Studies of Rock Magnetic Properties of Kufena Hill in Zaria Area
Northern Nigeria

1Oniku, S. A., 2Lawal, K. M. and 3Osazuwa, I. B

1Department of Physics, Federal University of Technology, Yola
2Department of Physics, Ahmadu Bello University, Zaria
3Federal University of Petroleum Resources, Efurun, Warri,

Corresponding Author: Oniku, S. A

Abstract
The rock of Kufena hill belongs to the Pan African orogeny and its existence is derived from the Zaria batholith. A study of the magnetic properties of the rocks of the Kufena hill was carried out with the aim of identifying the magnetic minerals controlling the magnetic susceptibility of rocks in the study area. A total of 18 oriented core samples spread across the hill were collected using a portable gasoline powered, water cooledacker drill fitted with one inch diameter diamond drill bit. The core samples were long enough to yield at least two specimens, giving a total of 36 specimens of dimensions 25 mm by 22 mm (standard paleomagnetic samples). The parameters investigated are: the concentration of magnetic minerals in the rock; the magnetic susceptibility and anisotropy of magnetic susceptibility. The result of this research work shows that the major mineral controlling the magnetic susceptibility in the study area is biotite. It has an average magnetic susceptibility value of 69.0 ± 0.62 x 10^-6 SI and the percentage concentration of magnetite was found to be about 17.94%. The research has also shown that the AMS ellipsoid, which is oblate, is controlled by the crystalline anisotropy of biotite, indicating that the shape parameter T depends to a large extent on magnetic carrier. The degree of anisotropy P was found to be fairly moderate with an average value of 1.085 ± 0.5. The magnetic fabric parameter (Lineation L, foliation F, and the shape parameter, T) within the site does not vary significantly, showing a uniform composition of minerals. The lineation has an average value of 1.0548 and the shape parameter is generally positive with a mean value of 0.358.

Keywords: Kufena hill, degree of anisotropy, fabric parameters, magnetic minerals, rock

INTRODUCTION
Rocks are generally regarded as a heterogeneous assemblage of minerals. The matrix minerals are mainly silicates or carbonates, which are diamagnetic in character (Lowrie, 1990). Interspersed in this matrix is a lesser quantity of secondary minerals (such as clay minerals) that have paramagnetic properties. The bulks of the constituent minerals in a rock contribute to the magnetic susceptibility but do not contribute to remanent magnetic properties, which are due to a dilute dispersion of ferromagnetic minerals (Lowrie, 1990). The variable concentrations of ferrimagnetic and matrix minerals result in a wide range of susceptibilities in rocks (Fig. 1).

The weak and variable concentrations of ferromagnetic minerals have been found to play a key role in the determination of the magnetic properties of rock that are significant geologically and geophysically (Tarling and Hrouda, 1993; Ellwood, 1978; Rochette et al., 1992). The most important factor influencing rock magnetism is the type of ferromagnetic minerals, its grain size and the manner in which it acquires a remanent magnetization, which is the magnetization acquired as their constituent magnetic minerals pass through their Curie or Neel temperatures.

Mineral magnetism derives its origin from the pioneering works given in the bench mark text by Thompson and Oldfied (1986). It investigates the inherent magnetic mineralogy and granulometry of natural samples without taken into consideration the intensity and direction of the earth’s magnetic field as recorded by the natural remanent magnetization of rocks and sediment samples. Thus, the magnetic parameters used in mineral magnetism are independent of the earth’s magnetic field at any point and are largely a function of the volume of magnetic minerals (O’Reilly, 1976).

The intention of this paper is to study rock magnetic properties of the rocks in Kufena hill, Zaria, granite intrusive which form part of the extensive Zaria batholith (Fig. 2), with a view to determining the minerals present within the study and their concentrations by measuring the magnetic susceptibility and the anisotropy of magnetic susceptibility.
Fig. 1: (a) Median values and ranges of the magnetic susceptibility of some common rock types, and (b) the susceptibilities of some important minerals (After, Lowrie 1990)

Geological Settings, Rock types, Structures and Sampling
The Older Granite inselbergs, whalebacks, granite pavements and isolated blocky mounds found in Zaria (Fig.2) and its surrounding regions are currently regarded as outcrops of a single batholith. This batholith initially known as the “Zaria granite” is one of a number of elongated north-south oriented granite bodies concordantly emplaced in the pre-existing gneisses of the Degree Sheet 21, Zaria (McCurry, 1970). The boundaries of the Zaria granite were modified by Webb (1972) who also proposed the name Zaria batholith for it. In the present form, the batholith is at least 90 km long and up to 22 km wide and extends from north of Zaria southwards to the vicinity of Kaduna town. The Zaria Granite Batholith belongs to a suite of syn to late tectonic granites and granodiorites that marked the intrusive phase of the late Pre-cambrian to early Paleozoic Pan African orogeny in Nigeria (McCurry, 1973). These granites intruded low grade metasediments and gneisses and were collectively called “Older Granite” to distinguish them from Mesozoic “Younger Granites” (Falconer, 1911) of the Jos Plateau and surrounding areas. The Pan African orogeny was dated 850 to 467 Ma and the Older Granites 618 to 467 Ma (Grant, 1969) using the Rb-Sr method. Ogezi (1977) used the same method to date a suite of aplite/pegmatite, medium to fine grained, and porphyritic rocks from Kutena granite inselberg where he got an age of 500 Ma and the porphyritic main rock as the host to other rocks 790 Ma. Ogezi (1977) concluded that the intrusion of the older granites must have started much earlier than generally thought.

The main rock unit of the batholith is coarse porphyritic biotite granite which is distinctly foliated in the field. The foliation is broadly oriented north-south and marked by sub parallel alignment of elongated and closely packed feldspar phenocryst, mainly microcline and a corresponding preferred orientation of biotite mica. Xenolith of gneisses and micro- as well as mafic clots in various stages of digestion also occur in the rock. These bodies conform in orientation to the general foliation trend. One variant of the granite can be found exhibiting a less distinct foliation most probably due to sparse distribution of the feldspar phenocryst. Close to the margin of the batholith, the granite tends to become rather granodioritic. The type locality is the River Kubani valley exposure of the western boundary of the batholith near Ahmadu Bello University (ABU) main campus. At this point, the batholith is in contact with local basement schist and there is an interbanding between the granite and the host schist. These interbanded rocks dip uniformly at 56° to the west. A similar phenomenon was reported by Webb (1972) in another contact area in the north near wurara.

Fig.2: A. the geology of parts of the quarter- degree sheets 101 and 102, after McCurry (B) the geology of parts of sheets 101, 102 and 104 showing principal areas of outcrop only (After Webb, 1972)
Sampling and Laboratory Procedures

Hand oriented core samples were drilled at twenty different points scattered randomly on the Kufena hill. At each point, core with diameter 30 mm, long enough to yield two specimens were obtained using the gasoline powered, water cooled portable acker drill equipment – model Packsack Diamond core drill. The cores of 30 mm diameter were trimmed to 25 mm diameter, and cut to a length of 22 mm to conform to the length/diameter ratio of 0.85 of Noltimier (1971). Out of the 40 specimen cut out, only 18 were close enough to perfect cylindrical shape of 25 mm x 22 mm (standard paleomagnetic samples). This low number was due to limitations in our acker drill equipment, in which the diameters of the drilled cores were 30 mm and these had to be trimmed to 25 mm.

In-situ measurement of the magnetic susceptibility was carried out randomly at the study site using the Bartington MS2F probe connected with MS2 meter. In the laboratory, the magnetic susceptibility measurements were carried out on each of the samples using the Bartington MS2B sensor (operating at low frequency) connected to MS2 meter linked to a computer (Fig 3). The anisotropy of magnetic susceptibility (AMS) measurements was carried out on each of the 18 specimen using the AMSWINBAR software supplied with the Bartington MS2 system.

![Fig. 3: Experimental set-up for measuring magnetic susceptibility and its anisotropy.](image)

PRINCIPLES AND METHODOLOGY

The magnetic susceptibility, \(K\), is defined by the ratio between the induced magnetization of the specimen and the inducing magnetic field. The magnetization disappears as soon as the field is removed. The spatial variations of \(K\) are referred to as the anisotropy of magnetic susceptibility AMS, given as a second rank tensor whose representation is an ellipsoid with \(K_1 \geq K_2 \geq K_3\) as principal axes. \(K_i\) is the magnetic lineation and \(K_i\) is the pole to the magnetic foliation. The bulk magnetic susceptibility, \(K_{nm}\) is the arithmetic mean of the principal susceptibilities given as

\[
K_{nm} = \frac{1}{3}(K_1 + K_2 + K_3)
\]

The degree of magnetic anisotropy is given by \(P\), where

\[
P = \exp\left(\frac{1}{2}\left[\eta_1 - \eta - (\eta_2 - \eta^2) + (\eta_3 - \eta^2)\right]\right)
\]

with

\[
\eta = \frac{\eta_1 + \eta_2 + \eta_3}{3}
\]

where

\[
\eta_1 = \log K_1, \eta_2 = \log K_2, \text{and} \eta_3 = \log K_3
\]

(Jelinek, 1981). The shape of the ellipsoid is represented by the parameter \(T\) given by,

\[
T = \left(\frac{2\eta_2 - \eta_1 - \eta_3}{(\eta_1 - \eta_3)}\right)
\]

For oblate shape,

\[
0 \leq T \leq 1
\]

and for prolate shape

\[-1 \leq T \leq 0
\]

The paramagnetic susceptibility is controlled mainly by ferromagnetic content, such as \(Fe^{3+}\), \(Fe^{2+}\) and (less important) of \(Mn^{2+}\) (Bleil and Petersen, 1982). An empirical correlation between susceptibility and Fe-content \(C_{Fe}\) (in weight %) (Dortman, 1976 and Petersen, 1985) is given by;

\[
K_p = 3.48C_{Fe}
\]

Where \(K_p\) is the mass susceptibility in m³kg⁻¹.

This correlation was derived for the minerals garnet, tourmaline, biotite, muscovite, amphibole, cordierite, and pyroxene with a Fe-content between 0 and 30% (Schon, 1996).

RESULTS

Rock magnetic experiment was carried out in an attempt to identify the magnetic minerals controlling the magnetic susceptibility, volume concentration of ferro- or ferrimagnetic minerals, and also to establish the magnetic fabric pattern using the anisotropy of magnetic susceptibility (AMS) studies of the Kufena hill, Zaria. The result is summarized in table 1.

The magnetic susceptibility \(K\), at the site was found to vary between \(6.1 \times 10^{-5}\) and \(8.5 \times 10^{-5}\) S I with an average value of \(6.9 \pm 0.62 \times 10^{-5}\). The degree of magnetic anisotropy, \(P\) is fairly moderate with values ranging from 1.010 to 1.302 with an average of 1.085 ± 0.5 (Table 1 and Fig. 4). The magnetic fabric parameters (lineation, \(L\), foliation, \(F\), and the shape factor, \(T\)) within the site do not vary significantly. The lineation \(L\) has an average value of 1.039, while the foliation \(F\) has an average value of 1.0548. The shape parameter \(T\) varies between 0.300 and 0.401, with an average value of 0.338 ± 0.042. A general positive correlation between \(P\) and \(K\) is
observed (Fig.4). A linear correlation is also observed between the degrees of magnetic susceptibility and the magnetic susceptibility (Fig.5). The percentage concentration of ferromagnetic mineral was calculated to be 17.94%.

Table 1: Magnetic susceptibility and Anisotropy of magnetic susceptibility data for Kufena rocks

<table>
<thead>
<tr>
<th>Sample code</th>
<th>K x 10^{3} (SI)</th>
<th>Mag. Lineation, L</th>
<th>Mag. Foliation, F</th>
<th>Degree of Anisotropy, P'</th>
<th>Shape parameter, T</th>
<th>K_{int}</th>
<th>K_{m}</th>
<th>K_{ext}</th>
</tr>
</thead>
<tbody>
<tr>
<td>KUF01</td>
<td>7.3</td>
<td>1.008</td>
<td>1.051</td>
<td>1.060</td>
<td>0.328</td>
<td>1.098</td>
<td>1.075</td>
<td>0.831</td>
</tr>
<tr>
<td>KUF02</td>
<td>6.2</td>
<td>1.006</td>
<td>1.054</td>
<td>1.061</td>
<td>0.333</td>
<td>1.097</td>
<td>1.084</td>
<td>0.829</td>
</tr>
<tr>
<td>KUF03</td>
<td>6.2</td>
<td>1.006</td>
<td>1.052</td>
<td>1.061</td>
<td>0.303</td>
<td>1.092</td>
<td>1.082</td>
<td>0.795</td>
</tr>
<tr>
<td>KUF04</td>
<td>6.5</td>
<td>1.005</td>
<td>1.049</td>
<td>1.045</td>
<td>0.318</td>
<td>1.095</td>
<td>1.080</td>
<td>0.830</td>
</tr>
<tr>
<td>KUF05</td>
<td>7.1</td>
<td>1.013</td>
<td>1.051</td>
<td>1.048</td>
<td>0.318</td>
<td>1.096</td>
<td>1.078</td>
<td>0.832</td>
</tr>
<tr>
<td>KUF06</td>
<td>6.9</td>
<td>1.011</td>
<td>1.051</td>
<td>1.056</td>
<td>0.330</td>
<td>1.093</td>
<td>1.080</td>
<td>0.805</td>
</tr>
<tr>
<td>KUF07</td>
<td>7.0</td>
<td>1.008</td>
<td>1.051</td>
<td>1.058</td>
<td>0.352</td>
<td>1.093</td>
<td>1.081</td>
<td>0.855</td>
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<tr>
<td>KUF08</td>
<td>6.2</td>
<td>1.006</td>
<td>1.053</td>
<td>1.062</td>
<td>0.381</td>
<td>1.095</td>
<td>1.082</td>
<td>0.835</td>
</tr>
<tr>
<td>KUF09</td>
<td>8.5</td>
<td>1.112</td>
<td>1.044</td>
<td>1.302</td>
<td>0.372</td>
<td>1.092</td>
<td>1.078</td>
<td>0.812</td>
</tr>
<tr>
<td>KUF10</td>
<td>5.5</td>
<td>1.003</td>
<td>1.122</td>
<td>1.140</td>
<td>0.333</td>
<td>1.096</td>
<td>1.065</td>
<td>0.823</td>
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<tr>
<td>KUF11</td>
<td>6.6</td>
<td>1.007</td>
<td>1.059</td>
<td>1.013</td>
<td>0.300</td>
<td>1.098</td>
<td>1.069</td>
<td>0.827</td>
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<tr>
<td>KUF12</td>
<td>6.1</td>
<td>1.005</td>
<td>1.052</td>
<td>1.015</td>
<td>0.390</td>
<td>1.089</td>
<td>1.075</td>
<td>0.817</td>
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<tr>
<td>KUF13</td>
<td>6.9</td>
<td>1.010</td>
<td>1.054</td>
<td>1.010</td>
<td>0.401</td>
<td>1.091</td>
<td>1.067</td>
<td>0.844</td>
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<tr>
<td>KUF14</td>
<td>6.9</td>
<td>1.012</td>
<td>1.053</td>
<td>1.049</td>
<td>0.351</td>
<td>1.090</td>
<td>1.086</td>
<td>0.835</td>
</tr>
<tr>
<td>KUF15</td>
<td>7.2</td>
<td>1.009</td>
<td>1.049</td>
<td>1.050</td>
<td>0.325</td>
<td>1.095</td>
<td>1.074</td>
<td>0.846</td>
</tr>
<tr>
<td>KUF16</td>
<td>7.5</td>
<td>1.111</td>
<td>1.047</td>
<td>1.205</td>
<td>0.323</td>
<td>1.092</td>
<td>1.064</td>
<td>0.876</td>
</tr>
<tr>
<td>KUF17</td>
<td>7.3</td>
<td>1.008</td>
<td>1.050</td>
<td>1.212</td>
<td>0.311</td>
<td>1.095</td>
<td>1.065</td>
<td>0.853</td>
</tr>
<tr>
<td>KUF18</td>
<td>7.8</td>
<td>1.100</td>
<td>1.042</td>
<td>1.147</td>
<td>0.322</td>
<td>1.094</td>
<td>1.077</td>
<td>0.891</td>
</tr>
</tbody>
</table>

**DISCUSSION OF RESULTS**

Intrusive or plutonic rocks are the result of cooling and solidification of magma at depth. The rocks can only be observed as the overlying rocks or sediments are removed by erosion, the magma in its liquid form is made up of freely moving ions which are mostly, oxygen, silicon, and smaller amount of aluminum, iron, magnesium, sodium and volatiles. As the magma cools through temperature, the movements of the ions slow down and the ions begin to arrange themselves into orderly patterns (minerals), a process called crystallization. The rate of cooling determines the size of the crystal. Slow cooling magma gives larger crystals, while fast cooling causes the ions to rapidly lose their motion, resulting in smaller crystal sizes.

The Kufena biotite-granite is part of the massive Zaria batholith which intruded the gneiss at about 618 ± 467 Ma. Macroscopic and microscopic observations of the rock units reveal that the major mineral compositions in the rocks are mainly quartz, feldspar and biotite. These minerals are formed as a result of late crystallization of ions and composed mainly of silicate oxides. The contribution to the magnetic susceptibility is therefore due to these three mineral, quartz, feldspar and biotite. But quartz and feldspar are diamagnetic with magnetic susceptibilities \(-0.62 \times 10^{-8}\) m\(^3\)kg\(^{-1}\) for quartz (Siegesmund and Becker, 2000) and \(-2.76 \times 10^{-8}\) SI for feldspar (Borradaile et al., 1987). These values are normally negligible contributions in tectonic studies (Borradaile and Henry, 1997). This makes biotite the major mineral controlling the magnetic susceptibility, as well as the anisotropy. The magnetic susceptibility values measured in this work (Table 1), with an average of 69.0 ± 6.2 \times 10^{-8} SI agrees with previously
reported values (Borradaile et al., 1987; Zapletal, 1990; Martin-Hernandez and Hirt, 2003 and Ferre et al., 2004).

The samples investigated show moderate anisotropies with a mean value 1.085 ± 0.5 and the shape parameter is generally positive with an average value 0.338. These values agree with those of (Siegesmund and Becker, 2000; Fatima and Hirt, 2003 and Ferre et al., 2004) for biotite.

The variations of the anisotropy of magnetic susceptibility (P') with magnetic susceptibility (K) (Fig. 4) show a fairly linear dependence. This occurs if the AMS is controlled by distinct mineral carrier (Ferre et al., 1999). In (fig. 5) there exist a generally positive correlation between P' and T, indicating an oblate ellipsoid shape. This shows that the magnetic fabric is controlled by the crystalline anisotropy of biotite. It also indicate that the magma within the earth flowed horizontally (Tian Li-Li et al., 2002), the direction of flow been dictated by the mean direction of AMS principal axis. Biotite is a late crystallizes mineral, consisting mainly of silicate and trace amount of magnetite (17.94 % for this work) which controls the magnetic susceptibility.

CONCLUSION
This research work has shown that the major mineral controlling the magnetic susceptibility in the study area is biotite. It has an average magnetic susceptibility value of 69.0 ± 0.62 x 10^-6 SI and the percentage composition of magnetite in this biotite was calculated to be 17.94 %. The research has also shown that the AMS ellipsoid, which is oblate, is controlled by the crystalline anisotropy of biotite, indicating that the parameter T depends to a large extent on magnetic carrier. The degree of anisotropy P' was found to be fairly moderate with an average value of 1.085 ± 0.5. The magnetic fabric parameter (Lineation L, foliation F, and the shape parameter, T) within the site does not vary significantly, showing a uniform composition of minerals. The lineation has an average value of 1.039, while the foliation has an average value of 1.0548 and the shape parameter is generally positive with a mean value of 0.338.

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REFERENCE


