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Reliability of Density of Rock Generated From Its P-Wave Velocity In Geophysics Interpretations And Geotechnical Studies

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Abstract: *A study was carried out to determine the reliability of rocks' P-wave velocity- generated densities in geophysics interpretations and geotechnical studies in areas where the rock samples for laboratory density measurements are either inaccessible or their collection is time and cost ineffective.Zaria Area was used for the study due to its complex geology. Seismic refraction data were collected along some profiles where different rock contacts have been recently exposed by erosion. The interpreted p-wave velocities were converted to their density equivalencies. Also, samples of the different rock types were cut at the exposed parts along the profiles, and their densities measures in the laboratory. The results suggest that the average density of about 2702* kgm^{-3} *of the porphyritic granite calculated from an average p-wave velocity of about* $4300ms^{-1}$ *agrees well with the average density of about 2677* kgm^{-3}*measured in the laboratory. Similar results were obtained for the other rock types in the area. A statistical analysis shows that the standard deviation between the calculated and measured density values is about 95.83 for porphyritic granite; it is about 130.37 for gneiss and about 83.26 for medium grain granite. These results suggest that the calculated standard deviations show closely bunched measured-calculated density values of the rock samples. This further suggests that in areas, partly or completely devoid of rock outcrops, basement rock densities calculated from p-wave velocities are reliable for geophysics interpretation and geotechnical studies. Also, in areas of complex geology, using rock p-wave velocity-generated densities is cost and time effective than using measured values, unless the area is wholly having rock outcrops.*

I. Introduction

Geoscientists have described 'Gravity' as the foundation of Geophysics (Osazuwa, 2006). Density is an important parameter for the determination of gravity. This is illustrated in the relation:

$$gravity g = G \iiint \rho \nabla \left(\frac{1}{r}\right) dv + \frac{1}{2}\omega^2 \nabla (x^2 + y^2)$$

where G is the universal gravitational constant, ρ is the density of the earth material, ∇ is the gradient vector, ω is the angular velocity of the earth rotation, r is the distance of the attracted body from the centre of the earth, and x and y are the respective projections of r on the x-and y-axes of the plane parallel or coplanar to the equatorial plane. The accuracy of Bouguer anomalies and their interpretation depend greatly on the assumed density of rocks or more accurately the density differences of rocks. It is known that gravity anomalies result from the difference in density, or density contrast, between a body of rock and its surroundings. Gravity generally relates to othergeophysical discipline either directly or indirectly. For example, both magnetics and gravity are potential fields, derivable from the inverse square law and there is an empirical relationship between them popularly known as the Poisson relation.This relation makes it possible to determine the pseudo field of one from the measured field of the other. Similarly, it is known that seismic wave velocity varies with the density of material within the earth. Generally, knowledge of the density of earth materials is very vital for plausible interpretation in geophysics. It aids interpretation in geophysics, more importantly, gravity method. It is useful in the computation of the compressibilities and other elastic parameters of rock samples for geotechnicalstudies and engineering works.

Density determination is always accorded priority because of the central role it plays in geophysics.Hence, several direct and indirect methods are employed in density determination. The direct methods commonly used are:

i. Measurement of mass and volume
ii. Use of Archimedes Principles (Kearey and Brooks,2006) and
iii. Use of Specific Gravity Bottle

Dobrin (1976) had suggested that when one wishes to determine density directly, representative samples of rock from surface outcrops, mines, or well cores and cuttings may be collected for measurement with a pyknometer or a Schwarz or Jolly balance. However, Dobrin, (1976) considered Nettleton’s method of density determination as more satisfactory for gravity reductions than direct measurements.

The indirect (or *in situ*) methods commonly used are:

i. Borehole density measurement using a density (gamma-gamma) logger (Kearey and Brooks,2006)
ii. Nettleton’s method of density determination which involves taking gravity observations over a small isolated topographic prominence and field data reduced using a series of different densities for Bouguer and terrain corrections (Kearey and Brooks,2006).
iii. Parasnis’ method of density determination (Parasnis, 1962)
iv. Density information from P-wave velocity of rocks which is the only method available for the estimation of densities of deeply buried rock units that cannot be sampled directly.

In Nigeria and in most developing countries, the direct methods listed earlier are commonly used for rock density determination. These methods are commonly employed in Nigeria because of availability of equipment/materialsand their cost effectiveness. These methods have some inherit problems associated with them. For example, it is not always easy to obtain good density values because of the difficulty of finding fresh unweathered rock. The methods are not applicable for the measurement of densities of deeply buried rock units that cannot be sampled directly. Also, these methods are not time effective and sometimes do not allow for interpretation in geophysics when urgency is required.

The methods require collecting the rock samples from the field and taking them to the laboratory for the density determination. Sometimes the area or part of the area covered by the geophysical survey is devoid of rock outcrop. The researcher collects the rock samples from the nearest outcrop to the research area, sometimes, more than a kilometer to the study area, on the assumption that there is no significant change in the geology between the sample source and the research area. Such assumption is very deceptive in areas of complex geology like Zaria Area where research has shown that the basement rock types vary significantly within a short distance (Ibe and Egwuonwu, 2012, Ibe,et. al, 2012, Ibe, 2016).

The terrain and Bouguer correction made in the reduction of gravity data requireknowledge of the densities of the rocks near the surface. In many areas near-surface densities are sufficiently homogeneous for an average density value to be obtainable from a few well-spaced determinations (Dobrin, 1976). In others, there are such sharp local variations in lithology that use of an average density value can introduce considerable error (Dobrin, 1976). This fact has long been known by geoscientists and it accounts for the reason why White (1949), for example, has described a gravity survey in Great Britain where three different densities had to be used for surface correction within a small area.

Interpretations involving rocks’ densities of most geophysical research works in Zaria and its environs have always been based on the densities of the rocks’ outcrops within the study area. In areas devoid of outcrop and where the depth to the basement is shallow, some researchers sink borehole or dig wells to collect rock samples for density determination. In places of complex geology, like Zaria Area, where the basement rock types in some locations differ significantly within 20 m (Ibe, 2008, Ibe, 2016) the number of boreholes/wells required for rock sample collection in any Gravity survey within 1 km^2 must be too muchunless accuracy is not a priority in the research. This suggests that borehole/well option for sample collection is neither time nor cost effective.

There is need to adapt a method of estimating the densities of rocks in areas of complex geology, that is wholly or partially devoid of rock outcrops, to ensure that appropriate densityvalues are used in all geophysics interpretations and in geotechnical and engineering studies. Hence, this study is aimed at addressing the problems associated with rock density determination in a Batholitic environment like Zaria Area which has complex geology and partly has rock outcrops.That is, this study discussed alternative technique of generating rock densities, which ensures that appropriate densities are used for geophysics, geotechnical and engineering studies. It involved using seismic refraction tomography to delineate different rock types in the research area and conversion of the p-wave velocities to their density equivalences.Samples of the seismic-delineated rock types were collected from some outcrops for laboratory density analyses.It also involved a statistical comparison between the measuredand P-wave velocity- generated densities.

II. The Study Area And Its Geology

Zaria area is bounded approximately by longitudes 7^o 12$^/$ to 7^o 47$^/$ E and latitudes 11^o 03$^/$ to 11^o 11$^/$ N.This study involved seismic refraction measurement in the vicinity of two valleys in Kubanni Basin (Figure 1), Zaria, Nigeria. Kubanni Basin is characterized by high concentration of valley networks. Most of the valleys in the basin are dry. Others are seasonal except the Kubanni River itself. Almost all the tertiary institutions in Zaria area are located in the Kubanni Basin.

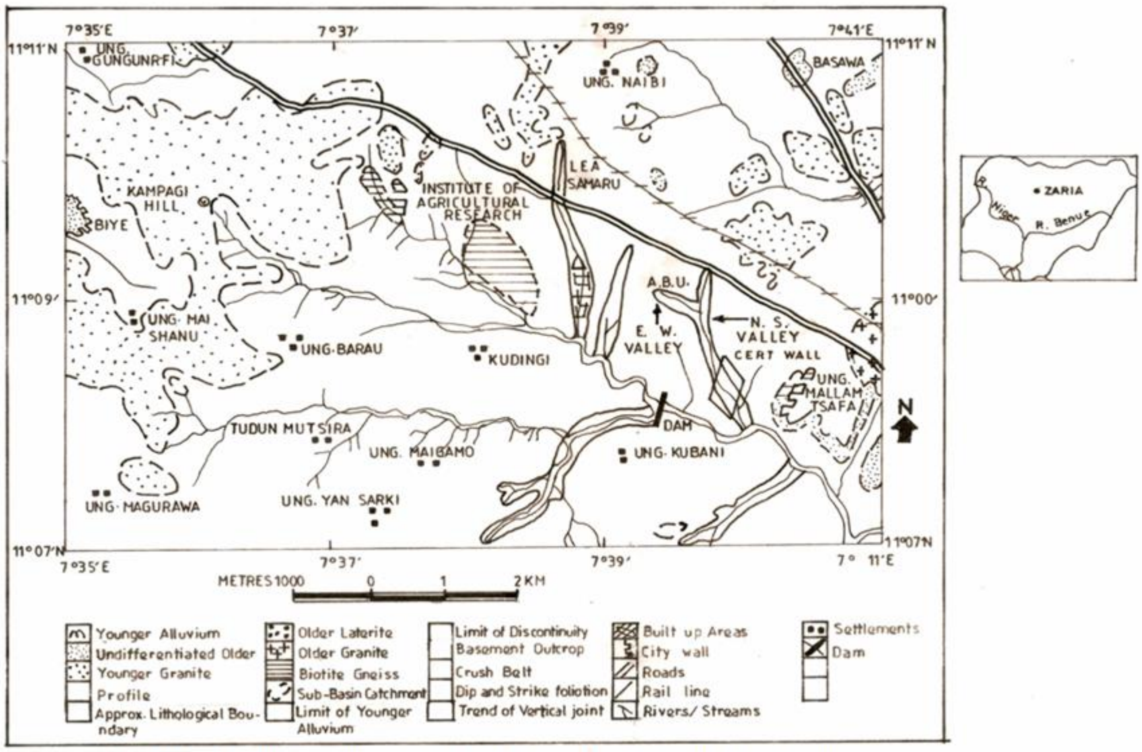

Fig 1: Map of Kubanni Basin in Zaria, Nigeria Showing valley Networks
(Adopted from Geology Department, Ahmadu Bello University, Zaria)

The area belongs to the Precambrian basement complex of northern Nigeria. It is composed of three rock types which include gneiss, porphyritic granite and medium grained granite. The porphyritic granite and medium grained granite were intruded into the gneiss during the Pan African (McCurry, 1973 and Garba and Schoeneich, 2003). The greater part of the area is covered with thick regolith mainly derived from in-situ weathering of the basement rocks.

Contacts of different rock blocks have been reported in the past in Zaria area. For example, McCurry (1970) reported that there are gneisses and granites mostly in the central and eastern parts of Zaria Area and the contacts between them are gradational. Another report by Webb (1972), confirmed that at a locality, 7 km south – west of Wurara, the contact of the Zaria Batholith with Schists is seen. The contact is sharp and there is no apparent contact metamorphism of the schist. Webb (1972) also observed that 2 km north – east of the university main campus (Ahmadu Bello University, Zaria), a similar sharp contact between granite and gneiss is seen. This evidence and the presence of numerous xenoliths of gneiss in the granite, south of the campus, suggests that the granite was intruded in a liquid condition and did not originate *in situ* by the regional granitisation of gneiss. Around and up to 2 km west of the campus, the gneiss are invaded by a complex of granite sheets and the margin of the batholith appears to be marked by repeated injection of granite. However, Shemang (1990) confirmed the contacts between different rock blocks in Zaria but suggested that the boundary between the Zaria granitic batholith and gneiss unit is sharp and not gradational.

Method of Study, Data Collection, Processing and Results

Seismic refraction tomography data were collected along some profiles laid across some parts of different rock contacts which have recently been exposed by erosion.Figure 2 shows one of the rock contact areas where profiles were laid for seismic data collection. The seismic field work was accomplished using a seismograph called ABEM Terraloc MK6. It is a multi- channel digital seismograph suitable for most seismic surveys including seismic refraction tomography.

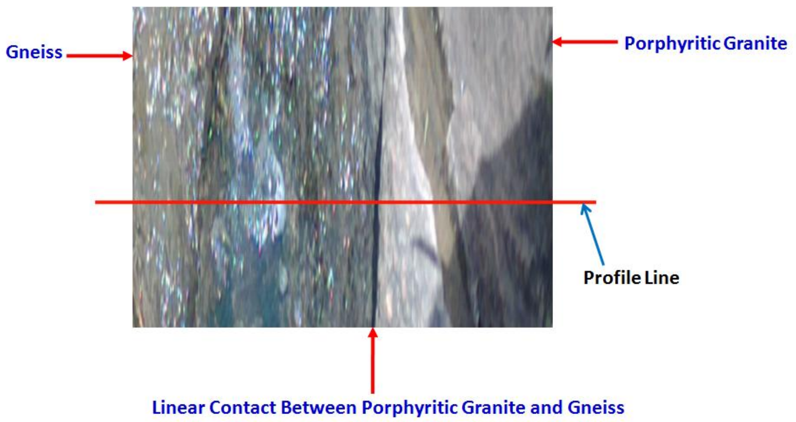

Fig. 2: Seismic Profile Line Across a Linear Contact Between Porphyritic Granite and Gneiss in the Vicinity of a valley in the Study Area

The data collected from the field were subjected to different stages of processing using "REFLEXW" software (Sandmeier, 2003) to enhance signal to noise ratio. The filtered data were tomographically inverted. Figures 3 and 4 show the tomograms for two of the profiles processed. The interpretation made for each tomogram is placed below it. The interpreted p-wave velocities were converted to their density equivalencies.

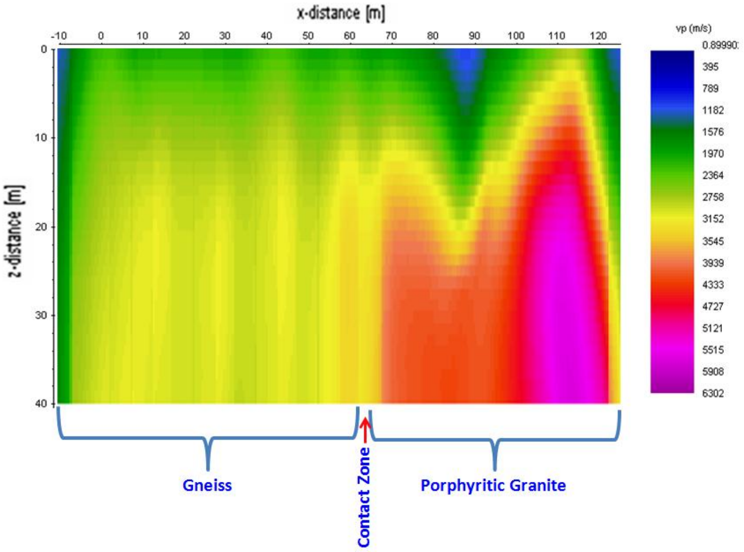

Fig. 3: Refraction Tomography Section for a Profile Across a Porphyritic Granite – Gneiss Contact

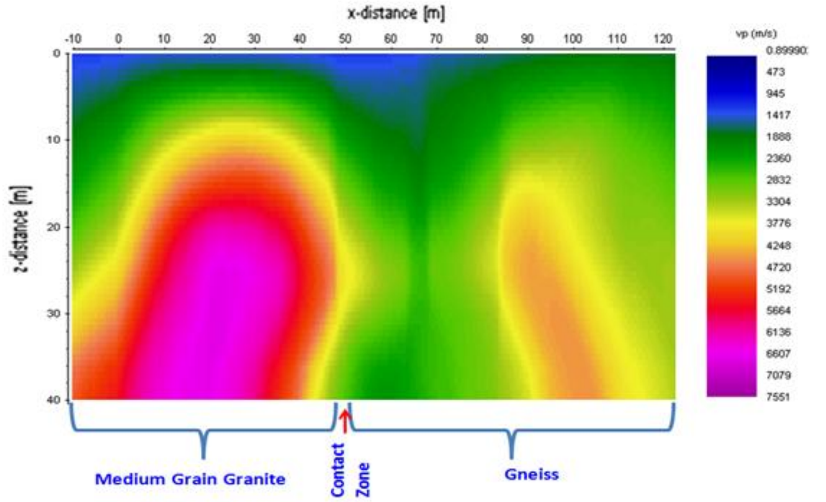

Fig. 4: Refraction Tomography Section for a Profile Across a Medium Grain Granite – Gneiss Contact

Samples of the different rock types at the contact areas were cut at the exposed parts along the profiles, and their densities measures in the laboratory. Tables 1 and 2show some of the rocksamples' source locations,theirmeasured and calculated densities and the statistical comparison between the measured and calculated densities forthe rock samples.The tables also show some of the p-wave velocities deduce from some of the tomograms. Most of the samples' locations are situated at the floor of two valleys where they are exposed by the erosive power of the seasonal streams that flow through the valleys.

Table 1: Statistical Comparison Between the Measured and Calculated Densities of Porphyritic Granite and Gneiss Samples Collected from the Same Source Contact Area

Approximate Sample Source Location		Approximate Sample P-wave Velocity Range		Average Sample Measured Density (Kgm^{-3})		Average Calculated Density (Based on Tomography Velocity) (Kgm^{-3})		Average Standard Deviation in Density Range	
Longitude	Latitude	Porphyritic Granite	Gneiss	Porphyritic Granite	Gneiss	Porphyritic Granite	Gneiss	Porphyritic Granite	Gneiss
7°39′28.1′′	11°08′53.2′′	4300 – 5280	3650 – 4500	2641	2765	2689	2747	95.83	130.37
7°39′29.7′′	11°08′52.8′′	4520 – 5760	3550 – 4400	2686	2632	2777	2693		
7°39′31.2′′	11°08′53.7′′	4380 – 5350	3600 – 4470	2691	2730	2724	2718		
7°39′32.2′′	11°08′53.1′′	4600 – > 5860	3700 – ≈4580	2738	2799	2822	2826		
7°39′34.1′′	11°08′53.5′′	4200 – 5200	3570 – 4430	2663	2747	2582	2707		
7°39′36.0′′	11°08′53.1′′	4480 – 5710	3500 – 4350	2704	2613	2748	2653		

Table 2: Statistical Comparison Between the Measured and Calculated Densities of Medium Grain Granite and Gneiss Samples Collected from the Same Source Contact Area

Approximate Sample Source Location		Approximate Sample P-wave Velocity Range		Average Sample Measured Density (Kgm^{-3})		Average Calculated Density (Based on Tomography Velocity) (Kgm^{-3})		Average Standard Deviation in Density Range	
Longitude	Latitude	Medium Grain Granite	Gneiss	Medium Grain Granite	Gneiss	Medium Grain Granite	Gneiss	Medium Grain Granite	Gneiss
7°39′44.4′′	11°08′29.8′′	4750 - 6010	3700 – 4600	2619	2688	2592	2786	83.26	130.37
7°39′44.0′′	11°08′30.9′′	5200 - > 6300	3520 – 4370	2794	2650	2803	2659		
07°39′42.6′′	11°08′31.8′′	5040 - 6240	3620 – 4490	2692	2774	2789	2736		
7°39′42.2′′	11°08′42.9′′	4860 - 6100	3550 – 4420	2608	2648	2674	2697		
7°39′43.8′′	11°08′44.2′′	4970 - 6160	3800 - ≈4710	2775	2893	2718	2881		
7°39′42.0′′	11°08′51.6′′	4700 - 5950	3740 – 4640	2634	2771	2576	2804		

III. Discussion

The interpreted p-wave velocities generated from the seismic refraction data obtained from a part of Zaria Area, Nigeria were converted to their density equivalencies in this study. The results suggest that the average density range of about 2582 – 2822 kgm^{-3}calculated from an average p-wave velocity range of about 4200 – 5610 ms^{-1} agrees well with therange, 2500 – 2810 kgm^{-3}(Telford *et al.*, 1976) usually associated with porphyritic granite. The calculated density range of about 2653 – 2881 kg m^{-3} and 2576 – 2803 kgm^{-3}encompass the density ranges for gneiss and medium grain granite respectively. Similarly, the results suggest that the average measured density ranges of the rock samples of about 2641 – 2738 kgm^{-3}, 2613 – 2893 kgm^{-3} and 2608 – 2794 kgm^{-3} encompass the density ranges for porphyritic granite, gneiss and medium grain granite respectively. Also, samples of the different rock types at the contact areas were cut at the exposed parts/outcrops for identification in the laboratory. The contacts were identified as porphyritic granite - gneiss andmedium grain granite - gneiss respectively.

This study also investigated how closely bunched the calculated density values are around the mean of the measured density values in order to ascertain the degree of variability between the calculated and measured densities of the rock samples. Hence, a statistical analysis shows that the standard deviation between the calculated and measured density values is about 95.83 for porphyritic granite; it is about 130.37 for gneiss and about 83.26 for medium grain granite.

Considering the high value ranges of the calculated and measured densities of the rock samples in this study the calculated standard deviations show closely bunched measured-calculated density values of the rock samples. That is, the calculated standard deviations reflect the fact that the measured and calculated density values are close together. There is no significant difference between the measured density and p-wave -generated density values. This further suggests that in geophysics interpretation involving densities of rocks samples, calculated densities from p-wave velocities can reliably be substituted for measured values if it is difficult to obtain the rock samples for density determination.

The Nettleton method of density determination has the advantage of averaging the effect of density variations more accurately than can be done from surface samples or direct methods. Even so, it gives information on densities only at relatively shallow depths and can be used only when the near-surface lithology is homogeneous (Dobrin, 1976). This implies that the method of estimating densities from p-wave velocities is a more accurate method and the only method available for the estimation of densities of deeply buried rock units.
The results of this study do notagree well with some results of previous studies on similar topic which suggested that the densities estimated from seismic velocities are not accurate. For example it has, long been shown that the empirical velocity-density curve of Nafe and Drake (1963) indicates that densities estimated from seismic velocities are probably not very accurate. It is important to note that the equipment, method/technique and software used in geophysics researches play significant role in the accuracy of the interpreted results. In this study, state of the earth equipment, method/technique and software were used and the densities estimated from seismic velocities agree very well with the measured densities.

IV. Conclusion

The results of this study have shown that the method of density estimation from seismic velocities is found to be reliable method forcalculating densities of rocks. With modern seismic methods and state of the earth equipment and software, the results obtained are reliable and there is no basis for questioningtheir accuracy.

It is known that even with the same direct method of density measurement, there are always little variations in the measured density values each time they are measured. The same variations are observed when the densities of rocks are estimated from seismic velocities. These do not imply that the method is not accurate. The variations may arise from handling of the seismic equipment, method/technique and software used for the study and environmental variation or combination of them.Densities of rocks estimated from accurately measured seismic velocities are accurate and very close to the measured density values. They can be used in geophysics interpretation and geotechnical studies where it is difficult to obtain the rock samples for density measurement or too costly and time ineffective to carry out density measurement.

In most geophysics interpretation, the researchers' interests are the average bulk densities over the survey areas. The accuracy of the determined average bulk density of any given area depends on the accuracy of the estimated or measured density of the various rock units/block that make up the area.Hence, in areas of complex geology, like Zaria Area, where basement geology differ significantly within a very short distance, it is recommended that rock densities used for geophysics interpretation and geotechnical studies are better estimated from seismic velocities. Using the measured densities of few outcrops in the area for the interpretation and studies may be very deceptive since the basement in the area is characterized by contacts of different rock blocks. Digging boreholes and wells to delineate the different rock types and to collect them for density measurement is neither time nor cost effective. Using seismic velocityestimated densities of the rocks for geophysics interpretation and geotechnical studies in Zaria Area is an approach that enhances adequate and comprehensive coverage, cost and time effectiveness and without compromising accuracy.

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