

PREDICTION OF COMPRESSIONAL WAVE VELOCITY AND FORMATION BULK DENSITY FROM ELECTRICAL RESISTIVITY IN THE SUB-SURFACE OF SOUTH-EAST AND SOUTH-SOUTH NIGERIA

ABSTRACT

The aim of this study is to predict seismic P-wave velocity (V_p) from electrical resistivity (R) observations, compute formation density (P) of consolidated layers in the subsurface and subsequently establish a relationship between (P) and (V_p) for the entire region covered. An electrical and seismic relationship in the subsurface in parts of South-East and South-South Nigeria has been established from predicted compressional wave velocity and formation densities of consolidated layers. The known formation and observed resistivity from field surveys formed the bulk of the baseline data for this study. The methodology involved the collection of known and observed electrical resistivity in the study. Using relevant empirical equations as initial models, the V_p and P were predicted and a relationship was established between using regression analysis. The predicted V_p and the corresponding P were corrected with earlier studies in the area to test their reliability. The model linking P and V_p developed in this study would be useful for future V_p prediction given resistivity values of interest. Findings from this research would also be useful for the estimation of some petrophysical parameters especially in the South-South region.

Keywords: Electrical Resistivity, P-wave velocity, Formation Density, South-East and South-South Nigeria, Petrophysical parameters.

1.0 INTRODUCTION

At different points on the Earth sub-surface, there exist different electrical properties relative to different geological materials or rocks. The different geological foundations is a function of a number of factors, which include variations in water contents, dissolved ions in water and material make-up (Imoukhuede et al., 2014). It is therefore, possible to acquire and classify zones with different electrical properties using resistivity investigations. The science of rock physics accounts for the link between geophysical observations and the core physical properties of rocks such as composition, porosity, and pore fluid content (Mavko, 2009). Petrophysics deals with the technical evaluation of laboratory data and downhole measurements for reservoir properties such as shale-volume fraction, porosity ϕ , permeability k , etc.

Several Resistivity investigations have been carried out in the South-East and South-South Nigeria; to explore for Groundwater as in (Imoukhuede et al., 2014; Ezomo, and Akujieze, 2011; Ezomo and Aiyohuyin, 2012); for subsurface characterization e.g bedrock in (Adegbola, 2010; Ezomo and Aiyohuyin, 2012; Ezomo, 2012; Badmus and Olatinsu, 2013; Agha, 2014; Obasi et al., 2015a); and for

foundation studies or/and Engineering site evaluation as in (Akintorinwa and Adesoji, 2009; Ozegin et al., 2013; Aku and Gani, 2015; Ebhohimen Victor, Luke Mamah, 2014; Obasi et al., 2015b; Ozegin et al., 2013); and road failue (Ebhohimen and Mamah, 2014), among othets.

Evidence abound that electrical resistivity and compressional wave velocity in heterogeneous near-surface materials can be correlated if the both parameters are known (Max et al., 2003). In the case when one of the parameters is unknown, the relationship between them can be used to derive the other (Faust, 1951). Electrical and seismic relationship in the subsurface as contained in (Faust, 1951), was a subject of debate as correlation between anomalous electrical conductivities and low velocities are increasingly observed in non-invasive deep crustal studies (Faust, 1951). Resistivity and velocity are both functions of porosity and this is also the unifying assumption in non-invasive experiments focusing on correlating deep crustal data of variable quality from approximately coincident regional studies (Max et al., 2003). The need to study varied near-surface materials for any such relationships especially as this may have implications for improved structural, petrophysical and environmental characterizations and for the development of algorithms for effective joint multidimensional interpretation of electrical and seismic field data (Max et al., 2003).

The compressional velocities with geological time and depth of burial of the rock were predicted in (Faust, 1951). In another study, Gardner introduced relation of density and P-wave velocity (Gardner, 1974). Given the values of velocity and density of the deep or near sub-surface materials therefore, the porosity and other petrophysical parameters of the medium can be estimated. In the same vein, if P-wave velocities are well predicted and knowing the porosity information of the area, shear wave velocities could also be obtained. Both the P-wave and S-wave velocities are important parameters for improved local seismic events location and seismic hazard studies. From resistivity data, the synthetic P-wave velocity log can be found using Faust's empirical relation (Faust, 1951). Synthetic P-wave velocity log used as input data in order to aims estimated density using Gardner 1974's empirical relationship. Finally, porosity log can be estimated from density. The values of resistivity and depth of consolidated layer from geophysical surveys might be shallow or very deep; depending on the burial of compacted sedimentary rocks.

The aim of this study therefore is to predict the compressional wave velocity and formation density in parts of the South-East and South-South Nigeria, using resistivity values obtained at the consolidated sub-surface layers; establish an empirical model linking the formation bulk density and compressional velocity for the region covered; and subsequently derive some petrophysical parameters in parts of the study area.

1.1 LOCATION AND GEOLOGY OF THE STUDY AREA

The study area comprising the South-East and South-South Nigeria. The study area is accessible through network of roads and well developed footpaths. The three major litho-petrological components of Nigeria geology are the Basement Complex that is Precambrian in age, Younger

Granites comprise several Jurassic magmatic ring complexes centered on Jos and other parts of north-central Nigeria, and Sedimentary Basins containing sediment of Cretaceous to Tertiary ages, comprise the Niger Delta, the Benue Trough, the Chad Basin, the Sokoto Basin, the Mid-Niger (Bida/Nupe) Basin and the Dahomey Basin, (Fatoye and Gideon, 2013; Afegbua and Ezomo, 2013a) and as shown in Fig.1.

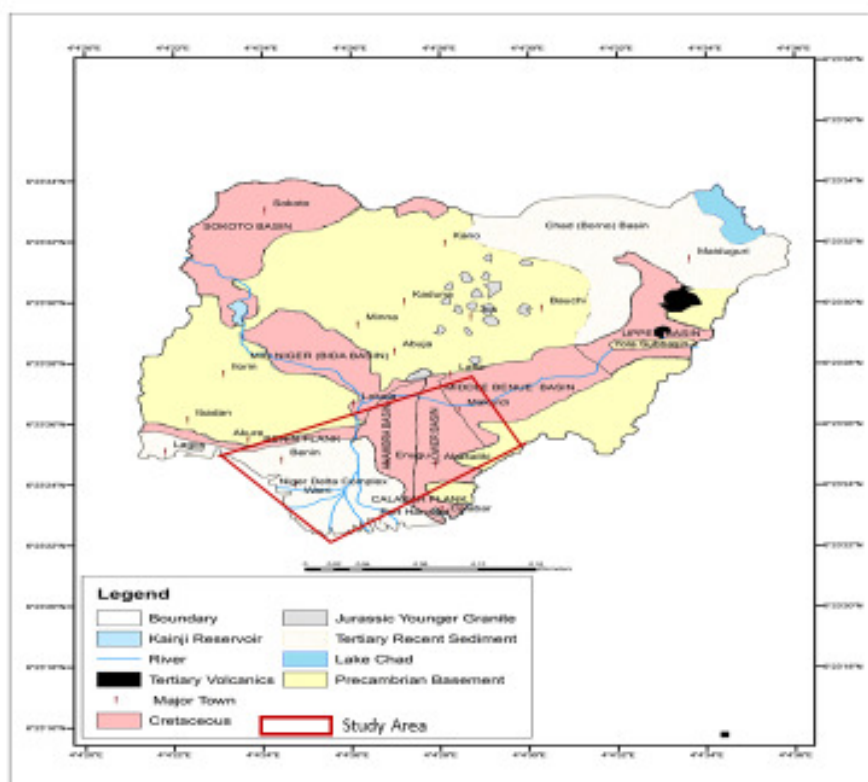


Fig. 1: Geological map of Nigeria (Modified after: Afegbua and Ezomo, 2013a)

The oldest sedimentary rocks in the south eastern Nigeria is the Asu river group (Albian) which comprise of sandstone, shales and lime stones, and these sediments lay unconformably on the Precambrian basement (granites, and biotite gneisses) (Obi et al., 2013). Sedimentation in the Anambra Basin commenced with the Early Campanian – Early Maastrichtian of the Enugu and Nkporo Formations (lateral equivalents) which consist of a sequence of bluish to dark grey shale and mudstone locally with sandy shales, thin sandstones and shelly limestone beds (Obi et al., 2013). The Asu River Group sediments in the Lower Benue Trough comprises predominantly of shales with localized sandstones, siltstones and limestones (Fatoye and Gideon, 2013). There are also extrusive and intrusive material of the Abakaliki Formation in the Abakaliki area and the Mfamosing Limestone in the Calabar Flank (Petters, 1982). Down dip, towards the Niger Delta, the Akata Shale and the Agbada Formation constitute the Paleocene equivalents of the Anambra Basin (Obi et al., 2013).

89 The onshore portion of the Niger Delta Province is delineated by the geology of southern Nigeria and
 90 southwestern Cameroon. The northern boundary is the Benin flank--an east-northeast trending hinge
 91 line south of the West Africa basement massif. The northeastern boundary is defined by outcrops of
 92 the Cretaceous on the Abakaliki High and further east-south-east by the Calabar flank--a hinge line
 93 bordering the adjacent Precambrian. Shallow marine clastics were deposited farther offshore and, in
 94 the Anambra basin, are represented by the Albian-Cenomanian Asu River shale, Cenomanian-
 95 Santonian Eze-Uku and Awgu shales, and Campanian/Maastrichtian Nkporo shale, among others
 96 (Nwachukwu, 1972; Reijers and others, 1997). The distribution of Late Cretaceous shale beneath the
 97 Niger Delta is unknown. The Tertiary section of the Niger Delta is divided into three formations,
 98 representing prograding depositional facies that are distinguished mostly on the basis of sand-shale
 99 ratios. The type sections of these formations are summarized in a variety of papers (e.g. Avbobvo,
 100 1978, Kulke, 1995, Doust, and Omatsola, 1990).

101 In the Eocene, the coastline shape became convexly curvilinear, the longshore drift cells switched to
 102 divergent, and sedimentation changed to being wave-dominated (Reijers and others, 1997). At this
 103 time, deposition of paralic sediments began in the Niger Delta Basin proper and, as the sediments
 104 prograded south, the coastline became progressively more convex seaward.

105 Deposition of the overlying Agbada Formation, the major petroleum-bearing unit, began in the Eocene
 106 and continues into the Recent. The formation consists of paralic siliciclastics over 3700 meters thick
 107 and represents the actual deltaic portion of the sequence. The clastics accumulated in delta-front,
 108 delta-topset, and fluvio-deltaic environments. In the lower Agbada Formation, shale and sandstone
 109 beds were deposited in equal proportions, however, the upper portion is mostly sand with only minor
 110 shale interbeds. The Agbada Formation is overlain by the third formation, the Benin Formation, a
 111 continental latest Eocene to Recent deposit of alluvial and upper coastal plain sands that are up to
 112 2000 m thick (Avbobvo, 1978).

113 2.0 MATERIAL AND METHODOLOGY

114 The bulk of available resistivity data collected from previous studies in the study area formed the
 115 baseline data for this study. Resistivity observations were also obtained through geophysical surveys
 116 in parts of South-East and South-South, Nigeria. The parameters of interest are the formation
 117 resistivity values acquired from the compacted layers in the subsurface, where the P-wave velocity
 118 value is expected to be highest.

119 The resistivity (ρ) of a consolidated layer and the P-wave velocity (V_p) are related by some formulae,
 120 which include:

$$121 \quad \text{Log } 10 \rho = m \text{Log } 10 V_p + c \quad (1)$$

with the respective constants m and c having different signs in unconsolidated and consolidated materials (Max et al., 2003). Faust (1951) found an empirical formula for velocity in terms of the depth of burial Z and the formation resistivity R as shown in equation 2:

$$V_p = a(RZ)^{\frac{1}{6}} \quad (2)$$

Here, V_p is the P-wave velocity and R , the resistivity of the consolidated layer at depth Z , while a is a constant which can be neglected or assigned 0.23 value in (Gardner, 1974). There exists two approaches of deriving the density of the layer using the values of P-wave velocity derived from equation 2. One of the approaches is the commonly used Gardner's equation (Gardner, 1974). Gardner's equation empirically derived values from a wide range of sedimentary rocks and written as:

$$\rho = aV_p^b \quad (3)$$

where: ρ = formation density, V_p = P-wave velocity, $a = 0.23$ and another constant, $b = 0.25$ (Gardner, 1974).

Using equation 2, the values of the compressional wave velocities were computed using known values of formation resistivity. The density of the medium were also evaluated using equation 3. With the resistivity and density, and adopting regression analysis, a model was established using equation 1.

The total porosity of a formation is given by equation 4, (Rider, 1986).

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \quad (4)$$

Where ρ_{ma} is the matrix density; ρ_f is fluid density and ρ_b is the formation bulk density from the study. Porosity is defined as the percentage of voids to the total volume of rock (Adewoye et al., 2013).

In order to test the reliability of the predicted P-wave velocities using the known resistivity values, P-wave velocities computed from resistivity data acquired through field work were correlated with some known P-waves velocities in some selected sites of the study area (Horsefall, et al., 2014; Essien, et al., 2013; Essien, et al., 2014). The resistivity data were carefully collected cutting across the study area, with different sedimentary rocks. The V_p and density for the States of Edo, Ebonyi, Anambra and Cross Rivers in the study area were at first instance, computed to test the approach adopted for

this research. The values of V_p and density for the entire study area were derived. The seismic velocity and density computed at the consolidated layers in the sub-soil were correlated to establish a relationship (model) between them. Using the computed formation bulk density, the porosity of some sites in the South-South region were equally estimated using log data.

3.0 RESULTS AND DISCUSSION

Results of resistivity observations from surveys in parts of the study area are presented in tables 1 to 4. The areas covered are Cross Rivers and Akwa Ibom states, Edo and Delta states, Rivers and Bayelsa States, and Anambra states. Constants 'a' and 'b' could be assumed as unity or assigned values using the Gardner's equation (Gardner, 1974). These constants have different values for consolidated and unconsolidated layers. However, the interest in this study was the consolidated layers.

Table 1: Resistivity (R), depth of consolidated layer (Z), predicted P-wave velocity (V_p) for each area and the derived formation density of consolidated layer (P) in some selected sites in Cross Rivers and Akwa Ibom States.

R	Z	A	V_p	b	P
506.3	17.3	0.23	835.7613	0.25	0.984545
4822.8	35.8	0.23	2618.489	0.25	2.07452
3254.2	22.5	0.23	2806.748	0.25	1.674089
1133.4	19.1	0.23	829.8377	0.25	1.234457
2241.3	15.8	0.23	1357.481	0.25	1.396083
5243.1	43.2	0.23	1682.574	0.25	2.220189

Table 2: Resistivity (R), depth of consolidated layer (Z), P-wave velocity (V_p) and formation density of consolidated layer (P) in some selected sites in Anambra States.

R	Z	a	V_p	b	P
564.2	14.2	0.23	307.1129	0.25	0.962836
3541.1	5.21	0.23	707.2167	0.25	1.186085
18180.2	51.1	0.23	2511.98	0.25	3.159562
607.3	2.5	0.23	3819.958	0.25	0.635269
13199.1	87.2	0.23	3120.19	0.25	3.333398
24089.2	89.5	0.23	3266.03	0.25	3.899719
4256.4	56.3	0.23	2186.021	0.25	2.251696
10856.2	114.5	0.23	17649.67	0.25	3.398152
19830.2	58.8	0.23	34697.27	0.25	3.344245
15143.7	69.4	0.23	20287.29	0.25	3.258516

9532.7	51.7	0.23	18892.22	0.25	2.696489
15995.2	48.7	0.23	29860.37	0.25	3.023442
9348.3	67.9	0.23	24332.07	0.25	2.872583
3375.1	37.5	0.23	1851.706	0.25	1.919559

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Table 3: Resistivity (R), depth of consolidated layer (Z), P-wave velocity (Vp) and formation density of consolidated layer (P) in some selected sites in Edo and Delta States.

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R	Z	a	Vp	b	P
813.1	51.2	0.23	1595.844	0.25	1.453702
8048.1	109.8	0.23	1374.45	0.25	3.120297
3512.6	67.2	0.23	2048.458	0.25	2.243218
2786.4	74.5	0.23	3957.494	0.25	2.172311
26357.4	77.9	0.23	2877.59	0.25	3.852405
29238.2	47.2	0.23	2901.65	0.25	3.48815
12985.3	80.4	0.23	1020.69	0.25	3.253112
24893.1	59.8	0.23	1063.28	0.25	3.554815
1278.1	97.9	0.23	3796.496	0.25	1.914075
652.43	119.4	0.23	2986.172	0.25	1.700226
2327.1	125.6	0.23	1104.21	0.25	2.366318
7525.1	27.9	0.23	2048.094	0.25	2.178468
11167.5	30.3	0.23	1271.05	0.25	2.454549
257623.1	128.2	0.23	1260.46	0.25	7.715076
1823.1	211.3	0.23	1466.81	0.25	2.535417

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Table 4: Resistivity (R), depth of consolidated layer (Z), P-wave velocity (Vp) and formation density of consolidated layer (P) in some selected sites in Rivers and Bayelsa states

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R	Z	a	Vp	b	P
1118	8.7	0.23	372.853	0.25	1.010677
998.7	17.9	0.23	685.2747	0.25	1.176777
472.3	11.1	0.23	200.9637	0.25	0.865979
1056.5	27.1	0.23	1097.527	0.25	1.323828
1067.4	30.5	0.23	1247.969	0.25	1.367032
1054.2	31.1	0.23	1256.782	0.25	1.369439
697.2	28.2	0.23	753.6732	0.25	1.205101

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Table 5 presented results of the predicted compressional wave velocities (V_p) and formation densities (P) using over 400 values of known electrical resistivity values from literatures and surveys in this study. The $\log_{10}V_p$ and $\log_{10}P$ were used to establish the model (equation 5) for the entire region. Using equation 5, P-wave velocity can be predicted given information of the formation density at the consolidated or unconsolidated layers. Most values of the predicted P-wave velocities for the study area, are well correlated with those obtained in (Tamunosiki et al, 2014; Horsefall, et al., 2014; Essien, et al., 2013; Essien, et al., 2014 etc.) in the same region. With the knowledge of P-wave velocity as predicted, the shear wave velocity of an area could also be estimated using the model in (Tamunosiki et al, 2014).

The density values computed from the predicted compressional velocities are useful for estimating some petrophysical parameters like the porosity, permeability etc, in the South-South region where the oil rich Niger Delta is located. Therefore, porosity values were estimated from the predicted P-wave velocity in Rivers and Bayelsa states of Niger Delta as shown in table 6. The porosity values are well correlated to those earlier obtained in (Anigun et al., 2012; Eshimokhai, and Akhirevbulu, 2012; Horsefall et al., 2015 and Adewoye et al., 2013), using different techniques. Fig. 2 is the line fit between $\log_{10}V_p$ and $\log_{10}p$, which is the output of linear regression between log of density and log of P-wave velocity.

Table 5: Some known values of resistivity, computed compressional wave velocities and densities covering the entire area of study. A total of 450 resistivity observations were collected.

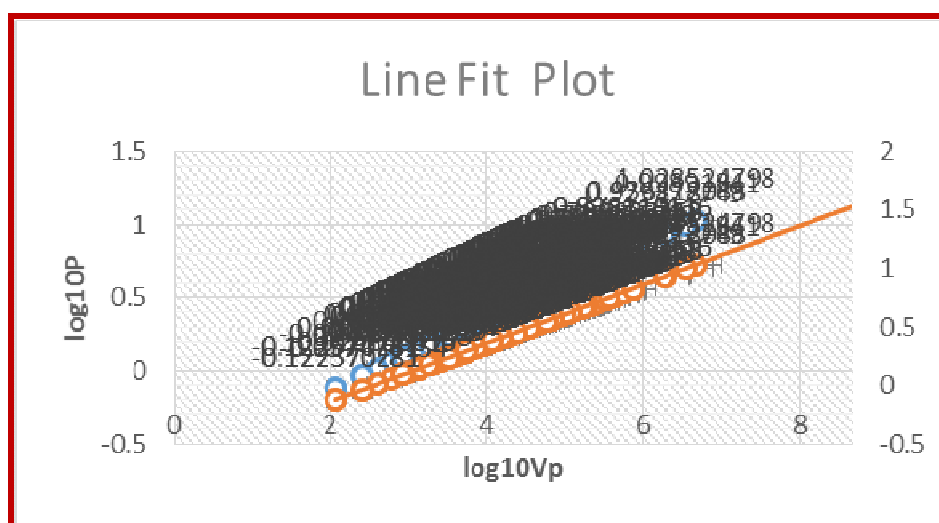
R	Z	a	V_p	b	$\log_{10}V_p$	P	$\log_{10}P$
671.2	19.5	0.23	2181.4	0.25	3.338735	1.571852	0.196412
1018.7	8.1	0.23	1375.245	0.25	3.13838	1.400628	0.146323
999.3	18.2	0.23	3031.21	0.25	3.481616	1.7066	0.232132
472.1	10.6	0.23	134.0433	0.25	2.921189	1.236019	0.092025
1056.4	26.8	0.23	4718.587	0.25	3.673812	1.906254	0.280181
1066.2	30.5	0.23	1419.85	0.25	3.733987	1.973443	0.295225
1052.2	30.9	0.23	2418.83	0.25	3.733906	1.97335	0.295204
696.8	27.8	0.23	3228.507	0.25	3.509002	1.733717	0.238978
503.3	11.5	0.23	264.6583	0.25	2.984374	1.281803	0.107821
579.9	6.3	0.23	608.895	0.25	2.784542	1.142519	0.057863
1242.1	55.9	0.23	1152.232	0.25	4.063417	2.385515	0.377582
57673.8	206.4	0.23	1983979	0.25	6.297537	8.632013	0.936112
662.4	34.7	0.23	3830.88	0.25	3.583299	1.809475	0.257552
8627.5	53.9	0.23	4753.708	0.25	4.889322	3.837589	0.584058
508813.4	54.8	0.23	1647.162	0.25	6.667188	10.67886	1.028525
1084.7	21.8	0.23	3941.077	0.25	3.595615	1.822349	0.260632

3837.6	17.87	0.23	1149.652	0.25	4.058033	2.378133	0.376236
33571.4	334.8	0.23	1873.23	0.25	6.272604	8.509004	0.929879
2025.9	30.11	0.23	1016.642	0.25	4.007178	2.309523	0.363522
467.9	42.2	0.23	3290.897	0.25	3.517314	1.742033	0.241056
813.6	51.2	0.23	6942.72	0.25	3.84153	2.099473	0.32211
8048.6	109.8	0.23	1479.38	0.25	5.168171	4.505787	0.653771
3512.6	67.2	0.23	3934.12	0.25	4.594847	3.239213	0.51044
2786.4	74.43	0.23	3455.292	0.25	4.53864	3.136085	0.496388
26357.4	77.9	0.23	3406.91	0.25	5.534289	5.562884	0.7453
29238.6	97.2	0.23	4735.32	0.25	5.675472	6.033867	0.780596
12985.3	80.2	0.23	1737.176	0.25	5.239475	4.694579	0.671597
24893.4	59.8	0.23	2481.22	0.25	5.394634	5.133179	0.710386
1298.3	98.4	0.23	2122.12	0.25	4.328219	2.778322	0.443783
647.4	119.6	0.23	1290.84	0.25	4.110753	2.45141	0.389416
2268.1	128.2	0.23	4146.737	0.25	4.685399	3.412539	0.533078
7539.1	27.9	0.23	3506.815	0.25	4.544772	3.147175	0.497921
10195.4	30.1	0.23	3116.923	0.25	4.70882	3.458858	0.538933
25839.1	125.4	0.23	34037.19	0.25	5.732424	6.234961	0.794834

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Fig. 2: Output of linear regression between log of density and log of P-wave velocity. Orange ring = data used for regression analysis; Orange line = linear forecast; Black clustered dots = data labels; Blue circles = % error.

The relationship obtained from the regression analysis using table 5 and fig. 2 is presented in equation 5. The minus (-) sign in equation 5 arose from the regression analysis.

$$\log_{10} \rho = 0.25 \log_{10} V_p - 0.64 \quad (5)$$

Using the estimated formation density in parts of the South-South region on table 6, matrix density $\rho_{ma} = 2.65 \text{g/cm}^3$ (sandstone) and fluid density $\rho_f = 1.1 \text{g/cm}^3$, the derived porosity of the formation ϕ , were computed as shown on table 6, using equation 4.

Table 6: Values of total porosity corresponding to formation density. R is the formation resistivity

R	Vp	P	ϕ
1118	372.853	1.010677	1.057628
998.7	685.2747	1.176777	0.950467
472.3	200.9637	0.865979	1.150981
1056.5	1097.527	1.323828	0.855595
1067.4	1247.969	1.367032	0.827721
1054.2	1256.782	1.369439	0.826168
697.2	753.6732	1.205101	0.932193

4. CONCLUSION

An electrical and seismic relationship in the subsurface in parts of South-East and South-South Nigeria has been established from the predicted compressional wave velocities and formation densities of consolidated layers. The known formation resistivity and observed resistivity from field surveys formed the bulk of the baseline data for this study. The predicted compressional seismic velocities and the corresponding formation densities are well corrected with earlier studies in the area. The model linking density and Vp velocity developed in this study would be useful for future Vp prediction given density values of formation of interest. Findings from this research would be useful for the estimation of some petrophysical parameters especially in the South-South region. The characterization petrophysics and environment and for the advancement of procedures for effective interpretation of electrical and seismic field data is also one of the likely benefits of the study.

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