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Further Evidences of Cataclasis in the Ife-Ilesa Schist Belt, Southwestern Nigeria.

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Abstract
The studied rock types form part of the lithologic unit of the Ife-Ilesa schist belt. The exposures of the rocks were studied in the field for their field relations, structure, texture and mineralogy and in the laboratory for their mineralogy, texture and micro-structure. Further analysis of the photomicrographs was carried out with "*ImageJ*" software. The results of the study complement each other. Field observation shows porphyroclasts of quartz and feldspar in fine-grained groundmass, mineral segregation and bands that are asymmetrically folded for study site 1 while it shows whitish rock with dark spots indicative of ground and congealed rock for study site 2. The rock exposed in study site 1 exhibited joints in various directions while that in study site 2 exhibited joints in two directions. The petrographic study reveals porphyroclastic texture, mineral segregation, rotated large grains, broken/jagged margins of the large grains and the growth of post deformational minerals in site 1 and in study site 2; it revealed textural characteristic that is similar to that of the rock in site 1, broken/jagged boundaries of the large quartz grains as in site 1, micro-fault, preferred orientation of grains and presence of new mineral grains. "*ImageJ*" revealed the same observations as the petrography as well as widest range (statistical) for minerals that fall into the minimum category, shortest range for minerals that fall into the maximum category and similarity between very coarse and fine grains. The very wide range of minimum and low range of maximum when compared with other rock types indicate uncoordinated production of the fine-grained materials and crushing effect of high pressure on the large grains, respectively. These observations point to shearing, crushing and grinding due to cataclasis. The similarity between large and fine crystals indicates that they are products of the similar parentage. The fabric revealed by this work points to the mylonitization of the rocks. The results of the study point to relic cataclastic fabric in a completely reconstituted rock. It is inferred that at least two episodes of high pressure metamorphism might have affected the rock. It is also inferred that the rocks experienced an episode of the chemical reconstitution with the attendant formation of new minerals. The rocks and by extension parts of the Ife-Ilesa schist belt must have experienced cataclastic metamorphism. The rocks can therefore be classified as mylonites.
Keywords: Cataclasis; Mylonite; Porphyroclasts; *ImageJ*; Ife-Ilesa.

1. Introduction

The geology of Ife-Ilesa schist belt has been studied by Hubbard (1975), Elueze (1977), Ajayi (1981) and Rahaman and Ajayi (1988). The last authors recognized two contrasting lithologies separated by the Ifewara fault system. The eastern lithology is composed of metasediments dominated by quartz muscovite schist, quartz schist, quartzites, quartzo-feldspathic gneisses and biotite garnet schist. The western group consists of volcano sedimentary sequence of pelitic schists, quartzites and metabasites or mylonites. The entire area has been affected by polycyclic episodes of deformation and metamorphism (Odeyemi, 1981).

Structures are well developed in the rocks of the area. Boesse and Ocan (1988) recognised two phases of deformation which produced folds of variable styles and large vertical fault zones in most rocks of the area. The area can be divided into two contrasting structural domains (Onyedim and Ocan, 2001). The NNE-SSW trending shear system (the Ifewara fault zone) in which the main structure is a NNE-SSW trending mylonitic foliation. This corresponds to the cataclastic rocks in the study area. Lithological units that include ridges of quartzite and quartzo-feldsparthic gneisses are parallel to this shear zone. The other dominant structures are NNW-SSE trending. It is interesting to note that an attempt to locate the study sites on the Geological Map of Okemesi Fold Belt (odeyemi, 1993) indicated that the study sites plot within the fault zone and close to one of the fault traces of the map.

In general, the major petrological units recognized in the area by Elueze (1988) and Odeyemi (1993) include migmatites, gneisses, amphibolites and metaclastics. The amphibolites occur as lenticular bodies of different varieties within Ife-Ilesa area while the metaclastics comprise strongly sheared varieties of mylonites and biotite schists. The quartzitic sequence occurs as massive quartzites, schistose quartzites and quartz schist (Anifowose and Borode, 2007). They also reported the existence of a series of faults that offset the fold trend as well as the display of strong foliation and shearing by the schists and schistose quartzites (an indication of displacements along sub-parallel planes). Anifowose *et al*., (2010), reported that the Ifewara fault has been traced and identified as the southern extension of the Zungeru fault in the northern part of Nigeria. The Ifewara-Zungeru fault zone which extends for about 550km within Nigeria is also believed to be continuous into the northern part of Africa.

The field evidence of the fault that separates these contrasting lithologies has initially been restricted to Ifewara area where narrow cataclasite of talcose has been identified (Rahaman and Ajayi, 1988). In this study, we present the petrographic evidence of occurrence of other cataclastic rocks (mylonites) in Ilesa area. The build-up of the knowledge of the geology of the Ife-Ilesa schist belt will be enhanced by this study.

2. Regional Geological Setting

The basement complex forms an important domain of the Pan-African mobile belt east of West African craton, south of Tuareg shield and northwest of Congo craton. The mobile belt extends from the Hoggar through Air, Adrar des Iforas and Gourma (Algeria) to the Dahomeyides in Ghana, Togo, Benin, Nigeria and Cameroon. The Dahomeyide fold belt constitutes the southern portion of the mobile belt. From the southeastern margin of West African craton eastwards, three major tectonic domains are present: the Voltain foreland basin with sedimentary sequences, the Beninian thrust and fold belt; and the Nigerian high grade migmatite-gneiss terrane. The rocks in the basin rest unconformably on the shield and progressively folded and metamorphosed westwards.

Plate tectonics models have been used to explain the evolution of this Pan-African belt. Burke and Dewey (1973) suggested that Dahomeyide fold belt evolved from the closure of an Atlantic Ocean type by continent-continent collision between passive western continent of Birrimia and active eastern continent of Dahomea. Continental fragmentation commenced in ca 1100 Ma and by ca 900 ± 100 Ma a paleo-ocean had developed east of the West African craton. The closure of the ocean began with subduction processes operating along an eastward dipping Benioff Zone. This was marked by widespread calc-alkaline volcanisms which are similar to those of modern day island arcs and active continental margins (Affaton *et al*., 1991). Behind the possible Pan-African arc were several often fault bound Pan-African volcano sedimentary sequences which latter evolved to schist belts among which is the Ife-Ilesa schist belt of southwestern Nigeria.

The Nigerian sector consists of two main areas: the Beninian gneisses and migmatite-gneiss. The gneisses are of high grade amphibolite facies, generally, consisting predominantly of quartzo-feldspathic and anatectic migmatitic granitoids.

3. Materials And Methods

Samples of the rock in study site 1 (N07^{0}37'06.7'', E004^{0}48'57'') were collected and labelled Il001 while those from study site 2 (N07^{0}37'05.4'', E004^{0}48'50.8'') were Il002. Thin sections were prepared and studied with the petrographic microscope. Twenty-two photomicrographs taken from the thin sections of the rocks were analysed with "*ImageJ*". Ten photomicrographs each of four other rock types [Akure gneiss (Ak002), Akure granite gneiss (Ak004), Akure and Igarra porphyritic granite (Ak003 and Ig005) and Igarra lamprophyre (Ig009)] were also analysed with "*ImageJ*" for the purpose of comparing the results with those of the rocks being studied.

Analyses of the photomicrographs with "*ImageJ*", were done as follows: (i) to view and trace the grains of the rock: Click *File* → *open* → then select file and the photomicrograph → *Process* → *Find Edges* and (ii) for the histogram: Go to *Analyze* and select *Histogram* which is displayed alongside the following statistical parameters: area [referred to as count (in pixels) in the software], mean, standard deviation, minimum, maximum and mode. Equal counts ensure that equal areas of the different photomicrographs were analysed for the purpose of comparison.

4 Results And Discussion

4.1 Mode of Occurrence and Field Characteristics

The The rocks exposures were encountered at the road-cut at the Iloko-Ijesa end of the Ibadan-Ife-Ilesa expressway (Fig.1). They form part of the major petrologic units of the Ife-Ilesa schist belt. They are in contact with the quartzite and the metaclastics (Elueze, 1988). They trend N-S and has minor joints of diverse trends. Site 1 consists of fine groundmass of mafic minerals with coarse and strained crystals of pinkish microcline and quartz. Bands or streaks that are irregular in width (ranging from about 8 to 50cm), consisting predominantly of pinkish microcline which are asymmetrically folded occur in the rock (Fig.2). The rock is generally dark coloured with pinkish and whitish tints of microcline and quartz. Site 2 consists of whitish or grayish coloured rock. The rock which is not difficult to de-aggregate is dotted with dark tints. Two sets of joints trending approximately N-S and E-W with those trending E-W predominating were recorded on the exposure (Fig.3). Powdery substances were observed in the grain contacts. Quartz was the major mineral identifiable in the hand specimens (Fig.3). The study of (i) the exposure, (ii) the hand specimen and (iii) the plotting of the location coordinate on the map suggests that the rock is a part of the quartzite schist described by Odeyemi (1993). Field observations of the Zungeru and Ilesa mylonites show a lot of similarities but the former seems to have experienced higher level of reconstitution. Therefore the mylonites of Ilesa are believed to have experienced similar tectonics like the Zungeru mylonites.

4.2 Petrography

Hornblende, microcline, biotite, quartz, plagioclase and opaque minerals constitute the main minerals in the thin sections of the rock in site 1. Large crystals of plagioclase feldspar and quartz in very fine groundmass of plagioclase, microcline, quartz and hornblende were recognized. The very fine groundmass of sheared, crushed and granulated minerals; the rotated large grains with broken/jagged margins, and the irregular shapes of the grains indicate porphyroclastic texture. The foliation is indicated under the microscope by the flow around the relic minerals (Fig.4). Hornblende exhibits prismatic form, high relief and cleavage in one direction. There is an association of dark minerals with the grains of hornblende. Microcline exhibits micro cracks, cross-hatched twinning and high relief. Biotite has high relief, flaky/lath-like form and cleavage in one direction. Some biotite grains cut across other grains indicating that the growth was post deformational (Fig. 4c). Some of the grains of quartz are very fine while others are coarse. Plagioclase contains inclusions of quartz and exhibits both carlsbad and albite twinning. Generally, the minerals have irregular shapes with sutured boundaries.

Antiperthitic texture and micro-banding or segregation of quartzo-feldsparthic as well as mafic minerals were also observed (Fig. 4a and b).

The thin sections of the rock in site 2 revealed that quartz is the main mineral identified under the microscope. Some of the quartz grains are relatively coarse grained in very fine groundmass. Some of the large quartz grains show broken/jagged boundaries indicative of rotation under high pressure. New generation biotite fills pre-existing discontinuities. The main structure identified in the thin sections of the rock is micro-faults. Coarse grained minerals, which are observed to be survivors of grinding and shearing, show preferred orientation (Fig.5) defining the foliation of the rock.

4.3 Image Analysis with "ImageJ"

(i) Rock Fabric The analysis of the images (photomicrographs) of the rock exposed in site 1 reveals a pattern that resembles a flow around a stirrer which is an indication that the rotation of the porphyroclasts most likely resulted in such a structure. The large crystals exhibit broken/jagged margins or boundaries which were most likely caused by the rubbing of their boundaries as they rotate under high pressure (Fig.6). This is an indication that the minerals have probably experienced crushing and granulation. The similarity in mineralogy displayed by the very fine and very large grains suggests that they are most likely products of the same parentage which grains suffered size reduction as a result of crushing and granulation.

The very fine grains show elongation with a trend that aligns with the rock foliation suggesting that the rock has experienced more than one stress regime. The segregation of quartzo-feldsparthic and mafic minerals which is an indication of stress also supports the more than one stress regime that the rock probably experienced. The disruption of the foliation or banding by the large grains is also in support of more than one stress regime experienced by the rock.

(ii) Grain Trace and Histogram Plot. The edges or boundaries of the grains were traced (Fig.6) and the histograms of the grain-counts were plotted (Fig.7) with "*ImageJ*". The histograms were analysed and the results summarized making it possible to compare the mylonites with gneiss, granite gneiss, porphyritic granite and lamprophyre.

The outcome is as outlined below:

All the histograms plotted from the grain count of the photomicrographs of the mylonites show a single peak (unimodal) with the mode (statistical) falling into the fine-grained area while other rock types except lamprophyre which share similar textural characteristics with the mylonites have several peaks (multi-modal) and higher average mode (Fig. 7) (Tables 1&2). The analysis of the histograms shows that the mylonites have very large grain sizes like the other rock types. The histograms further show them having maximum values which is an indication of very large crystals in the rock. The range of the maximum [253-255 (Table 2)] is the narrowest and highest compared with those of the other rock types. The minimum shows the mylonite having the widest range (0-14) compared with all other rock types indicating a peculiarity of uncontrolled development of the finest grains (texturally) as a result of crushing and shearing. These further support the idea that the studied rocks experienced shearing, crushing and granulation due to cataclasis. Indications from the minimum and maximum values as well as the broken/jagged edges of the grains point to the fact that the rocks exhibit porphyroclastic texture.

The field observations and petrographic studies revealed extremely fine grained groundmass which is in conformity with the explanation of Garg (2003) that cataclastic structure is characterised by the development of extremely fine mass under the influence of severe crushing and shearing effects of dynamic metamorphism. Turner and Verhoogen (1960) in the course of describing cataclasites explained that with decrease in grain size and development of banded structure, cataclasites grade into mylonites. This therefore, supports the band or streak of microcline observed in the rock which also serves as an additional indication that the rock has indeed experienced cataclastic metamorphism. Microscopically, the rock exhibits porphyroclastic texture as it reveals large crystals of quartz and feldspar with broken/jagged margins in extremely fine grained groundmass in site 1 and large grains of quartz, with broken/jagged margins, in fine grained groundmass in site 2. Analysis with "*ImageJ*" also lends support that the rocks possess porphyroclastic texture. This textural characteristic is a further indication of cataclastic metamorphism as it shows that the grains have experienced rotation, granulation, shearing and crushing. The micro-banding or mineral segregation as seen in the thin sections of site 1 and the preferred orientation as seen in the thin sections of site 2 as well as the foliation are indications of high pressure metamorphism.

In line with field observation and petrography, it is believed that the image analysis of the photomicrographs gave indications that the rocks have experienced (i) shearing, crushing and granulation under high pressure, (ii) banding as well as foliation and (iii) preferred orientation. It is further believed that the rocks have probably experienced more than one episode of high pressure metamorphism in line with the suggestion of Odeyemi (1981).

It is considered in this study that the cataclastic metamorphism experienced by the rocks in this area and by extension the Ilesa schist belt, is a result of the earth movement which culminated in the development of Iwaraja fault that has been variously reported (Ajibade *et al*., 1979, Odeyemi, 1993, Anifowose and Borode, 2007; Anifowose *et al*., 2010, Kolawole and Anifowose, 2011). The adapted map of Odeyemi (1993) (Fig.1) shows that the study sites plotted within the Iwaraja fault zone thereby further confirming the field and petrographic observations as well as the results of image analysis.

It can be inferred that the rocks might have experienced more than one episode of high pressure metamorphism in that the development of broken/jagged margins of the rotated large grains as well as that of the very fine groundmass (the period of crushing, shearing and granulation) are most likely the products of one episode while the development of foliation, bands or streaks and folding as well as preferred orientation most likely represent the products of another episode. The development of the biotite flakes that fill discontinuities as well as cut across other minerals grains most likely represent the stage of chemical reconstitution of the rock.

Garg (2003) explained that cataclastic structure is characterised by the development of extremely fine rock mass under the influence of severe crushing and shearing effects of dynamic metamorphism. Turner and Verhoogen (1960) explained that the activity of cataclastic metamorphism can be inferred without ambiguity from the nature of the fabric which they imprint upon the affected rocks. In this light therefore, the textural and structural features identified in these rocks constitute evidences which make it possible to infer that the rocks have experienced cataclastic metamorphism. On the basis of the recognition of relic cataclastic fabric and the evidences of reconstitution, the rocks are therefore believed to be mylonites.

5. Conclusion

In conclusion, (i) the field observation, fabric and the outcome of the image analysis of the photomicrographs using "*ImageJ*" show unambiguously that, the rocks and consequently the Ilesa schist belt, experienced cataclastic metamorphism; (ii) it is believed that the rocks might have experienced more than one episode of high pressure metamorphism; and (iii) the rocks have been mylonitized.

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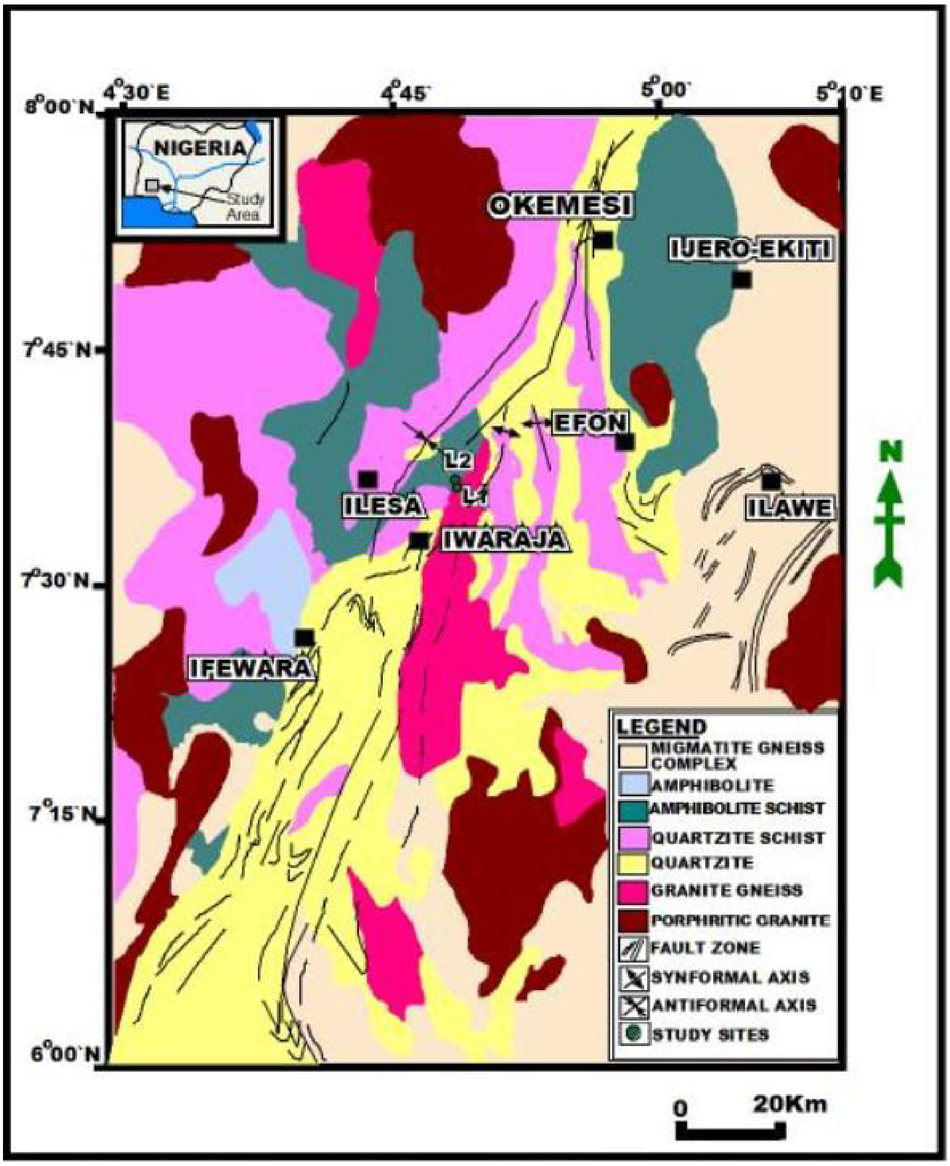

Fig.1: Geological Map of Okemesi Fold Belt Showing Study Sites (Adapted from Odeyemi, 1993).

Fig.2: Field Photograph of Mylonite (Site1), Ilesa, showing the folded bands {Pen (arrowed) is 15cm long}.

Fig.3: Field photograph of Mylonite (site 2), Ilesa, showing joints and dotted tints of mafic minerals.

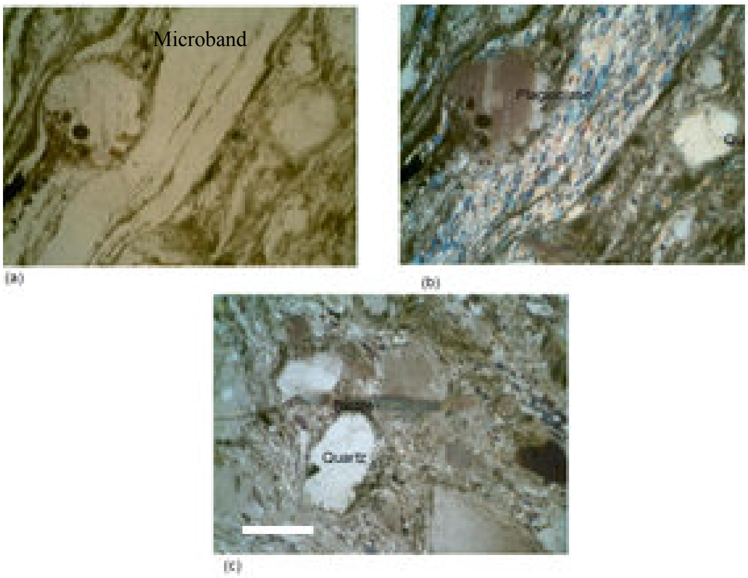

Fig.4: Photomicrograph of Mylonite (Il001) showing (i) micro-banding, (ii) rotated grains and (iii) large grains in fine granulated groundmass. (a) ppl, (b) CN and (c) post deformation biotite (CN). X100. Bar scale: 2um.

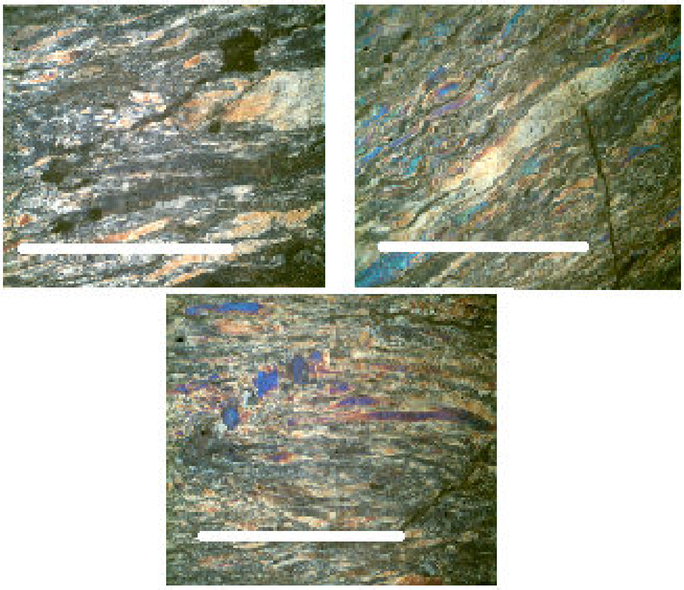

Fig.5: Photomicrograph of Mylonite (Il002) showing (i) micro-fault, (ii) preferred orientation of grains and (iii) new greenish flakes of biotite. All photomicrographs are under CN. X100. Bar scale: 1mm.

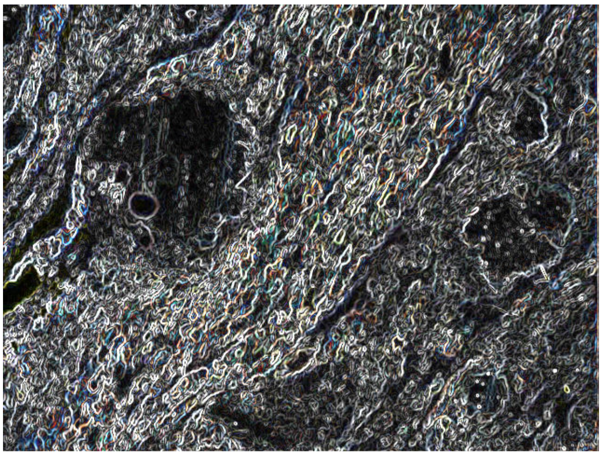

Fig.6: Trace of the edges of the grains in the photomicrograph of Mylonite (Il001) with "ImageJ".

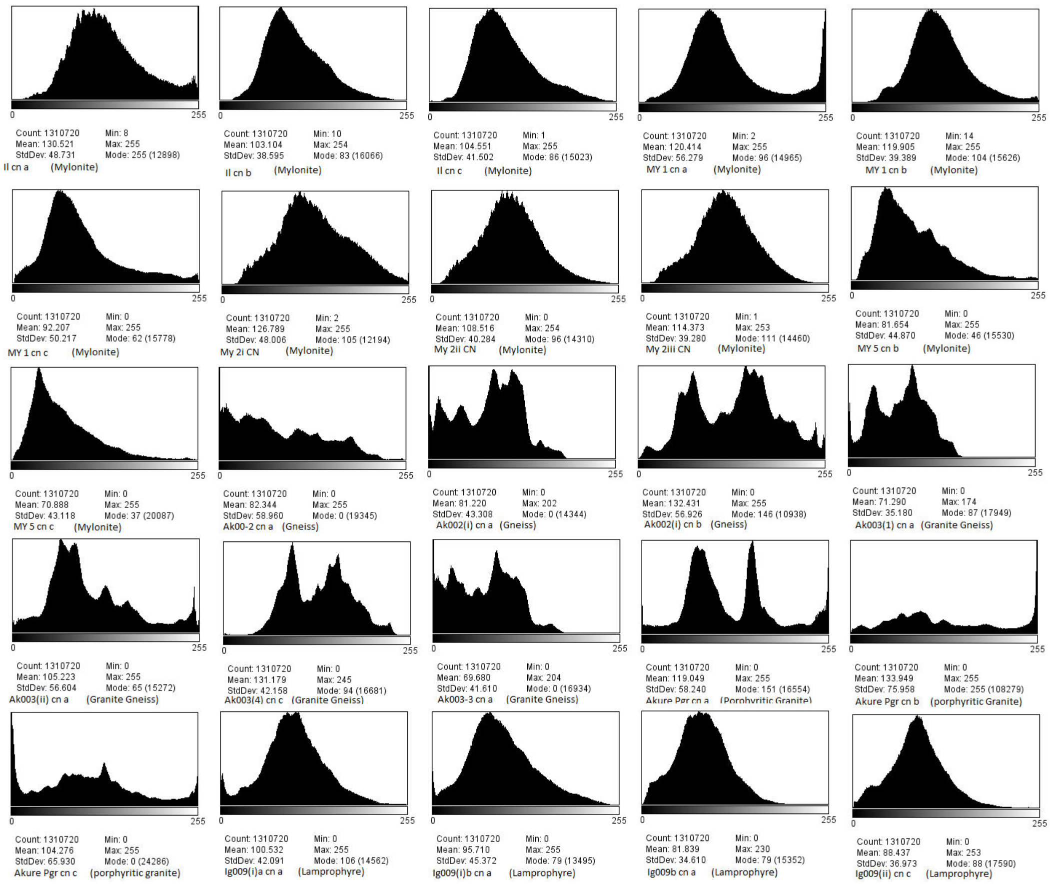

Fig. 7: Histogram plot of the grains of Mylonites compared with those of gneiss, granite gneiss, porphyritic granite and lamprophyre using "*ImageJ*".

Table 1: Analysis of Histogram

S/No	Specimen Code	Rock Type	Area (Pixels)	Mean	Std. Dev.	Min.	Max.	Mode
1.	IL cn a	Mylonite	1310720	131	48.7	8	255	255
2.	IL cn b	Mylonite	1310720	103	38.6	10	254	83
3.	IL cn c	Mylonite	1310720	105	41.5	1	255	86
4.	MY 1 cn a	Mylonite	1310720	120	56.3	2	255	96
5.	MY 1 cn b	Mylonite	1310720	120	39.4	14	255	104
6.	MY 1 cn c	Mylonite	1310720	92	50.2	0	255	62
7.	My 2i CN	Mylonite	1310720	127	48.0	2	255	105
8.	My 2ii CN	Mylonite	1310720	109	40.3	0	254	96
9.	My 2iii CN	Mylonite	1310720	114	39.3	1	253	111
10.	MY 5 cn b	Mylonite	1310720	82	44.9	0	255	46
11.	MY 5 cn c	Mylonite	1310720	71	43.0	0	255	37
1.	Ak00-2 cn a	Gneiss	1310720	82	59.0	0	255	0
2.	Ak002(i) cn a	Gneiss	1310720	81	43.3	0	202	0
3.	Ak002(i) cn b	Gneiss	1310720	132	56.9	0	255	146
4.	Ak002-3 cn a	Gneiss	1310720	127	64.0	0	255	255
5.	Ak002-2 cn c	Gneiss	1310720	75	48.0	0	220	2
1.	Ak003(1) cn a	Granite Gneiss	1310720	71	35.0	0	174	87
2.	Ak003(ii) cn a	Granite Gneiss	1310720	105	56.6	0	255	65
3.	Ak003(4) cn c	Granite Gneiss	1310720	131	42.2	0	245	94
4.	Ak003-3 cn a	Granite Gneiss	1310720	70	41.6	0	204	0
5.	Ak003(5) cn c	Granite Gneiss	1310720	128	47	0	250	135
1.	Akure Pgr cn a	Porphyritic Granite	1310720	119	58.2	0	255	151
2.	Akure Pgr cn b	Porphyritic Granite	1310720	134	76.0	0	255	255
3.	Akure Pgr cn c	Porphyritic Granite	1310720	104	65.9	0	255	0
4.	Pgr Igarra cn a	Porphyritic Granite	1310720	142	58.0	2	255	201
5.	Pgr Akure cn a	Porphyritic Granite	1310720	112	50.0	0	238	155
1.	Ig009(i)a cn a	Lamprophyre	1310720	101	42.1	0	255	106
2.	Ig009(i)b cn a	Lamprophyre	1310720	96	45.4	0	255	79
3.	Ig009b cn a	Lamprophyre	1310720	82	34.6	0	230	79
4.	Ig009-03 cn b	Lamprophyre	1310720	88	37.0	0	253	88
5.	Ig009(iii) cn a	Lamprophyre	1310720	14	51	0	255	108

Table 2: Summary of Analysis of histogram

S/No	Rock Type	Range of Means	Mean of Means	Range of minimum	Range of maximum
1.	Mylonite	71-131	107	0-14	253-255
2.	Gneiss	75-132	99	0	202-255
3.	Granite gneiss	70-131	101	0	174-255
4.	Porphyritic granite	104-142	122	0-2	238-255
5.	Lamprophyre	82-114	96	0	230-255