss of the melt fraction developed from the rocks, the timing and rates of melt loss being impossible to constrain.

Anatexis or partial melting is the most commonly invoked mechanism for migmatite formation (Ashworth, 1985). The availability of fluid or H₂O is the single most critical aspect to melt production (Johannes and Holtz, 1990); it may be sourced from a hydrous fluid, or the breakdown of a hydrous mineral such as muscovite, biotite or hornblende. The result of the addition of water to an anhydrous system is the lowering of the melting point at a given pressure. In Ikare area, there are enough petrographic evidences (discussed above) of presence and breakdown hydrous mineral phases like biotite and

amphiboles. This was observed in the quartzo-feldspathic gneiss and the pelitic gneiss.

Conclusion

The rock types differentiated in this study within the MGQC are: grey gneiss, charnockitic gneiss, granite gneiss, pelitic gneiss, porphyritic granite and quartzite. Minor rock types in the study area are the mafic and ultramafic components which are made up of basic schist and amphibolites. Combination of regional structural mapping through the application of remote sensing and GIS with detailed field mapping shows that the area was affected by at least four episodes of deformation D_1 , D_2 , D_3 and D_4 . The earliest deformation episode (D_1) is a rare E-W trending isoclinal fold which is at variance with the common north-south structural trend in the country. Petrographic studies also confirm that the area was affected by three episodes of metamorphism. The first metamorphic episode (M_1) produced the pre-tectonic garnet contemporaneously with the pervasive mineralogical banding. The second metamorphic event (M_2) gave rise to widespread breakdown of biotite to produce sillimanite and growth of syn-tectonic garnet. The last episode of metamorphism (M_3) is the development of post-tectonic garnet which overprints an existing foliation and enclosed earlier formed sillimanite. Petrographic studies further show that the mineral assemblage within the quartzo-feldspathic rocks changed from hydrous phases to anhydrous phases as one traverses from the southern part of the study area to the northern part. Reaction textures indicate that the transition zone between the amphibolite facies rocks and granulite facies rocks is achieved by a prograde dehydration reaction while rehydration reactions took place during the waning retrograde stage. Morphological characteristics of the migmatites shows that the amount of neosomes (leucosomes) are more in the southern area (Aiyegunle) than in the northern part (Ikare Area) contrary to what is expected as one moves from an area of lower metamorphic grade to area of higher metamorphic grade. This suggests that the nature of the transition was due to increase in temperature and / or reduction of fugacity of water from south to north. Dehydration reactions were promoted in the north where the water fugacity was relatively low.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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REFERENCES

- Ashworth JR (1985). Introduction. In: Migmatites. pp. 1-35. Blackie and Sons Ltd, Glasgow.
- Baldwin JA, Powell R, Brown M, Moraes R, Fuck RA (2005). Modeling of mineral equilibria in ultrahigh-temperature metamorphic rocks from the Anapolis-Itaucu Complex, central Brazil. *Journal of Metamorphic Geology* 23:511-531.
- Brown M (1994). The generation, segregation ascent and emplacement of granite magma: the migmatite-to-crustally derived granite connection in thickened orogens. *Earth-Science Reviews* 36:83-130.
- Brown M, Averkin YA, McLellan EL, Sawyer EW (1995). Melt segregation in migmatites. *Journal of Geophysical Research* 100:15655-15679.
- Cenki B, Kriegsman LM, Braun I (2002). Melt-producing and melt-consuming reactions in the Achankovil cordierite gneisses, South India. *Journal of Metamorphic Geology* 20:543-561.
- Dempster, AN (1966). 1:250,000 Nigerian Geological Survey Sheet 61. Geological Survey Nigeria Akure.
- Dunkley DJ, Clarke GL, Harley SL (1999). Diffusion metasomatism in silica-undersaturated sapphirine-bearing granulite from Rumdoodle Peak, Framnes Mountains, east Antarctica. *Contributions to Mineralogy and Petrology* 134:264-276.
- Eskola P (1933). On the differential anatexis of rocks. *Bulletin de la Commission Geologique de Finlande* 103:12-25.
- Ferré EC, Caby R (2006). Granulite Facies Metamorphism and Charnockite Plutonism: Examples from the Neoproterozoic Belt of Northern Nigeria. *Proceedings of the Geologists' Association - Geological Society of London* 118(1):47-54.
- Fountain DM, Salisbury MH (1981). Exposed cross-sections through the continental crust: implications for crustal structure, petrology and evolution. *Earth and Planetary Science Letters* 56:263-277.
- Hansek EC, Janardan AS, Newton RC, Prame WKBN, Ravindra KGR (1984). Arrested charnockite formation in southern India and Sri Lanka: *Contribution Mineral Petrol* 96:225-244.
- Harley SL (1989). The origin of granulites: A metamorphic perspective. *Geological Magazine* 126:215-247.
- Harlov DE, Johansson L, Van den Kerkhof A, Forster HJ (2006). The role of advective fluid flow and diffusion during localized solid-state dehydration: Sondrum Stenhuggeriet, Halmstad, SW Sweden. *Journal Petrology* pp. 3-33.
- Holland TH (1893). The petrology of Job Charnocks' tombstone; *Journal Asiatic Society Bengal* 62:162-164.
- Holland TH (1900). The Charnockite series, a group of Archean hypersthenic rocks in Peninsular India. *Memoirs of the Geological Survey of India* 28:119-249.
- Howie RA (1955). The geochemistry of the charnockitic series of Madras, India. *Transaction of the Royal Society of Edinburgh* 82:725-769.
- Janardhan AS, Newton RS, Smith JV (1979). Ancient crustal metamorphism at low P_{H_2O} : charnockite formation at Kabbaldurga, south India. *Nature* 278:511-514.
- Janardhan AS, Newton RS, Hansen EG (1982). The transformation of amphibolites facies gneiss to charnockite in southern Karnataka and northern Tamil Nadu, India. *Contribution to Mineralogy and Petrology* 79:130-139.
- Janardhan AS, Jayananda M, Shankara MA (1994). Formation and tectonic evolution of granulites from the Biligirirangan and Nilgiri Hills, South India: Geochemical and isotopic constraints. *Journal of Geological Society of India* 79:27-40.
- Johannes W, Holtz F (1990). Formation and composition of H_2O -undersaturated granitic melts. In: JR Ashworth, M Brown (Ed.). High-temperature metamorphism and crustal anatexis. *The Mineralogical Soc. Series 2*. Unwin Hyman, London, pp. 87-104.

- Lee SR, Cho M (2003). Metamorphic and Tectonic Evolution of the Hwacheon Granulite Complex, Central Korea: Composite P-T Path Resulting from Two Distinct Crustal-Thickening Events. *Journal of Petrology* 44(2):197-225.
- Markku V, Pentti H (1999). Structural and metamorphic evolution of the Turku migmatite complex, southwestern Finland. *Bulletin of the Geological Society*
- Merhnet KR (1968). *Migmatites and the origin of granitic rocks*, Elsevier, Amsterdam.
- Miyashiro A (1994). *Metamorphic Petrology*. Oxford University Press, New York.
- Newton RC (1992a). An overview of charnockite; *Precambrian Research* 55:399-405.
- Newton RC (1992b). Charnockite alteration: evidence for CO₂ infiltration in granulite facies metamorphism. *Journal Metamorphic Geology* 10:383-400.
- Ocan OO (1991). The Petrology of Rocks around Idanre Area, South-Western Nigeria, Ph.D. Thesis, Obafemi Awolowo University, Ile-Ife, Nigeria, Unpublished.
- Olawejun VO (1987). Charnockite - granite association in SW Nigeria: rapakivi granite type and charnockitic plutonism in Nigeria? *Journal of African Earth Sciences* 6:67-77.
- Oyawale AA, Adeoti FA, Ajayi TR, Omitogun AA (2020). Applications of Remote Sensing and Geographic Information System (GIS) in Regional Lineament Mapping and Structural Analysis in Ikare Area, Southwestern Nigeria. *Journal of Geology and Mining Research* 12(1):13-24. DOI.10.5897/JGMR2019.0310
- Percival JA, Fountain DM, Salisbury MH (1992). Exposed crustal cross sections as windows on the lower crust. In: Fountain, D. M., Arculus R, Kay RW (eds) *Continental Lower Crust, Developments in Geotectonics*, 23. Amsterdam: Elsevier, pp. 317-362.
- Powell R, Downes J (1990). Garnet porphyroblast bearing leucosomes in metapelites: mechanism and an example from Broken Hill, Australia. In: *High Temperature Metamorphism and Crustal Antaxis* (eds Ashworth JR, Brown M), The Mineralogical Society Series 2 London. Unwin-Hyman. pp. 105-123.
- Pichamuthu CS (1960). Charnockite in the making. *Nature* 188:135-136.
- Rahaman MA (1976). Review of the basement geology of Southwestern Nigeria. In Kogbe, C.A. (ed.): *Geology of Nigeria*. Elizabethan Pub. Co. Lagos. pp. 41-58.
- Rahaman MA (1988). Recent advances in the study of the basement complex of Nigeria. In: PO Oluyide, WC Mbonu, AE Ogezi IG Egbuniwe, A.C. Ajibade and A.C. Umeji (eds.), *Precambrian Geology of Nigeria*. Geological Survey of Nigeria, Kaduna, pp. 11-41.
- Rahaman MA, Ocan OO (1988). Nature of granulite facies metamorphism in Ikare area, southwestern Nigeria. In: Oluyide PO, Mbonu W, Ogezi AE, Egbuniwe IG, Ajibade AC, Umeji AC (eds), *Precambrian Geology of Nigeria*, Geological Survey of Nigeria, pp: 157-163.
- Ramsay JG (1967). *Folding and Fracturing of Rocks*, McGraw hill, New York. 568 p.
- Ravindra Kumar GR (2004). Mechanism of arrested charnockite formation at Nemmara, Palghat region, southern India. *Lithos* 75:351-358.
- Sawyer EW (2012). *Atlas of Migmatites*. The Canadian Mineralogist, Special Publication 9. NRC Research Press, Ottawa, Ontario, Canada, 371p.
- Sawyer EW, Dombrowski C, Collins WJ (1999). Movement of melt during synchronous regional deformation and granulite- facies anatexis, an example from the Wuluma Hills, Central Australia. In: *Understanding Granites: Intergrating New and Classical Techniques*, Special Publication, 158 (eds Castro, A., Fernandez C, Vignersse JL), pp. 221-237, Geological Society, London.
- Scheuven D (2002). Metamorphism and microstructure along a high temperature metamorphic field gradient: the north-eastern boundary of the Kralovsky hvozdz unit (Bohemian Massif, Czech Republic) *Journal of metamorphic Geology* 20:413-428.
- Spear FS, Kohn MJ, Cheney JT (1999). P-T paths from anatectic pelites. *Contributions to Mineralogy and Petrology* 134:17-32.
- Srikantappa C, Raith M, Spiering B (1985). Progressive charnockitization of a leptynite-khondalite suite in Southern Kerala, India – evidence for formation of charnockites through decrease in fluid pressure. *Journal of the Geological Society of India*. 26:849-872.
- Srikantappa C, Raith M, Touret JLR (1992). Synmetamorphic high-density carbonic fluids in the lower crust: Evidence from the Nilgiri granulite, South India. *Journal of Petrology* 33:733-760.
- Thompson AB (1982). Dehydration melting of politic rocks and the generation of H₂O undersaturated granitic liquids. *American Journal of Science* 282:1567-1595.
- Thompson AB, Ridley JR (1987). Pressure–temperature–time (*P–T–t*) histories of orogenic belts. *Philosophical Transactions of the Royal Society of London, Series A* 321:27-45.
- Vielzeuf D, Holloway JR (1988). Experimental determination of the fluid-absent melting relations in the politic system. Consequences for crustal differentiation. *Contributions to Mineralogy and Petrology* 98:257-276.
- Waters DJ (1988). Partial melting and the formation of granulite facies assemblages in Namaqualand, South Africa. *Journal of Metamorphic Geology* 6:387-404.
- Waters DJ, Whales CJ (1984). Dehydration melting and the granulite transition in metapelites from southern Namaqualand, South Africa. *Contributions to Mineralogy and Petrology* 88:269-275.
- White RW, Powell R (2010). Retrograde melt-residue interaction and the formation of near-anhydrous leucosomes in migmatites. *Journal of Metamorphic Geology* 28:579-597.
- White RW, Powell R (2011). On the interpretation of retrograde reaction textures in granulite facies rocks. *Journal of Metamorphic Geology* 29:131-149.
- White RW, Powell R, Holland TJB (2001). Calculation of partial melting equilibria in the system Na₂O-CaO-K₂OFeO- MgO-Al₂O₃-SiO₂-H₂O (NCKFMASH). *Journal of Metamorphic Geology* 19:139-153
- White RW, Powell R, Clarke GL (2003). Partial melting at low pressures: Migmatites from Mt Stafford, central Australia. *Journal of Petrology* 44:1937-1960.
- White RW, Powell R, Halpin JA (2004). Spatially-focused melt formation in aluminous metapelites from Broken Hill, Australia. *Journal of Metamorphic Geology* 22:825-845.
- Winkler HGF (1974). *Petrogenesis of Metamorphic Rocks*. Springer, Berlin, 320 p.