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## RESEARCH ARTICLE

## SITE-DEPENDENT GEOLOGICAL MODEL FOR DENSITY ESTIMATION IN THE NIGER DELTA BASIN, NIGERIA

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## ABSTRACT

Seismic and Well-log data covering three wells in tau( $\tau$ ) Field in the Niger Delta were used for density modelling. Using Hampson Russell Software, Gardner's and Lindseth's relations were localized and subsequently transformed to obtain local fits constants for sand and shale lithologies which were used to achieved the final models. The seismic inversion was performed using four steps: well-to-seismic tie, geology model, acoustic impedance inversion and density prediction. A relationship was established between impedance and density. Pairing Gardner with those by Lindseth approaches and also obtained the average, the final models are  $\rho = 0.1572Z_p^{0.2126} - 16997Z_p^{-1} + 1.5625$  and  $\rho = 0.09045Z_s^{0.1935} - 7093.5Z_s^{-1} + 1.4706$  for sandstones lithology;  $\rho = 0.3185Z_p^{0.3103} - 6510Z_p^{-1} + 1.42855$  and  $\rho = 0.16145Z_s^{0.2308} - 34203.5Z_s^{-1} + 1.42855$  for shale lithology. These models yield a new concept which will contribute to global knowledge. In the absence of density log, these equations can be used to estimate density in the area.

## KEYWORDS

Density, Velocity, Parameters, Sandstones, Shale, Seismic Inversion, Seismic Data and Well-Log Data.

## 1. INTRODUCTION

Mathematical modelling aims to describe the different aspects of the real world, the interaction and dynamics through mathematics so as to solve problems (Marion and Lawson, 2015). It could be seen as the third pillar of science and engineering, with the fulfilment of theoretical analysis and experimentation (Quarteroni, 2009). A model clarifies our views on how the world functions as ideas can be expressed and fundamental predictions identified.

Crossplotting density with rock properties, lithology and pore fluid indicate density with the property that gives the best differentiation between hydrocarbon reservoirs and other fluid types (Koughnet et al., 2003). A proper estimate of density is required to determine the location of shale in the reservoirs in the case of oil sands or heavy oil developments. Differences in densities caused buoyancy of hydrocarbons to occur because of their respective fluids; the flow through the reservoir is in response to differential pressures that exist in a reservoir rock.

The challenge is that density values overlap for sands and shales with shales having a generally lower velocity than sand. This makes density not a good lithological indicator. Inversion for a third parameter such as density is unstable. This requires the inclusion of constants on the parameters to achieve a better result.

Well logs are necessary to enhance the evaluation of different density-velocity equations with reference to Gardner's and Lindseth's relationship used to estimate accurate constants for improve density estimates, both

from p- and s-wave velocities. Well-log data originate from a constant recording obtained in a borehole and documents diverse geological parameters (Oluwatoyin, 2016). There are two methods for well-log testing, open-hole or Logging-While-Drilling (LWD). Open -hole logs take place when drilling is complete and in the uncased portion of the well (Xavier et al., 2015; Lyaka and Mulibo, 2018). This makes accurate density estimates significant for characterization of reservoir.

3D Seismic data is also required. Seismic waves are generated by a source through the subsurface. After reflection at geological boundaries, they return to the surface and are received by geophones and displayed in the seismograph as seismic trace. Travel times of the waves at different ranges from the source are measured and converted to depth values to enable the mapping of the subsurface geological interfaces. Seismic methods are used for explorations like detection and mapping of subsurface boundaries; for identification of physical properties of each subsurface unit.

Density may be easily predictable via seismic inversion to establish relationships between rock properties. The properties of lithology, fluid of a medium may not be concluded with only P-wave statistics but also from the S-wave reaction (Barnola and White, 2001). Two parameters accurately estimated from PP and PS seismic inversion are P-impedance, S-impedance or  $V_p$ ,  $V_s$  (Wu et al., 2015; Zhang et al., 2017). Inversion for rock density even with reasonably noisy data is not stable. This requires a constant to be included on the parameters when using a density-velocity relation to soothe the inversion.

Seismic inversion eliminates the effect of the wavelet within the seismic

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bandwidth and forces well ties to be made; also separates basin properties from the overburden and offers measureable estimates on the reservoir properties. Moreso, seismic inversion converts the seismic view of the earth reflections as a function of time to the earth velocity as a function of depth. This is because seismic data measurements are taken at the earth's surface and involve sending a sound pulse through the earth and recording the echoes from the reflecting boundary. The more the sound pulse travel, the pulse become more distorted resulting in less evidence due to noise and other factors as it returns back to the surface. It helps extract underlying models of the physical characteristics of rocks and fluids from seismic and well-log data; it is also used as a tool to locate hydrocarbon bearing sections in the subsurface.

The survey noted energy that travelled via the deposits of rock and fluids in the ground. Two main parameters of seismic inversion are low frequency and wavelet (band pass filter imposed by seismic acquisition). The low frequency component was derived from well data; high frequency from seismic data. For better interpretation of seismic data, seismic inversion increases data efficiency and quality to better rock effects assessment. It eliminates the influence of the wavelet within the seismic bandwidth.

Seismic inversion method requires seismic data and wavelet estimated from the data. To obtain seismic data, a survey is carried out by firing a short at the surface; it travels to the subsurface and the time was measured for the acoustic energy to travel to a reflection surface and return to the receiver surface. This information acquired, leads to seismic data. To obtain well information, measurements were taken in proportion to equipment on the drill rig (Kelly Bushing).

Density modelling is very necessary to improve density assessments for reservoir classification. It provides evidence for describing a reservoir to identify lithology (Kearey et al., 2002). It gives the accurate distinction among hydrocarbon basins and other fluids. Bulk density from petrophysical investigation is an essential acoustic pointer of the shale occurrence helps the determination of quality of coal (Gray et al., 2006). Differences in densities caused buoyancy of hydrocarbons to occur because of their own media.

**2. LOCATION AND GEOLOGY OF THE STUDY AREA**

The Gulf of Guinea is where Niger Delta is positioned between latitudes 3°N and 6°N; longitudes 5°E and 8°E (Kafisanwol et al., 2018; Igbinigie and Akenzua-Adamczyk, 2018). The investigation area is τ Field, located in the southwest of Port Harcourt, Rivers State (Figure 1). The depobelts form one of the deltas which is characterized by regression and it is the largest in the world with an area of 3 x 10<sup>5</sup>km<sup>2</sup> region; sediment capacity of 5 x 10<sup>5</sup>km<sup>3</sup>; deposit width of above 10<sup>4</sup>m (Ehigiator and Chigbata, 2017; Obi et al., 2016; Abbey et al., 2018). The oil classification in this basin is Akata-Agbada (Ibe and Oyewole, 2019; Olisa, 2018). Figure 1 also presents Benin Flank; Calabar Flank (Didei and Okumoko, 2017). The Akata development is made largely of sea shales. The formation has an estimated thickness of up to 7 x 10<sup>3</sup>m (Oghenemeruo and efetobore, 2019). The Agbada development remains the main oil deposit component. The Benin zone thickness is about 0.28 x 10<sup>3</sup>m but may be up to 2.1 x 10<sup>3</sup>m in the region of extreme settling (Lucas and Omodolor, 2018). The grains of these rocks are identified due to their shapes, sizes, mineral structures, the age and time of admission (Fozao et al., 2019; Tamunobereton et al., 2011). Niger Delta experiences wet and dry seasons; average rain in a month during wet season is about 135 mm and this falls to 65 mm during dry season (Atat and Umoren, 2016).

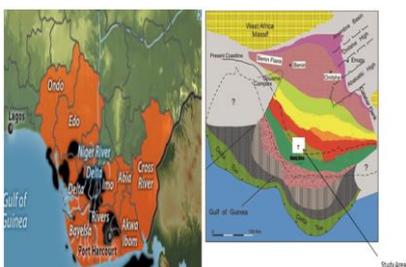


Figure 1: Geology map of Niger Delta and Study area

**2.1 Theoretical Basis**

**2.1.1 Density Log**

A zone with higher density defines the number of electrons with greater

densities. It reduces the GR strongly; thus, a lower count rate of GR is noted at the sensors; similarly for a zone with low density. A low density formation decreases the GR less than a zone with high density; therefore a higher GR count rate is noted (Tamunobereton-ari et al., 2013). Equation 1 defines the connection.

$$n_e = \frac{N_{an}Z}{A} \rho \tag{1}$$

where  $n_e$  is the electron density number in electron cm<sup>-3</sup>;  $N_{an}$  is the number of Avogadro.

**2.1.2 Gamma Ray Log**

This is a data source used to determine lithology. A scintillation detector in the tool used to detect gamma rays and the numbers detected are noted in API. Radioactive elements are seen in illite, in organic matter as well as thorium in heavy minerals like zircon, sphene and others. Minerals are more abundant in shales than sandstones; therefore, shales have higher gamma ray API responses compared to sand.

**2.1.3 Sonic Log**

It enables the determination of  $V_p$ . It is the most accurate log; not affected by the magnitude of the hole, production temperature and salt content. Sonic log also accounts for the time of the creation. Where first arrival is not taken as the head waves of the energy refracted along the borehole wall are cases of severe borehole damage or fractures, gas is present within the pore spaces at high porosity. Caving and rugosity can induce spikes on the sonic response (Odofin, 2014).

**2.1.4 Well-Log Data**

Well-log data originate from a constant recording obtained in a borehole and documents diverse geological parameters (Oluwatoyin, 2016). The measurements derive from three techniques: mechanical, spontaneous or natural and induced (Xavier et al., 2015; Moradi et al., 2016). On a large scale, lithology, bed thickness, compaction, and reserve estimates may also be ascertained through well-log tests (Moradi et al., 2016). A collection of well-log data encompassing a geographical area provides material to define reservoir geometry, correlate beds, and map structures (Lyaka and Mulibo, 2018). Reservoir properties then can be described through combining well-log and core-plug records.

**2.1.5 Description of Seismic Surveying**

Seismic waves are generated by vibrating the ground to produce signal which travel to different boundary of the earth. After reflection at geological boundaries, they arrived back at the shot location and received by detectors and displayed in the seismograph as seismic trace. Travel periods are noted and converted to depth values to enable the mapping of the subsurface geological interfaces. Seismic methods are used for explorations like recognition of rock interfaces; for identification of targets. It is well suited to map layered sedimentary sequences. Seismic method may be performed on land and in ocean. It is also used mostly in offshore and onshore studies (Kearey et al., 2002).

**3. MATERIALS AND METHOD**

**3.1 Materials**

Hampson Russell Software was used for data loading, processing, cross-plots, wavelet extraction, computation of synthetic seismic trace, differentiation between measured depth and true vertical depth. Data acquired from the onshore Niger Delta oilfield are well Location, Suites of Logs (figure 2), Seismic data from 3D survey (figure 3), Geology, Check shot data, Marker and Base map.

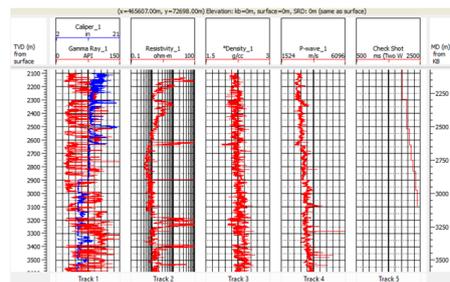


Figure 2: Suite of introduced logs for well Q showing log signatures of Caliper, GR, Resistivity, Density and  $V_p$

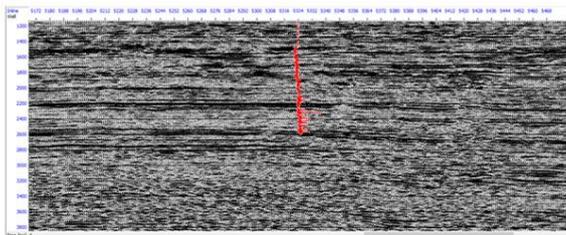


Figure 3: Inline and Crossline baseline seismic section between 1200-3800ms showing p-wave logs

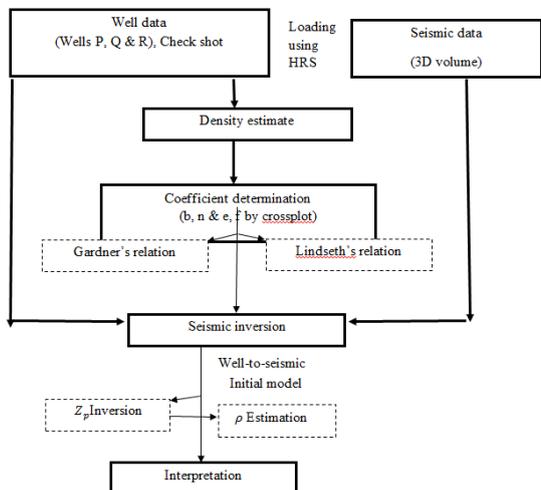


Figure 4: Workflow for Density estimate using well log and seismic inversion

3.2 Method

Seismic inversion is the procedure of changing reflection records into a numerical rock phenomenon account of a basin. Geophysicists do seismic investigations to have data concerning the geology of oil/gas field. The survey noted energy that travelled via the deposits of rock and fluids in the ground. Two main parameters of seismic inversion are low frequency and wavelet (band pass filter imposed by seismic acquisition). The low frequency component was derived from well data; high frequency from seismic data. For better interpretation of seismic data, seismic inversion increases data efficiency and quality to better rock effects assessment. It eliminates the influence of the wavelet within the seismic bandwidth.

Seismic inversion method requires seismic data and wavelet estimated from the data. To obtain seismic data, a survey is carried out by firing a short at the surface; it travels to the subsurface and the time was measured for the acoustic energy to travel to a reflection surface and return to the receiver surface. This information acquired, leads to seismic data. To obtain well information, measurements were taken in proportion to equipment on the drill rig (Kelly Bushing).

Three wells (P, Q and R) with collection of logs such as caliper, gamma ray, resistivity, density and sonic velocity ( $V_p$ ) were studied. S-wave sonic was made available from Castagna curve. The Seismic data has a leading frequency of 60Hz. Inline from 4503 - 5563; Cross line 1540 - 2028 per the volume ranging from 350 to 5200ms. Log headers were checked if the estimated depths are comparative to Kelly Bushing and subsea. Necessary conversions were made with reference to TVDSS. The  $V_p$  and  $V_s$  in Gardner's and Lindseth's connections were used to calculate density. A linear regression line was subjected to these relations to assess the factors b and n from Gardner's relation; e and f from Lindseth's relation for sand and shale lithology. Other procedures employed are presented in figure 4. We used Hampson Russell software to process the data and evaluate the signal. We applied negligible edits; stretch and compression to the data to link the seismic and well log reflectors better. Once the wavelet was identified, a synthetic seismic trace was computed for well log to original seismic correlation. Synthetic seismograms (trace) were generated from original sonic and density well log after the removal of spurious values (figure 5); multiply sonic and density logs to have impedance logs as stated before. We converted well data in unit of depth to unit of time using check shot calibrated in time-depth curve; the wavelet must tie the phase and frequency of seismic information. Well to seismic tie was established in time using statistical wavelet extracted from the data. Calculation of

density from impedance requires a known velocity. The already density-velocity relation evaluated from localizing Gardner and Lindseth constants to those of local fits is used to estimate the density from impedance.

Theoretically, we have localized Gardner and Lindseth equations to parameters in our region of interest using b and n as constant coefficients for local fits and continue with the solution to obtained density models for sandstone and shale lithologies from seismic inversion using impedance.

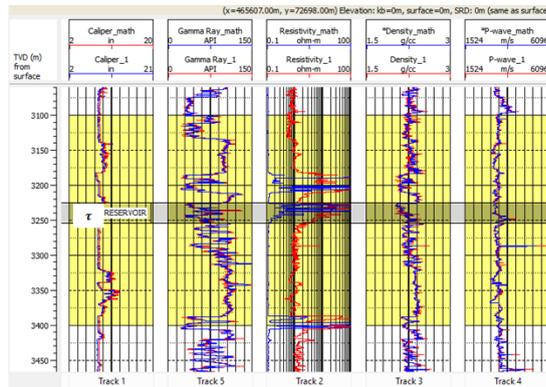


Figure 5: De-spiking of  $V_p$  wave,  $\rho$  and other logs using log filtering utility of HRS (filtered logs in blue, unfiltered logs in red).

4. RESULTS

Pairing Gardner with those by Lindseth approaches and also obtained the average, the final models are  $\rho = 0.1572Z_p^{0.2126} - 16997Z_p^{-1} + 1.5625$  and  $\rho = 0.09045Z_s^{0.1935} - 7093.5Z_s^{-1} + 1.4706$  for sandstones lithology;  $\rho = 0.3185Z_p^{0.3103} - 6510Z_p^{-1} + 1.42855$  and  $\rho = 0.16145Z_s^{0.2308} - 34203.5Z_s^{-1} + 1.42855$  for shale lithology. The result of inversion is seen in figure 6 to 13. The curves show some errors of the predictable densities from the impedance inversion.

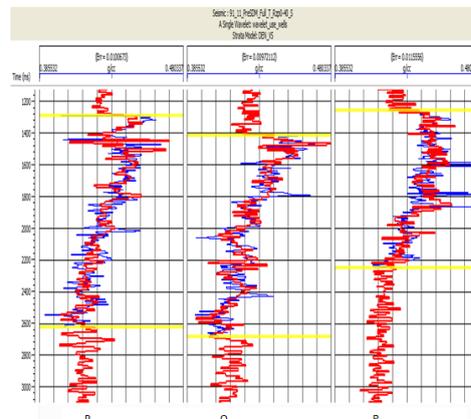


Figure 6: Density assessed from the impedance log inversion with constants from  $V_s$  for sand obtained through Gardner approach with estimated errors

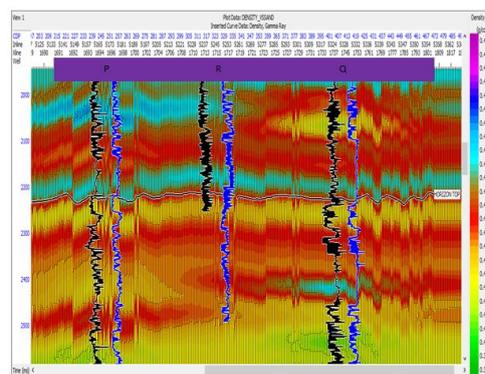
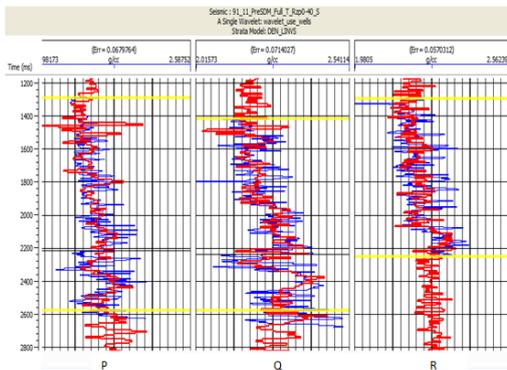
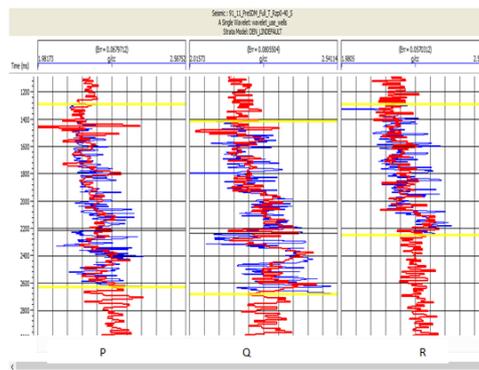


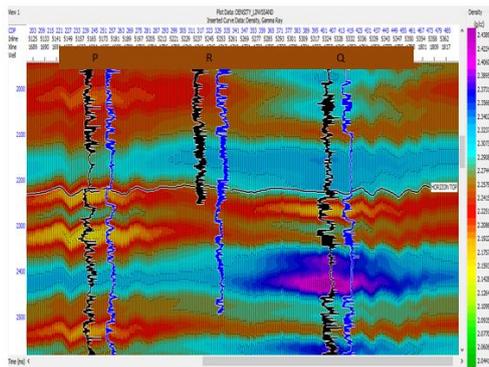
Figure 7: A cross section of density obtained from the impedance inversion using local fit constant from  $V_s$  for sand obtained through Gardner approach.



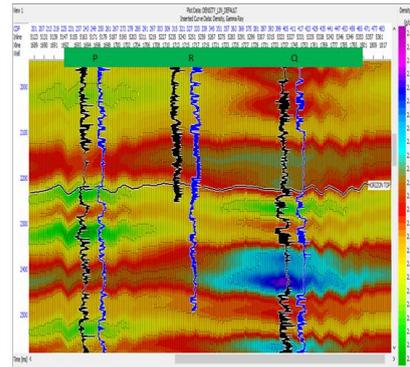
**Figure 8:** Density obtained from the impedance log inversion using local fit constant from  $V_s$  for sand obtained through Lindseth approach with estimated errors.



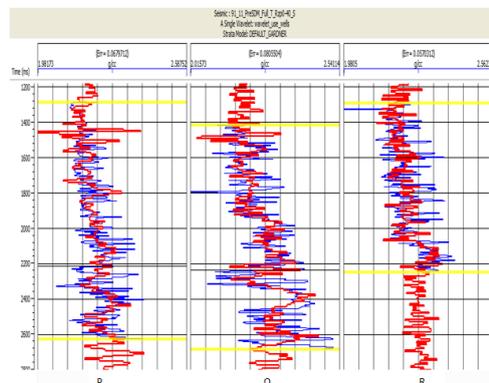
**Figure 12:** Density assessed from the impedance log inversion using Lindseth's default parameter obtained through Lindseth approach with estimated errors.



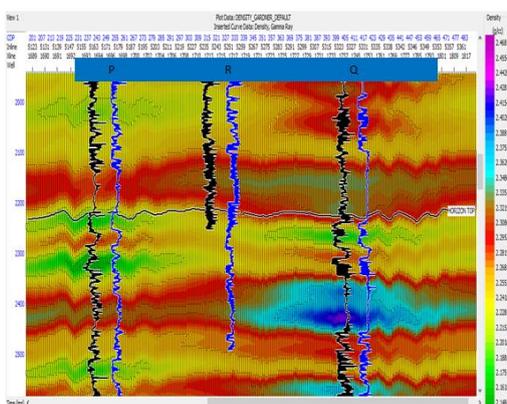
**Figure 9:** A cross section of density assessed from the impedance log inversion using Lindseth's default parameter obtained through Lindseth approach.



**Figure 13:** A cross section of density assessed from the impedance log inversion using Lindseth's default parameter obtained through Lindseth approach.



**Figure 10:** Density estimated from the impedance log inversion using default parameter of Gardner obtained through Gardner approach with estimated errors.



**Figure 11:** A cross section of  $\rho$  assessed from impedance inversion by means of default parameter obtained through Gardner approach.

**5. DISCUSSION**

Impedance relates with velocity as

$$Z = \rho V \tag{2}$$

Equations were obtained from those of Gardner's relation and similarly, from those of Lindseth relations; substituted in equation 2; rearranged for density as the subject. We obtained equations 3 to 10 from seismic inversion as

$$\rho = 0.3144 Z_p^{0.2126} \tag{3}$$

where  $0.3144 = x = q \left(\frac{1}{r+1}\right)$ ;  $0.2126 = y = \frac{r}{r_s+1}$ ,  $q = b = 0.23$ ;  $r = n = 0.27$ , the coefficient  $q$  and the constant  $r$  are local fit constants for sand obtained through seismic inversion analysis,  $\rho$  is density and  $Z_p$  is P-impedance.

GARDNER (Sandstones) from S-impedance

$$\rho = 0.1809 Z_s^{0.1935} \tag{4}$$

where  $0.1809 = x_s = q \left(\frac{1}{r_s+1}\right)$ ;  $0.1935 = y_s = \frac{r_s}{r_s+1}$ ,  $q = b = 0.12$ ;  $r_s = n = 0.24$ , the coefficient  $q$  and the constant  $r_s$  are local fit constants for sand obtained through seismic inversion analysis,  $\rho$  is density and  $Z_s$  is S-impedance.

GARDNER (shale) from P-impedance

$$\rho = 0.6370 Z_p^{0.3103} \tag{5}$$

where  $0.6370 = x = q \left(\frac{1}{r+1}\right)$ ;  $0.3103 = y = \frac{r}{r_s+1}$ ,  $q = b = 0.52$ ;  $r = n = 0.45$ , the coefficient  $q$  and the constant  $r$  are local fit constants for shale obtained through seismic inversion analysis,  $\rho$  is density and  $Z_p$  is P-impedance.

GARDNER (shale) from S-impedance

$$\rho = 0.3229 Z_s^{0.2308} \tag{6}$$

where  $0.3229 = x_s = q^{\left(\frac{1}{r_s+1}\right)}$ ;  $0.2308 = y_s = \frac{r_s}{r_s+1}$ ,  $q = b = 0.23$ ;  $r_s = n = 0.30$ , the coefficient  $q$  and the constant  $r_s$  are local fit constants for sand obtained through seismic inversion analysis,  $\rho$  is density and  $Z_s$  is S-impedance.

LINDSETH (sandstone) from P-impedance

$$\rho = 3.125 - \frac{33994}{Z_p} \quad 7$$

where  $3.125 = \frac{1}{e}$ ;  $33994 = \frac{f}{e^2}$ ,  $e$  and  $f$  are local fit constants ( $e = 0.320$ ,  $f = 3481$ ) for sand obtained from seismic inversion analysis,  $\rho$  is density and  $Z_p$  is P-impedance.

LINDSETH (sandstone) from S-impedance

$$\rho = 2.9412 - \frac{14187}{Z_s} \quad 8$$

where  $2.9412 = \frac{1}{e}$ ;  $14187 = \frac{f}{e^2}$ ,  $e$  and  $f$  are local fit constants ( $e = 0.340$ ,  $f = 1640$ ) for sand obtained from seismic inversion analysis,  $\rho$  is density and  $Z_s$  is S-impedance.

LINDSETH (shale) from P-impedance

$$\rho = 2.8571 - \frac{13020}{Z_p} \quad 9$$

where  $2.8571 = \frac{1}{e}$ ;  $13020 = \frac{f}{e^2}$ ,  $e$  and  $f$  are local fit constants ( $e = 0.350$ ,  $f = 1595$ ) for shale obtained from seismic inversion analysis,  $\rho$  is density and  $Z_p$  is P-impedance.

LINDSETH (shale) from S-impedance

$$\rho = 2.8571 - \frac{68407}{Z_s} \quad 10$$

where  $2.8571 = \frac{1}{e}$ ;  $68407 = \frac{f}{e^2}$ ,  $e$  and  $f$  are local fit constants ( $e = 0.350$ ,  $f = 8380$ ) for shale obtained from seismic inversion analysis,  $\rho$  is density and  $Z_s$  is S-impedance.

In order to obtain our final model, we paired our equations obtained by Gardner approach with those obtained by Lindseth approach using seismic inversion analysis and also obtained the average. This procedure yields a new concept which will contribute to global knowledge. This concept yields the development of site dependent geological model for density estimation using seismic inversion analysis in the  $\tau$  field, Niger delta sedimentary basin as

**SANDSTONES LITHOLOGY** (from P-impedance)

$$\rho = 0.1572Z_p^{0.2126} - 16997Z_p^{-1} + 1.5625 \quad 11$$

where  $Z_p$  is P-impedance,  $0.1572 = \frac{x}{2}$ ;  $x = q^{\left(\frac{1}{r+1}\right)}$ ;  $0.2126 = y = \frac{r}{r+1}$ ,  $q = b = 0.23$ ;  $r = n = 0.27$ ,  $16997 = \frac{f}{2e^2}$ ,  $1.5625 = \frac{1}{2e}$ ;  $e = 0.320$ ;  $f = 3481$ ; the coefficient  $q$  and the constant  $r$  are local fit constants for sand.

**SANDSTONES LITHOLOGY** (from S-impedance)

$$\rho = 0.09045Z_s^{0.1935} - 7093.5Z_s^{-1} + 1.4706 \quad 12$$

where  $Z_s$  is S-impedance,  $0.09045 = \frac{x}{2}$ ;  $x = q^{\left(\frac{1}{r_s+1}\right)}$ ;  $0.1935 = y_s = \frac{r_s}{r_s+1}$ ,  $q = b = 0.12$ ;  $r_s = n = 0.24$ ,  $7093.5 = \frac{f}{2e^2}$ ;  $1.4706 = \frac{1}{2e}$ ;  $e = 0.340$ ;  $f = 1640$ ; the coefficient  $q$  and the constant  $r$  are local fit constants for sand.

**SHALE LITHOLOGY** (from P-impedance)

$$\rho = 0.3185Z_p^{0.3103} - 6510Z_p^{-1} + 1.42855 \quad 13$$

where  $Z_p$  is P-impedance,  $0.3185 = \frac{x}{2}$ ;  $x = q^{\left(\frac{1}{r+1}\right)}$ ;  $0.3103 = y = \frac{r}{r+1}$ ,  $q = b = 0.52$ ;  $r = n = 0.45$ ,  $6510 = \frac{f}{2e^2}$ ,  $1.42855 = \frac{1}{2e}$ ;  $e = 0.350$ ;  $f = 1595$ ; the coefficient  $q$  and the constant  $r$  are local fit constants for shale.

**SHALE LITHOLOGY** (from S-impedance)

$$\rho = 0.16145Z_s^{0.2308} - 34203.5Z_s^{-1} + 1.42855 \quad 14$$

where  $Z_s$  is S-impedance,  $0.16145 = \frac{x}{2}$ ;  $x = q^{\left(\frac{1}{r_s+1}\right)}$ ;  $0.2308 = y_s = \frac{r_s}{r_s+1}$ ,  $q = b = 0.23$ ;  $r_s = n = 0.30$ ,  $34203.5 = \frac{f}{2e^2}$ ;  $1.42855 = \frac{1}{2e}$ ;  $e = 0.350$ ;  $f = 8380$ ; the coefficient  $q$  and the constant  $r$  are local fit constants for shale.

However, well-log data was used to estimate the local fit constants from the transformed equations using Hampson Russall Software. The results are shown in Figures 7, 9, 11 and 13 with the black colour. After seismic inversion, these same figures show clear evidence of improvement with the blue indication. These models achieved from inversion yield a better result for estimation of density.

## 6. CONCLUSION

We have obtained constants for specific rocks for the density-impedance relations in the  $\tau$  field. The new approach for density estimation (density-impedance model for characterization of zone or basin) is very reliable and accurate. The evaluation of equation which fits the data well is necessary; local constraints should be assessed with either  $V_p$  or  $V_s$  or both, since these relations may have been solved empirically. Geology may upset these coefficients meaningfully and could result in loss of evidence if default parameters are not investigated. This new concept (models) [equations 11 to 14] will contribute to global knowledge as it yields the development of site dependent geological model for density estimation using seismic inversion analysis in the  $\tau$  field, Niger delta sedimentary basin.

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