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Relationship between Magnetic Susceptibility and Gravity of Basement Rocks in Southwestern Nigeria.

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Abstract: *Geophysical properties of Basement rocks within and around parts of Ado-Ekiti, Ekiti-State, South-Western Nigeria were correlated with the aim of establishing empirical relationship between the two properties. The principal Basement rocks in the study area are; Charnockite, Migmatite, Granite Gneiss and Quartzite. Fresh rock samples were taken from thirty (30) locations cutting across the geology of the study area. A total of three hundred (300) Magnetic Susceptibility measurements were obtained from the established locations. Simple pendulum principle and Archimede's principle were employed to determine the gravity and the specific gravity repectively. The results were presented as Maps, Tables and Cross plots. The magnetic susceptibility (MS), gravity and specific gravity values range from 2.113 X 10^{-4} to 9.305 X 10^{-4}, 935055.46 mGal to 1038167.647 mGal and 2.61 to 2.83 respectively. The crossplots of the magnetic susceptibility and gravity shows good correlation with coefficient of correlation (R) ranging of 85%. The established relationship between the two geophysical parameters reveals that the potential fields is a function of both the gravitational and magnetic fields existing in the rocks as a result of the content Fe-bearing minerals present in the rock. This further proves that the magnetic susceptibility of a rock can be determined by estimation from the gravity readings. Hence the established equations can be used to evaluate rock potential field parameter using either of the two measured geophysical parameters.*

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I. Introduction

Magnetic susceptibility values are important in interpreting regional magnetic anomalies and in crustal modelling (Kjetil, 2012). Mineralogical alteration of rocks contributes to changes in their physical and mechanical properties (Frolova *et al.*, 2014). Iron minerals in rocks serves as cementing materials which determines the magnetic susceptibility of the rock matrix, Fe-bearing minerals like siderite and pyrites have relatively high susceptibilities as samples of rocks rich in siderite have the highest values (Kjetil, 2012). Susceptibility mainly reflects the magnetite contents of rocks and density is closely correlated to magnetic susceptibility, mineral composition and thus to chemical composition of rocks (Herbert, 1976). Quartz is a stable mineral which can not decompose easily to give room for cementing minerals to aggregate with its constituents. The finer-grained rocks are usually stronger than coarse grained varieties as a result of higher grain to grain contacts in fine-grained samples (Bell, 2007). The fine-grained samples such as siltstone and shales usually have highest magnetic susceptibilities compared to carbonates and coarser grained conglomerates and sandstones in sedimentary terrain. Direct knowledge of density can be used to predict gravity anomaly that density mapping for iron-ore can be potentially used for ore mineral prospecting (Omosanya *et al.*, (2012). Density values of rock samples can be utilized to delineate iron ore zones in Iron-Ore deposit, and this can be used to develop geology map of an area (Amigun and Ako, 2009). All these assertions show gravity and magnetic susceptibility of rocks can be well correlated.

1.1 Gravity Prospecting Method

Gravity method determines the spatial distribution of subsurface rock density which causes small changes in earth gravitational field. The objective here is to determine spatial variation in the acceleration due to gravity (g) which depends on the mass (density and volume) underlying the survey area. The force of attraction between the gravimeter mass 'M' and a body of mass 'm' depends on:

$$F = Gm\left(\frac{M}{r^2}\right) \quad (1)$$

Where G is the acceleration due to gravity, 'r' is the distance between the two masses 'm' and 'M'.

Since F = Mg (2)
then,

$$Mg = Gm\left(\frac{M}{r^2}\right) \quad (3)$$

$$g = \frac{Gm}{r^2} \quad (4)$$

Like magnetics, radioactivity, and some electrical techniques, gravity is a natural-source method. Local variations in the densities of rocks near the surface cause minute changes in the gravity field. Gravity and magnetics techniques often are grouped together as the potential methods, but there are basic differences between them. **(**Telford *et. al.,* 1990).

1.2 Magnetic Prospecting Method

Magnetic method determines subsurface spatial distribution of rock magnetization properties, J (Susceptibilities and Remanence) which causes small changes in earth magnetic (Geomagnetic) fields. The external field originates from the outward part of the earth. The spatial variations of the main field which are usually smaller than the main field are nearly constant in time and place and caused by local magnetic anomalies in the near-surface crust of the earth. These are the targets in magnetic prospecting.

Iron minerals in rocks serves as cementing materials which determines the magnetic susceptibility of the rock matrix. Quartz is a stable mineral which cannot decompose easily to give room for cementing minerals to aggregate with its constituents. Granite has three dominant minerals which are feldspar (alkali and plagioclase), biotite and quartz. Mineralogical alteration of rocks contributes to changes in their physical and mechanical properties (Frolova *et al.,* 2014).

'As the ferromagnetic minerals mostly belong to accessory minerals that are often sensitive indicators of geological processes, the magnetic susceptibility is a useful parameter in solving some petrologic problems (Jackson *et al.,* 1998).

1.2 Description and Accessibility of the Study Area

The study area is Ado-Ekiti, Ekiti-State, South-western Nigeria. Ado-Ekiti is the capital city of Ekiti-State and lies between Longitude 5^0 00'E and 5^0 30'E and Latitude 7^0 30'N and 7^0 45'N (Figure 1), covering a total area of 346.5km^2. The study area is accessible through major and street roads. There are also foot paths across the rocky environments within and around the outskirt of the town.

1.3 Geology of the Study Area

Ado-Ekiti and its environs are dominated by crystalline rocks which consist mainly of migmatite-gneiss-quartzite complex, older granites, quartzite, charnockites, and fine to medium grained granites (Ayodele and Ajayi, 2016). In the study area, there is a close association between the charnockites and granitic rocks due to their field relationship as documented in the basement complex rocks of Nigeria (Figure 2).

Rocks like older granite, charnockite, phylite and quartz veins got intruded into Migmatite-quartzite complex which is the oldest among them. This intrusion took place during Pan-African orogeny (Rahaman, 1979). Migmatite covers over 50% of the study area (Fig. 1.2) which host intrusion of other rocks. The quartzite in the study area exhibits white to gray colour due to varied iron oxide in the rock. Quartzite is very defiant to chemical weathering. It forms ridges and resistant hilltops.

The charnockitic rocks outcrops within the study area are massive, dark-greenish in colour with medium to coarse grained texture. The charnockites in Ado-Ekiti fall within those that occur along the margins of Older Granites bodies especially the porphyritic granites (Rahaman, 1979). Petrological studies reveal that charnockite contains quartz, alkali feldspar, plagioclase and biotite as major mineral.

The Older Granites comprise of felsic and mafic minerals. The felsic minerals include quartz, orthoclase, plagioclase feldspar and muscovite while the mafic group comprise of the black coloured biotite and the dark green to black hornblende of the amphibole group (Talabi *et al.,* 2014).

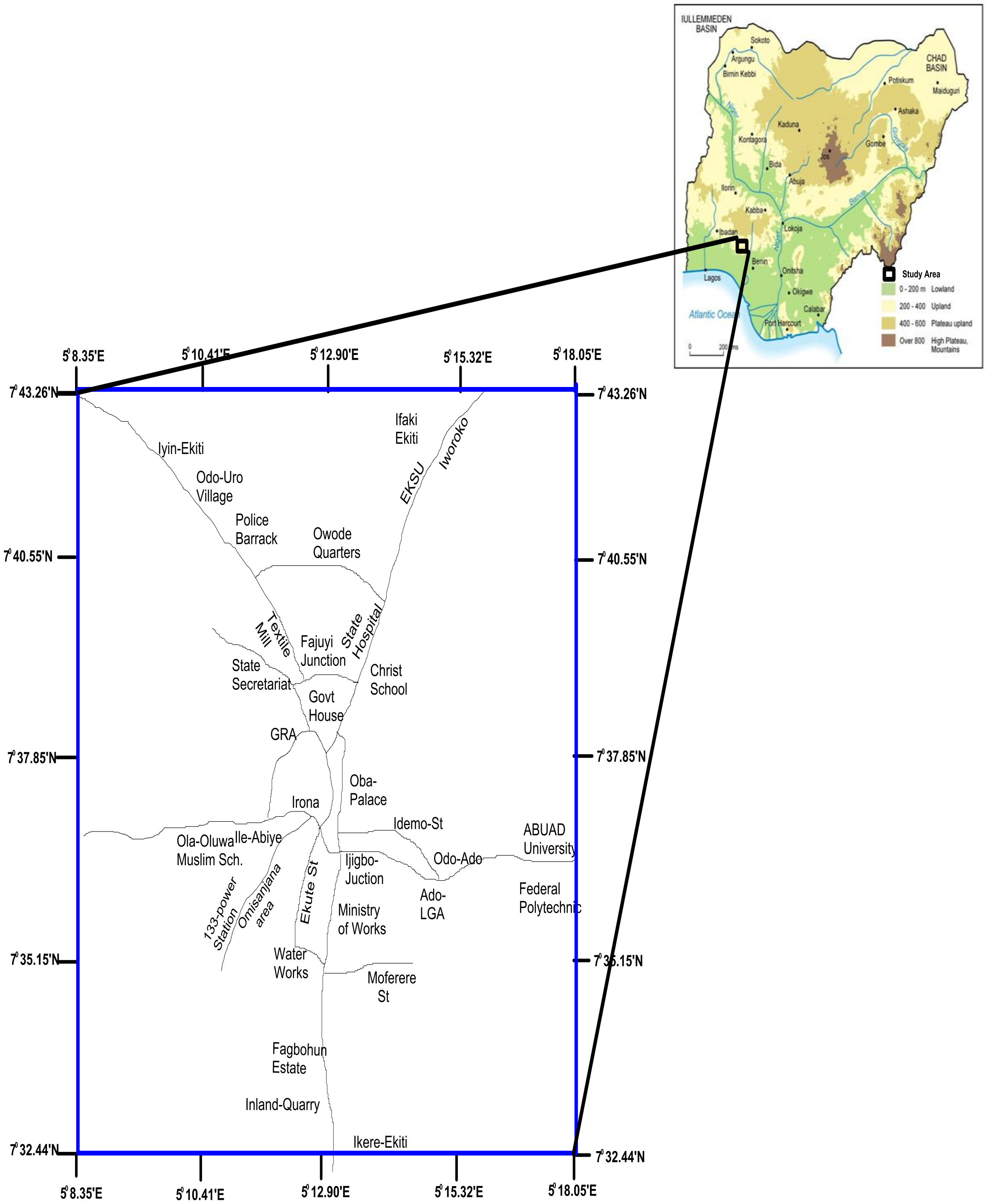

Figure 1: Map of Nigeria Showing Relief, Morphology and the Road Networks within the Study Area.

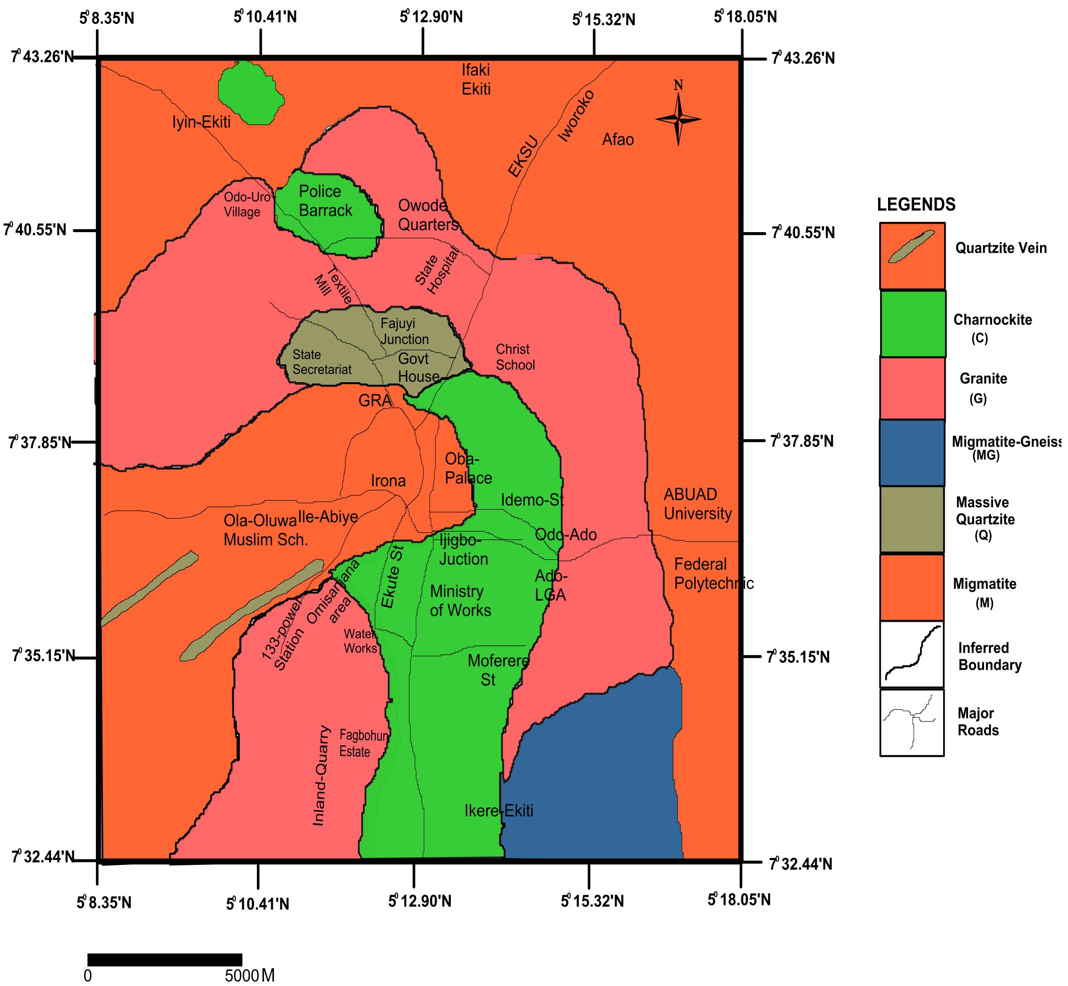

Figure 2: Geology Map of Ado-Ekiti Study Area

1.3 Geomorphology, Climate and Vegetation

The topography of the study area indicates a general gentle slope. The area is defined by extensive hills which are surrounded by settlements. Majority of the rocks are as high as 250m above mean sea level (Talabi *et al.,* 2014). It is generally an upland area. The climate is the lowland tropical rain forest type with distinct wet and dry seasons. The dry season comes up between November and April while the wet season prevails between May and October. The mean monthly temperature of the area is 29^{0}C while the mean relative humility is about 75 %. The mean total rainfall is about 1700 mm (Talabi *et al.,* 2014). The vegetation is an evergreen high forest composed of many varieties of hardwood. An important aspect of the vegetation is the prevalence of tree crop.

II. Materials And Method Of Study

This research employed the use of gravity and magnetic geophysical methods of each of the rock sample. The specific gravity, gravity and the magnetic susceptibility were determined and correlated with each other.

2.1 Gravity Determination

2.1.1 Materials used for the determination of Gravity

The materials used for the determination of the Gravity values are: swing rope, roof clip, electric weighing balance, meter rule, hammer and stop-watch. Sledge hammer was used to take samples from the field, while small hammer was used to break the samples into smaller samples for the analysis. Electric Weighing Balance was used in determining the weight of each sample in other to obtain a uniform weight for the experiment, while the meter rule was used to measure the varying length of the rope and the varying distances away from the floor to the ceiling. The swing rope is 5 m long cotton rope with about 5 mm thickness. It was used to hang the samples against the ceiling of the laboratory room while the clip was used to hook the swing rope against the ceiling. Time in seconds was determined with the use of stop-watch after the completion of the number of oscillations.

2.1.2 Procedures involved in the Determination of Gravity

Thirty samples of different rock types (charnockite, migmatite, granite, gneiss and quartzite) were taken from different locations within the study area (Figure 3). Six samples of varying weights ranging from 3-4 kg were taken within each of the rock types distributed in the study area with the aid of sledge hammer. The samples were further broken into smaller sizes of equal weight of approximately 60 gm.

The pendulum rope was hung to the ceiling of the laboratory with the aid of the clips nailed against the ceiling. The height of the ceiling to the floor was 3.6 m. Each of the samples was set at lengths of 3.2 m tied on the rope tightly. The sample on the pendulum was held at an angle of about 60^0 to the perpendicular axis against the ceiling. The pendulum was set in motion until it completes fifty (50) to and fro oscillations. Time taken to make fifty (50) oscillations was recorded twice as 't_1' and 't_2' in seconds. An average time-taken (t) for fifty (50) oscillations was recorded in seconds, while the period (T) was calculated by dividing the total time (t) for the fifty oscillations by 50 (no of oscillations). The square of the period (T^2) was also calculated. The length 'L' of the rope was further varied to 3.0 m, 2.8 m, 2.6 m, 2.4 m and 2.2 m with the sample attached. The square of the period (T^2) was also calculated at the varying lengths. Values of swing rope length (L) were plotted against square of period (T^2). The gradient was then determined from the plot.

Using the Galileo equation of simple pendulum motion, which states "The period (T) for a simple pendulum does not depend on the mass or the initial angular displacement, but depends only on the length (L) of the string and the value of the gravitational field strength (g)," Where;

$$T = 2\pi\sqrt{\frac{L}{g}} \quad (5)$$

$$T = 2\pi\sqrt{\frac{(h-L)}{g}} \quad (6)$$

Where, T = period,
L = length of the rope,
h = distance between the floor and the sample before swinging and
g = acceleration due to gravity.
Linearizing the equation we have:

$$T^2 = \frac{4\pi^2(h-L)}{g} \quad (7)$$

$$T^2 = \frac{4\pi^2 h}{g} - \frac{4\pi^2 L}{g} \quad (8)$$

$$T^2 = -\frac{4\pi^2 L}{g} + \frac{4\pi^2 h}{g} \quad (9)$$

Where $-\frac{4\pi^2}{g}$ is the gradient (m) of the graph. The negative sign signifies deceleration during the pendulum motion. The values of gradient (m) calculated from the graph was equated with the gradient $-\frac{4\pi^2}{g}$ of the linearized equation (equation 3.5) without the negative sign to obtain the gravity (g) values.

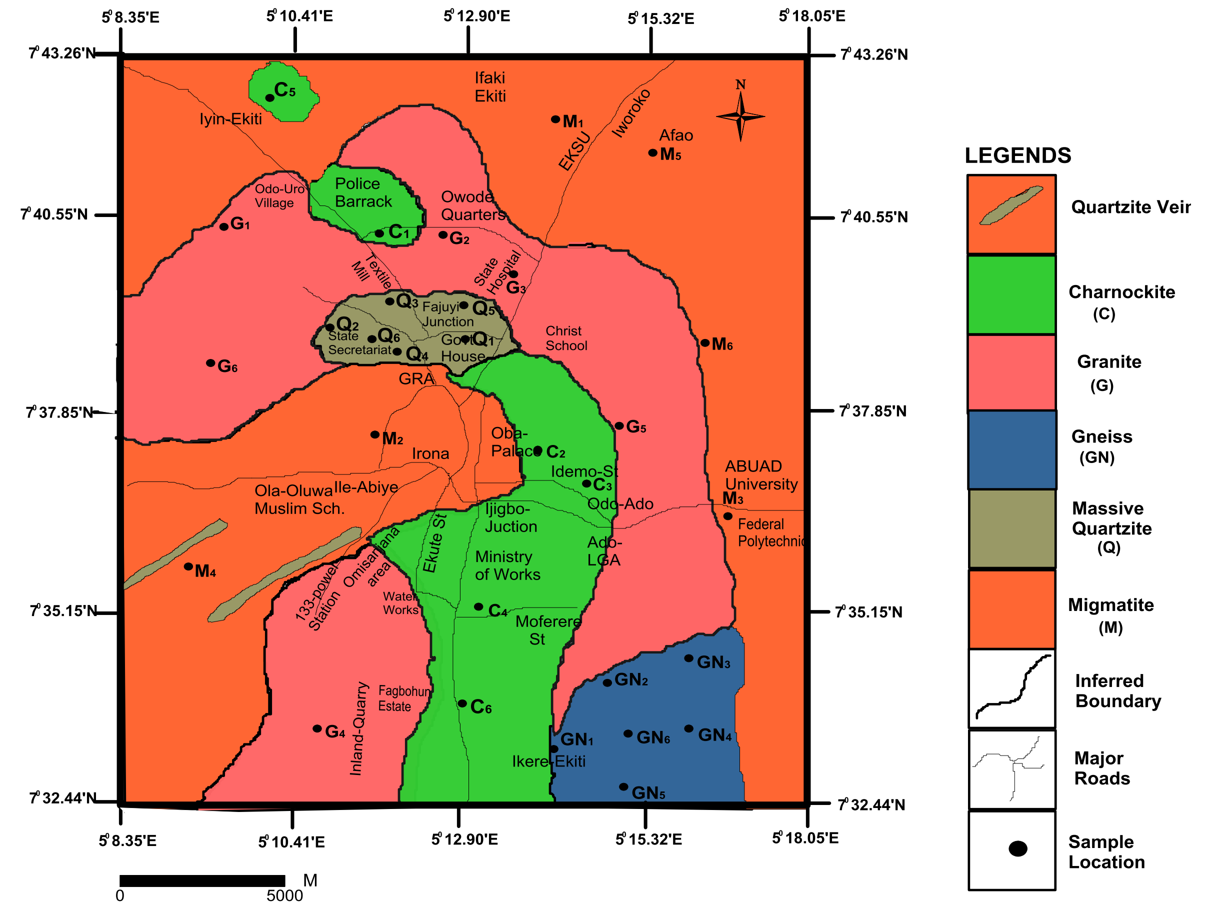

Figure 3: Map of the Study Area Showing the Sampling Points

For example

For sample C_1

$$\frac{4\pi^2}{g} = 4.0419 \quad (10)$$

Where g = $\frac{4\pi^2}{4.0419}$ = 9.956706274m/s^2 = 995.6706274cm/s^2 = 995.6706274Gal = 995670.6274mGal

2.2 Magnetic Susceptibility Measurement

Magnetic susceptibility meter which measures the amount of Iron-bearing minerals in rocks was used for the study. It determines the “magnetisability” of rocks in their natural environments. It detects how convenient a rock can retain magnetic property after been exposed to an external magnetic field.

The instrument used for the measurement of the rock magnetic susceptibility is the Mag-Rock Magnetic Susceptibility Meter. A Global Positioning System (GPS) was used to take the geographic coordinates of the sample locations. The sensor of the instrument and the rock surface were cleaned with methylated spirit before taking each measurement. Ten readings were taken at each of the sampling locations. A total of three hundred (300) measurements were taken at the thirty sampling locations which were distributed across the geology of the study area.

2.3 Specific Gravity (SG) Determination

Specific gravity (SG) is a reflection of the amount of heavy elements (especially Fe and Mg) present in a rock. In most cases, specific gravity can serve as an indirect means of determining the amount of stable and potentially durable minerals in aggregates. The significant values of specific gravity in this study are a reflection of presence of pyroxene and iron minerals in the rock units within the study area. The densities of samples of the thirty rock samples were determined in the laboratory by adopting the bulk density and buoyancy techniques.

The materials used for the determination of the bulk density are; electric weighing balance, tripod-stand, beakers, thread and about 2 litres of water. Small sizes of the sample were first weighed on the weighing balance to determine the weight in air ‘Wa’, which ranges from 26 to 79 gm. The weight of the beaker half-full with water was also weighed as ‘W_b’. Rock sample was then hung on the clip of the tripod stand with aid of the thread and suspended into the water and then weighed as 'Wc'. Weight of the sample in water 'Ww' was determined by subtracting the weight of the beaker with water 'W_b' from weight of the beaker with water and the suspended sample 'Wc'. Bulk density (ρ) was then determined by:

$$\rho = \frac{W_a}{W_a - W_w} \quad (11)$$

The Specific gravity of each sample was then calculated by multiplying the bulk density (ρ) obtained with the density of water (ρ_w) which is equal to 0.9986g/cm^3, i.e.

$$SG = \rho \times \rho_w \quad (12)$$

$$SG = \rho \times 0.9986 \quad (13)$$

By applying the buoyancy method, the weight of the rock sample in air was determined and the volume of water displaced (Vs) in the beaker was measured. The bulk density of the rock sample was calculated by dividing the weight of the sample in air (Wa) by the displaced volume of water (Vs) and multiplying by the density of water (0.9986 g/cm^3).

$$\rho = \frac{W_a}{V_s} \quad (14)$$

$$SG = \rho \times \rho_w \quad (15)$$

$$SG = \rho \times 0.9986$$

III. Results And Discussion

3.1 Gravity Results

The gravity map generated from the laboratory data is as shown in Figure 4. Table 1 shows the values of the gravity for each of the sample analyzed. The gravity distribution within the study area ranges from 935000 - 104000 mGal (Figure 3). Relatively low gravity values (< 985000 mGal) were observed at the central and the southeastern part of the study area. This falls within the region underlain by gneiss and quartzite rock. However, relatively high gravity values (> 985000mGal) were observed within the areas underlain by migmatite, charnockite and granite. This shows that migmatite, granite and charnockite are denser than other rock types within the study area. This may reflect in their weathering-end.

3.2 Magnetic Susceptibility Result

Magnetic susceptibility map developed from the in-situ rock magnetic susceptibility measurements of the outcrops within the study area is as shown in Figure 5. The magnetic susceptibility values at each location are shown in Table 2. The magnetic susceptibility value within the study area ranges from 0 – 9.5 X 10^{-4} (Figure 4). Relatively low magnetic susceptibility values (< 4.0 X 10^{-4}) were observed at the north-central and south-eastern parts. While other areas underlain by migmatite, granite and charnockite characterized by relatively high magnetic susceptibility values (> 4.0 X 10^{-4}). Quartzite rock did not exhibit any magnetic susceptibility value due to lack of iron mineral.

3.3 Specific Gravity

Table 4 and 5 shows the result of the specific gravity test within the study area. Specific gravity values in the study area range from 2.59 – 2.84 (Figure 6). It shows relative low values (< 2.71) in the areas mostly underlain by quartzite and gneiss. However, relatively high values (> 2.71) of specific gravity are observed around the areas underlain predominantly by charnockites, migmatite and granite. Where quartzite and gneisses dominated, relatively low values were observed.

IV. Relationship between the Gravity(G) and Magnetic Susceptibility (MS)

The regression plot of Gravity (G) against the Magnetic Susceptibility(MS) of the rock samples is as presented in Figure 7. The trend line shows a direct relationship between the two parameters with 0.85 coefficient of correlation (R). This indicates relatively a strong correlation between the gravity and the Magnetic Susceptibility.

The empirical equation representing the relationship between Gravity and the Magnetic Susceptibility is given as;

$$G = 0.1127MS + 936304 \quad (16)$$

Where MS= Magnetic Susceptibility

G = Gravity

Table 1: Gravity Values of each of the Rock Sampled

Sample	Rock Type	Gravity (m/s^2)	Gravity (Gal or cm/s^2))	Gravity (mGal)
C1	Charnockite	9.956706274	995.6706274	995670.6274
C2	Charnockite	10.03359008	1003.359008	1003359.008
C3	Charnockite	9.975060808	997.5060808	997506.0808
C4	Charnockite	9.845036712	984.5036712	984503.6712
C5	Charnockite	9.885468575	988.5468575	988546.8575
C6	Charnockite	10.09229453	1009.229453	1009229.453
M1	Migmatite	10.0832778	1008.32778	1008327.78
M2	Migmatite	10.03180638	1003.180638	1003180.638
M3	Migmatite	10.09538131	1009.538131	1009538.131
M4	Migmatite	10.10934145	1010.934145	1010934.145
M5	Migmatite	10.04737144	1004.737144	1004737.144
M6	Migmatite	10.09538949	1009.538949	1009538.949
G1	Granite	10.36587525	1036.587525	1036587.525
G2	Granite	10.38167647	1038.167647	1038167.647
G3	Granite	10.1116705	1011.16705	1011167.05
G4	Granite	10.13632045	1013.632045	1013632.045
G5	Granite	10.11840488	1011.840488	1011840.488
G6	Granite	10.09719608	1009.719608	1009719.608
GN1	Gneiss	10.00284649	1000.284649	1000284.649
GN2	Gneiss	9.386061732	938.6061732	938606.1732
GN3	Gneiss	9.48774606	948.774606	948774.606
GN4	Gneiss	9.547127686	954.7127686	954712.7686
GN5	Gneiss	9.495718839	949.5718839	949571.8839
GN6	Gneiss	9.83694611	983.694611	983694.611
Q1	Quartzite	9.350734021	935.0734021	935073.4021
Q2	Quartzite	9.772938667	977.2938667	977293.8667
Q3	Quartzite	9.76791535	976.791535	976791.535
Q4	Quartzite	9.728411191	972.8411191	972841.1191
Q5	Quartzite	9.904528559	990.4528559	990452.8559
Q6	Quartzite	9.3505546	935.05546	935055.46

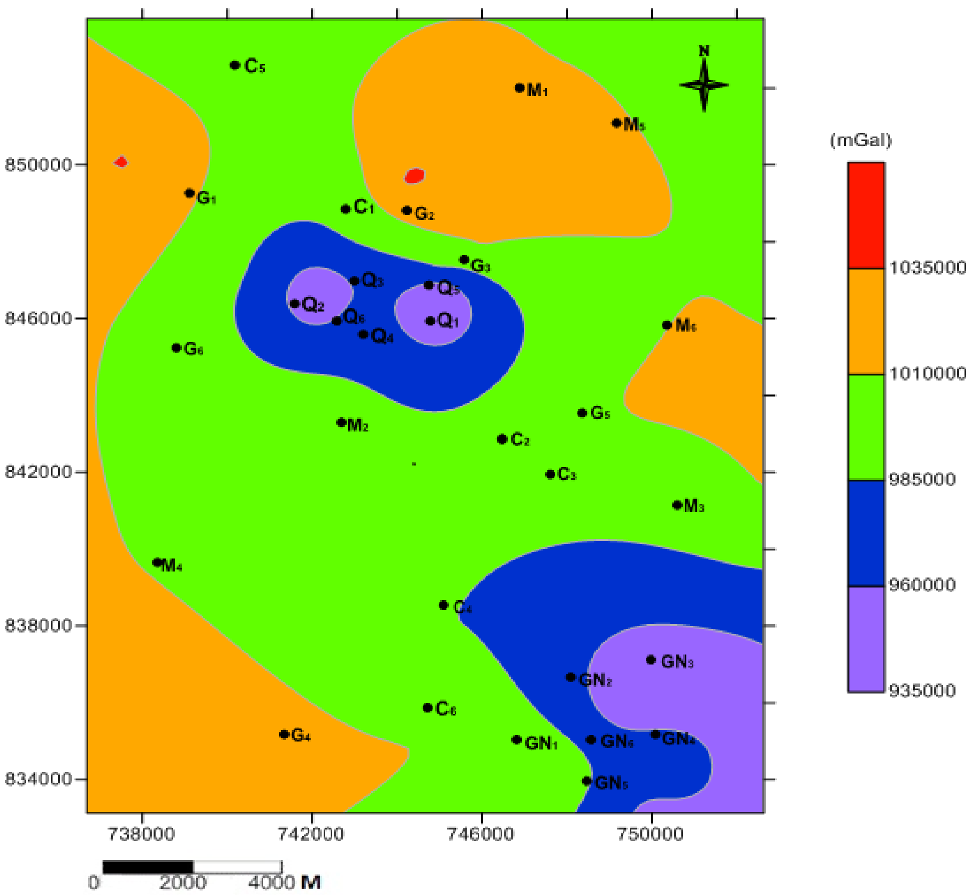

Figure 4: Gravity Map of the Study Area

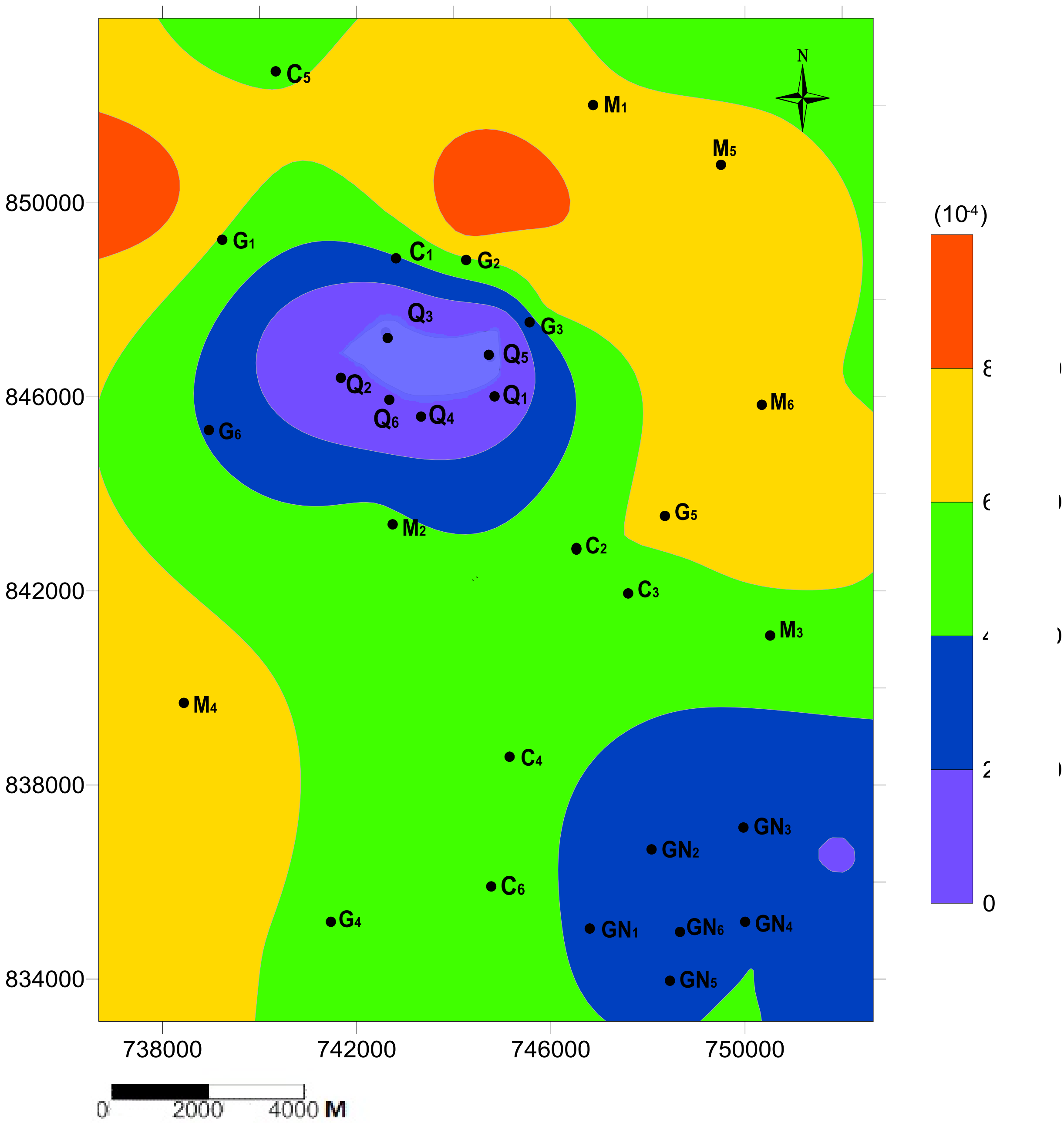

Figure 5: Magnetic Susceptibility Map of the Study Area

Table 2: Magnetic Susceptibility Results in the Study Area

Sample	Rock Type	**Average Magnetic Susceptibility(10^{-9})**	**Average Magnetic Susceptibility(10^{-4})**
C1	Charnockite	594200	5.942
C2	Charnockite	593300	5.933
C3	Charnockite	512600	5.126
C4	Charnockite	443000	4.430
C5	Charnockite	487100	4.871
C6	Charnockite	465000	4.650
M1	Migmatite	535800	5.358
M2	Migmatite	465200	4.652
M3	Migmatite	560200	5.602
M4	Migmatite	790700	7.907
M5	Migmatite	589600	5.896
M6	Migmatite	585300	5.853
G1	Granite	930500	9.305
G2	Granite	921700	9.217

G3	Granite	688400	6.884
G4	Granite	581600	5.816
G5	Granite	787900	7.879
G6	Granite	539200	5.392
GN1	Gneiss	338400	3.384
GN2	Gneiss	211300	2.113
GN3	Gneiss	186100	1.861
GN4	Gneiss	248100	2.481
GN5	Gneiss	412000	4.120
GN6	Gneiss	402800	4.028
Q1	Quartzite	0	0
Q2	Quartzite	0	0
Q3	Quartzite	0	0
Q4	Quartzite	0	0
Q5	Quartzite	0	0
Q6	Quartzite	0	0

Table 4: Specific Gravity Values in the Study Area

S/N	Sample	Rock Type	**Density In g/cm^3**	**Specific Gravity From Density (G_1)**	**Specific Gravity From Buoyancy (G_2)**	**Average Specific Gravity (G)**
1	C1	Charnockite	2.594	2.619	2.6153	2.7679
2	C2	Charnockite	2.663	2.706	2.7022	2.7059
3	C3	Charnockite	2.649	2.701	2.6972	2.7143
4	C4	Charnockite	2.612	2.702	2.6982	2.6552
5	C5	Charnockite	2.624	2.651	2.6477	2.7234
6	C6	Charnockite	2.659	2.679	2.6756	2.6954
7	M1	Migmatite	2.831	2.8270	2.8519	2.8395
8	M2	Migmatite	2.821	2.8171	2.7778	2.7976
9	M3	Migmatite	2.820	2.8156	2.7914	2.8035
10	M4	Migmatite	2.803	2.7994	2.8412	2.8203
11	M5	Migmatite	2.827	2.8233	2.8344	2.8289
12	M6	Migmatite	2.849	2.8447	2.7654	2.8051
13	G1	Granite	2.664	2.6603	2.6552	2.6578
14	G2	Granite	2.673	2.6693	2.7000	2.6847
15	G3	Granite	2.651	2.6473	2.5882	2.6178
16	G4	Granite	2.648	2.6444	2.5537	2.5991
17	G5	Granite	2.657	2.6531	2.7554	2.7043
18	G6	Granite	2.659	2.6549	2.5965	2.6257
19	GN1	Gneiss	2.650	2.6463	2.6957	2.6710
20	GN2	Gneiss	2.640	2.6433	2.6714	2.6574
21	GN3	Gneiss	2.658	2.6544	2.6465	2.6505
22	GN4	Gneiss	2.654	2.6498	2.6776	2.6637
23	GN5	Gneiss	2.649	2.6448	2.6934	2.6691
24	GN6	Gneiss	2.660	2.6558	2.6891	2.6745
25	Q1	Quartzite	2.594	2.5904	2.6190	2.6047
26	Q2	Quartzite	2.663	2.6596	2.6316	2.6456
27	Q3	Quartzite	2.649	2.6453	2.6667	2.6560
28	Q4	Quartzite	2.612	2.6083	2.6154	2.6119
29	Q5	Quartzite	2.624	2.6208	2.6332	2.6270
30	Q6	Quartzite	2.659	2.6555	2.6566	2.6561

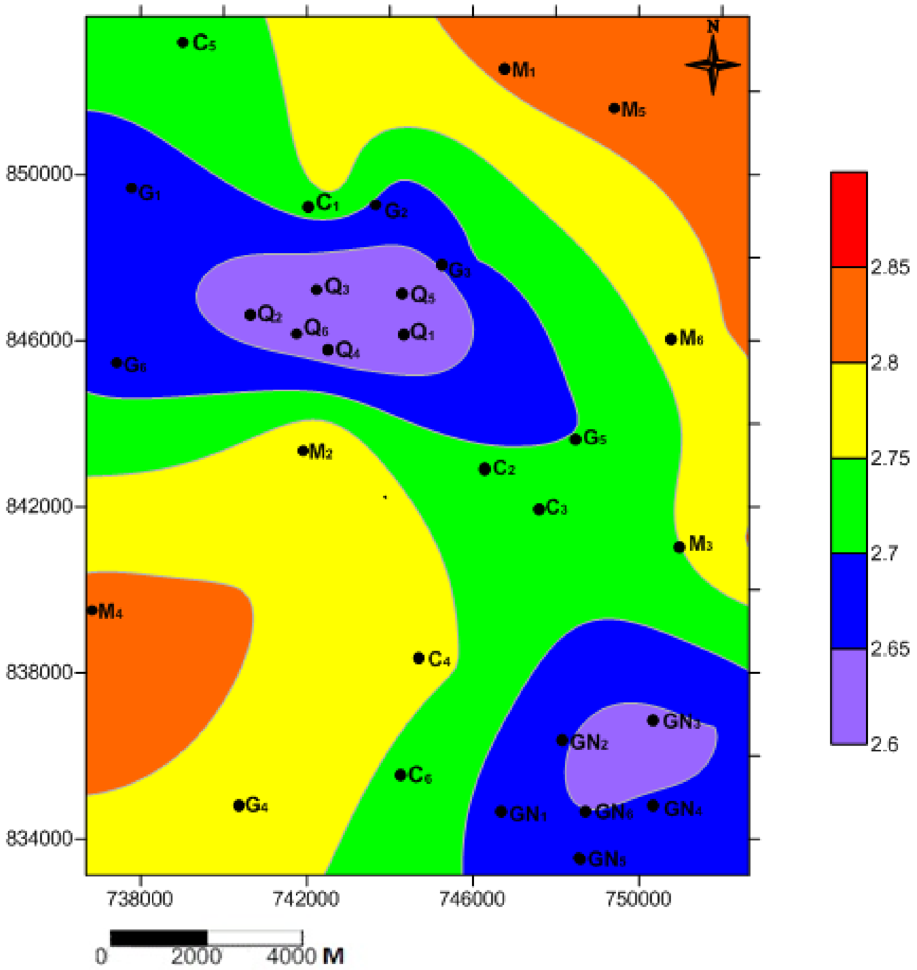

Figure 6: Specific Gravity Map of the Study Area

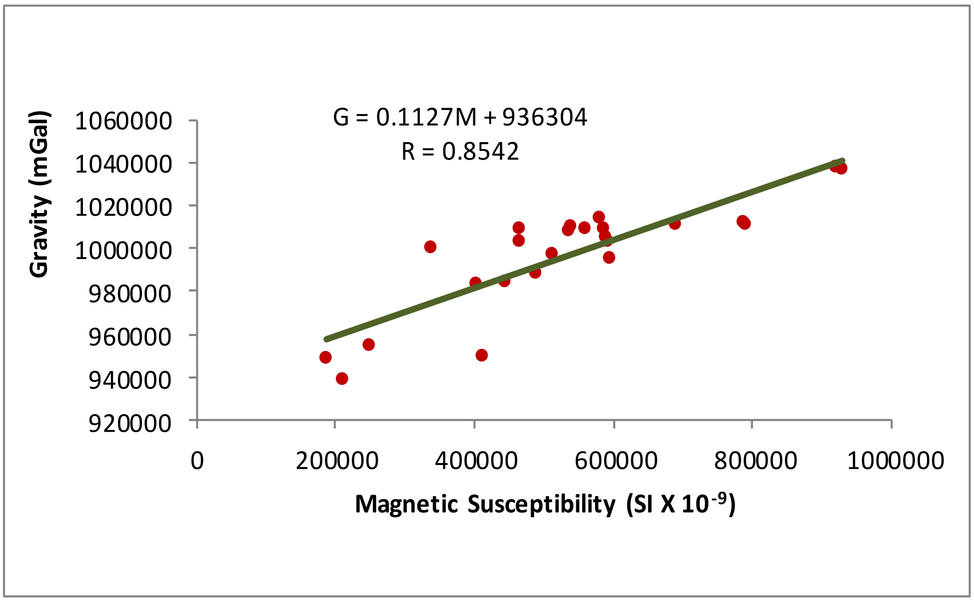

Figure 7: Crossplot of the Magnetic Susceptibility(M) and Gravity (G)

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