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MECHANICAL PROPERTIES OF RESERVOIR ROCKS IN BORNU BASIN NIGERIA FROM SONIC DERIVED ELASTIC CONSTANTS

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ABSTRACT

Knowledge of geo-mechanical competency of a reservoir rock is necessary before the hydrocarbon in such a formation can be exploited. Such useful information can be obtained from elastic parameters determined from exploratory well logs. This study analytically predicted the S-wave and P-wave velocities from sonic logs of ten exploratory wells from Chad Basin Nigeria. With the determined rock properties, the geo-mechanical constants were computed, and the values used for further interpretation of formation substructure. The computed parameters are useful in well planning, risks assessments and safety optimization. The results of the study show that the Bulk modulus and the ratio of Shear modulus to compressibility are relatively low but falls within the acceptable range for reservoir production. The average Bulk modulus is lower than the threshold value of 2.07×10^{10} Pa in which fluids can be safely produced at any rate.

Keyword: Elastic constants, Modulus, Mechanical competency, reservoir, Bornu Basin.

INTRODUCTION

It is usually an easy exercise in oil field operations to estimate the compressional wave (P-wave) velocity from sonic logs and seismic check shots. This is not the same for Shear wave (S-wave) velocity which is useful in many engineering applications. In order to calculate the elastic parameters (Bulk, Shear and Young’s moduli, Poisson's ratio, and Lame's constants) of a formation, the P- wave, S- wave and density logs need to be available. However, where the S-wave logs do not exist, they can be derived from a P-wave log or core log laboratory analysis. The P-wave logs have been utilized in this study because of its availability. There is therefore the need to extract the S-wave velocities from P-wave velocities and moduli (Eyinla and Oladunjoye, 2014). Records of S-waves velocities when combined with P-waves logs allow further rock property and elastic constant analysis. P-wave velocity in a material varies directly with the material strength and inversely with the density of the material.

Elastic properties such as velocity, density, impedance and Vp/Vs ratio are important in reservoir characterization because they are related to the reservoir properties. Knowledge of rocks properties is useful in the exploration and exploitation of mineral resources and Civil Engineering works (Tiab and Donaldson, 1999). These properties are affected by geological factors such as depth of burial, lithology and anisotropy. Production of sand along with oil and gas is a common problem associated with many unconsolidated rocks materials. Estimating formation strength using elastic constants helps to determine if the formation is strong enough to produce at high flow rates without sand. It is also useful in well planning like in determining formation fracture pressure which is necessary for drilling safety optimization.

In seismic method of geophysical exploration, subsurface geology imaging is optimized by characterizing the waves that travel through the earth material. Sound waves generated at the surface impinge on the rock material causing it to undergo stress and deformation. The material however, returns to its original form after the passage of the wave, which is then picked by a receiver and stored. The received signal is then used to measure the elastic properties of the material. Thus, the strain and deformation on the material is dependent on the elastic properties of the rocks.

The tendency of the rock material to resist the deformation or to restore itself to the original size and shape after the wave passage defines its elasticity (Emujakporue and Ekine, 2009). The constant of proportionality on the relationship between the applied force and the deformations is called the elastic constant or modulus (Sheriff and Geldart, 1995; Omudu and Ebeniro, 2005).

When a sound wave encounters a medium of different acoustic impedance obliquely, mode conversion takes place, and compressional and shear waves are generated. The ratio of compressional wave velocity (*Vp*) to shear-wave velocity (*Vs*), or *Vp/Vs* is sensitive to the fluid in the pores existing in the sedimentary rocks as well as in differentiating lithologies. Vp/Vs ratio in the gas saturated environments is much lower than liquid saturated environments (Tatham, 1982). Pictett (1963), in his work on the porous environment for the Vp/Vs ratio obtained a range of 1.6 to 1.75 for sandstones, 1.9 for limestone and 1.8 for dolomite. Gregory (1977) has computed a Poisson's ratio of about 0.1 for most dry rocks and unconsolidated sands.

Compressional wave (Vp) and shear wave (Vs) velocities obtained from sonic well logs, beyond being used as a tool for lithology discrimination, can be utilized to compute the rocks elastic properties from which the material's geo-mechanical competency can be inferred. It is a common practical inherent problem of producing sand along with oil and gas, especially with many unconsolidated rocks. Parameters like Poisson ratio, Young's, Shear and Bulk moduli are used for characterizing rock mechanical properties and hence the mechanical competency of the reservoir to produce hydrocarbon. Estimation of these parameters from exploratory well logs in Chad basin Nigeria is the main objective of this study.

Geology of the Bornu Basin

Bornu Basin is one of the inland basins in Nigeria and constitutes about 6.5% of the entire Chad Basin, covering about three States of the northern Nigeria, namely Bornu, Jigawa and Yobe States (Nwankwo, 2007). It is located within longitudes 9^{o} E and 14^{o} E and latitudes 11^{o} N and 14^{o} N (Fig. 1). The sediments of the basin dated Cretaceous to Recent with a number of stratigraphic traps within the sedimentary

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sequence. There are many published works on the evolution and geology of Chad Basin (Avbovbo et al., 1986; Olugbemiro et al., 1997; Matheis, 1976; De Klasz, 1978; Okosun, 1995).

The identified stratigraphic units of the basin are Bima Sandstone, Gongila Formation, Fika Shale, Kerri-Kerri and Chad Formations (Okosun, 1995; Nwankwo and Nwosu, 2016). The source rocks are mainly the shale component of the Gongila Formation and the Fika Shale (Olugbemiro et al., 1997; Obaje et al., 2006; Adepelumo et al., 2010; Petters and Ekweozor, 1982). The Bima Formation is the oldest stratigraphic unit in the area (Albian-Cenomanian) and lies on the basement complex. It consists predominantly of feldspathic coarse to pebbly sandstone with thin purplish clay and shaly interbeds representing both lacustrine and marine transgressive deposition respectively. The Gongila Formation is a transitional sequence and overlies the continental Bima Sandstone conformably. It consists of thin to moderately thick inter beds of shale, silty sandstone and sandstone with the sandstone being more dominant at the base. The sandstone is fine to coarse grained with colour ranging from white, brown, yellow, purple to grey. The Gongila and Bima Sanstones form the reservoir rocks of the basin. The Fika Shale is blue-black, fissile, fossiliferous, and occasionally gypsiferous with argillaceous sandstone and limestone intercalations while the Kerri-Kerri Formation is of Paleocene age, and represents an unconformable continental sequence of flat lying grits, sandstone and clays. The sandstones are coarse to fine grained. The Chad Formation with a total thickness ranging from 300 m to 1,200 m, is the youngest stratigraphic unit in the basin. The sequence consists of massive and gritty clays, loosely to uncemented sands and silts.

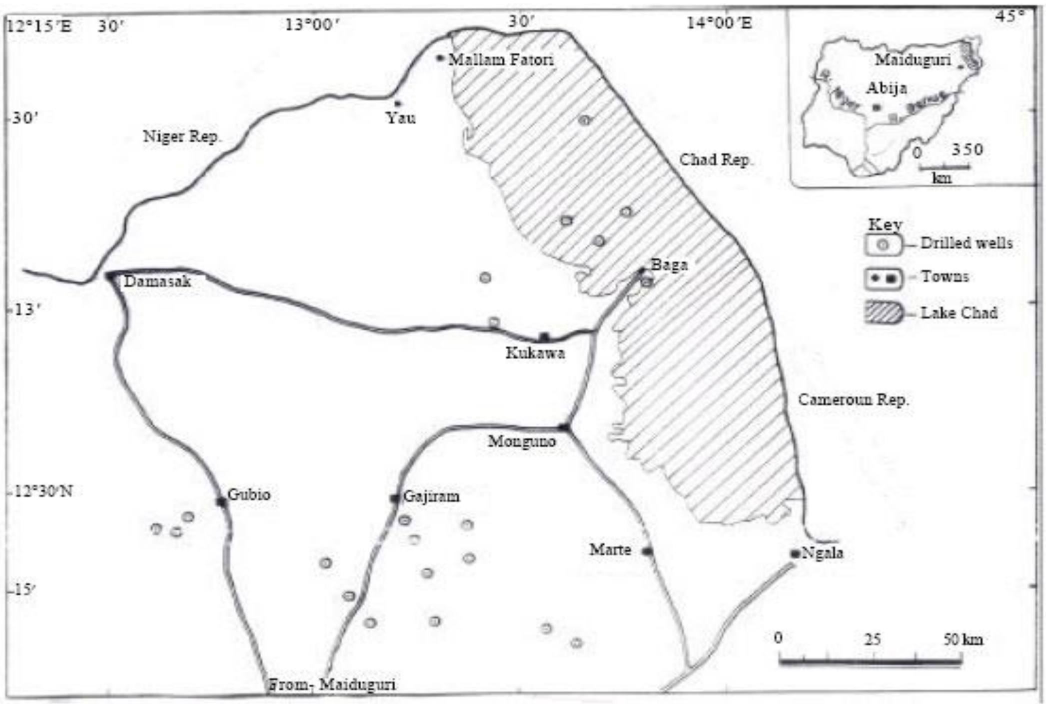

Fig. 1: Location map of the study area (Ali and Orazulike, 2010)

MATERIALS AND METHODS

The basic data for this study is composite logs containing gamma ray, resistivity and sonic logs from ten exploratory wells in Bornu Basin. The data was given by the Nigerian National Petroleum Corporation through its exploration arm, NAPIMS Maiduguri. The logs were digitized at 10 m intervals at particular depths of interest (sand units). The gamma ray logs were used to delineate the sediment boundaries of different stratigraphic units (sand and shale), while the seismic wave interval transit times through a foot of the formation Δt, was estimated from the sonic log. Shale shows higher levels of radioactivity due to absorption of heavy radioactive elements while clean sandstones normally exhibit low level of radioactivity. Reservoir rocks intervals with appreciable thickness were considered for the analysis. Since no core data was available, the compressional and shear wave velocities were respectively computed from sonic logs using the expression:

$$\frac{1}{Vp} = \frac{1}{\Delta t}\ x\ \frac{304800}{1}\ m/s \qquad 1$$

and

Vs_{sand} = (0.80416)Vp – 0.85588)(Castagna and Greenby, 1993) 2

The elastic constants derived are as follows:

1. The Lame's constants:

$$\lambda = \rho V_p^2 - 2\mu \qquad 3$$

where μ is the rigidity or shear modulus which defines the extent a material can withstand shearing, and is given by

$$\mu = \rho V_s^2 \qquad 4$$

ρ is the bulk density estimated by employing the empirical relation of compressional wave velocity and bulk density given by Gardner et al. (1974) and Tezcan et al. (2006) respectively as:

$$\rho = 0.23 {V_p}^{0.25} \qquad 5$$

$$\rho = 16 + 0.002 V_p \qquad 6$$

The bulk density approximated by Gardner et al. (1974) was higher than that of Tezcan et al. (2006) by about 0.02 to 0.1 g/cm^3. However, equation (6) was utilized in carrying out all the computations in this study as it gives better approximate values than other considered models.

2. The Young's Modulus:

$$E = \mu\left(\frac{3\lambda+2\mu}{\lambda+\mu}\right) \qquad 7$$

3. The Poisson's ratio is ratio of strain in a perpendicular direction to the strain in the direction of force:

$$\sigma = \frac{E-2\mu}{2\mu} \qquad 8$$

4. The Bulk Modulus defines the extent a material can withstand squeezing:

$$K = \frac{E}{3(1-\sigma)} \qquad 9$$

5. The Compressibility:

$$\beta = K^{-1} \qquad 10$$

The combined modulus of strength is defined as

$$B = K + \frac{4}{3}\mu \qquad 11$$

A homogeneous and isotropic media has been assumed in the computation. The computed parameters are represented on Tables 1 – 6.

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Table 1: Formation Parameters for Wadi-1

Sand Unit Interval (m)	Vp m/s	Vs m/s	ρ Kg/m^3	μ 10^{10}Pa	λ 10^{10}Pa	K 10^{10}Pa	E 10^{10}Pa	β 10^{-10} Pa^{-1}	B 10^{10}Pa
1460-1610	4541.8	3651.5	2541	3.39	5.24	7.50	8.83	0.133	11.838
2000-2060	2767.4	2224.6	2245	1.11	1.72	2.46	2.90	0.406	5.037
2265-2410	3403.3	2736.0	2364	1.77	2.74	3.92	4.61	0.255	0.360
2710-2750	4549.3	3657.5	2542	3.40	5.26	7.53	8.87	0.133	12.055
2915-3210	4354.3	3500.9	2515	3.08	4.77	6.82	8.03	0.147	7.156

Table 2: Formation Parameters for Masu-1

Sand Unit Interval (m)	Vp m/s	Vs m/s	ρ Kg/m^3	μ 10^{10}Pa	λ 10^{10}Pa	K 10^{10}Pa	E 10^{10}Pa	β 10^{-10} Pa^{-1}	B 10^{10}Pa
2000-2200	3467.4	2787.5	2347	1.66	2.57	3.67	4.32	0.272	3.539
2390-2450	4105.6	3300.7	2478	2.70	4.18	5.98	7.04	0.167	0.515
2510-2590	4115.0	3308.3	2479	2.71	4.20	6.01	7.08	0.166	0.566
2800-2845	4322.8	3475.4	2510	3.03	4.69	6.71	7.90	0.149	2.392
2970-3085	3926.8	3156.9	2450	2.44	3.78	5.41	6.37	0.185	0.007

Table 3: Formation Parameters for Kanadi-1

Sand Unit Interval (m)	Vp m/s	Vs m/s	ρ Kg/m^3	μ 10^{10}Pa	λ 10^{10}Pa	K 10^{10}Pa	E 10^{10}Pa	β 10^{-10} Pa^{-1}	B 10^{10}Pa
1575-1620	2988.2	2402.2	2289	1.32	2.04	2.92	3.44	0.342	0.911
1740-1790	4549.3	3657.5	2542	3.40	5.26	7.53	8.87	0.133	17.960
2185-2250	2796.3	2247.8	2251	1.14	1.76	2.52	2.97	0.400	1.995
2380-2500	4118.9	3311.4	2480	2.72	4.21	6.02	7.09	0.166	6.436
2800-2890	4549.3	3657.5	2542	3.40	5.26	7.53	8.87	0.133	17.963
2920-2980	4482.4	3603.7	2533	3.29	5.09	7.28	8.58	0.137	15.681

Table 4: Formation Parameters for Ziye-1

Sand Units Interval (m)	Vp m/s	Vs m/s	ρ Kg/m^3	μ 10^{10}Pa	λ 10^{10}Pa	K 10^{10}Pa	E 10^{10}Pa	β 10^{-10} Pa^{-1}	B 10^{10}Pa
1630-1685	4233.3	3403.4	2497	2.89	4.47	6.40	7.54	0.156	4.551
1910-1970	3810.0	3063.0	2432	2.28	3.53	5.05	5.95	0.198	0.371
2330-2360	2770.9	2227.4	2246	1.11	1.72	2.47	2.91	0.405	5.316
2550-2660	2770.9	2227.4	2246	1.11	1.72	2.47	2.91	0.405	5.316
2720-2780	4293.0	3451.4	2506	2.98	4,62	6.61	7.78	0.151	5.589
2840-2900	3958.4	3182.4	2455	2.49	3.85	5.51	6.48	0.182	1.256
3110-3200	4762.5	3829.0	2571	3.77	5.83	8.35	9.83	0.119	18.703

Table 5: Formation Parameters for Gubio-1

Sand Units Interval (m)	Vp m/s	Vs m/s	ρ Kg/m^3	μ 10^{10}Pa	λ 10^{10}Pa	K 10^{10}Pa	E 10^{10}Pa	β 10^{-10} Pa^{-1}	B 10^{10}Pa
1785-1800	2848.6	2289.9	2261	1.19	1.84	2.63	3.09	0.381	0.070
2420-2470	2770.9	2227.4	2246	1.11	1.72	2.47	2.91	0.405	0.008
2765-2790	2746.0	2207.3	2241	1.09	1.69	2.42	2.85	0.414	0.001
2890-2945	2540.0	2041.7	2198	0.92	1.42	2.03	2.39	0.493	0.167
3165-3220	2605.1	2094.1	2211	0.97	1.50	2.15	2.53	0.466	0.075
3250-3280	2721.4	2187.6	2236	1.07	1.66	2.37	2.79	0.422	0.001

Table 6: Formation Parameters for Herwa-1

Sand Units Interval (m)	Vp m/s	Vs m/s	ρ Kg/m^3	μ 10^{10}Pa	λ 10^{10}Pa	K 10^{10}Pa	E 10^{10}Pa	β 10^{-10} Pa^{-1}	B 10^{10}Pa
1530-1560	2822.2	2268.7	2256	1.16	1.80	2.57	3.03	0.389	3.499
2100-2130	2673.7	2149.2	2226	1.03	1.59	2.28	2.68	0.439	4.852
3420-3690	4482.4	3603.7	2533	3.29	5.09	7.28	8.58	0.137	11.848
3750-3810	4417.4	3551.4	2524	3.18	4.92	7.05	8.30	0.142	10.091
4230-4260	4549.3	3657.5	2542	3.40	5.26	7.53	8.87	0.133	13.841
4620-4700	4417.4	3551.4	2524	3.18	4.92	7.05	8.30	0.142	10.091

Statistics and geostatistics

The statistical analysis of the variables from six wells were carried out. The variables are Vp, Vs, density, Lame's constants, shear modulus, Young' modulus and compressibility (Table 7).

Table 7: Statistics for 85 Sand Units Intervals

Variable	Min	Max	Mean	Std. Dev.	Variance	Skew	Kurtosis
Vp	2326.72	4762.50	3375.61	600.53	360636.29	0.00073	0.161480
Vs	1870.20	3829.00	2713.69	482.98	233269.68	0.00070	0.161536
ρ	2149.86	2571.05	2348.47	87.65	7682.52	0.00486	0.170364
μ	0.75	3.77	1.86	0.73	0.53	0.00176	0.168570
λ	1.16	5.83	2.88	1.13	1.28	0.00340	0.168940
K	1.17	8.35	4.12	1.62	2.62	0.00312	0.169339
E	1.96	9.83	4.85	1.92	3.69	0.00769	0.168208
β	0.12	0.60	0.31	0.10	0.01	0.00211	0.112566

RESULTS AND DISCUSSION

The result of the study (Tables 1 – 6) shows that Vp and Vs give a linear relationship. Seismic velocities of rock samples provide vital information about the physical characteristics that may be useful in both Civil Engineering works and oil production. The computed Poisson's ratio and Vp/Vs for all the wells under study are nearly constant which is indicative of dry and porous sandstone. A Vp/Vs value of 1.24 and σ of 0.304 was obtained for all the wells. This very low Vp/Vs ratio might also suggest that the area is more gas prone and has good porosity which is indicative of hydrocarbonl-bearing sand channel. It also

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suggests that the shale content within the reservoir rocks is low. The Vp/Vs value of 1.24 obtained for the basin also compares favourably with a value of 1.7 and 1.6 determined by Pickett (1963) for Calcareous and clean sandstones respectively. Similarly, an average poisson ratio of 0.304 suggests that the Chad Basin sandstone is unconsolidated and dry.

The Modulus of strength for the Chad Basin Nigeria varies from very low average of 0.054 x10^{10} Pa in Gubio-1 Well to 10.16 x 10^{10} Pa in Kanadi-1 with a Basin average of 5.64 x 10^{9} Pa. This value is lower than the threshold value of 2.07 x 10^{10} Pa in which fluids may be produced safely at any rate (Eyinla and Oladunjoya, 2014). In addition, hydrocarbon bearing tertiary sediments could produce below a certain optimum flow rate without the problem of sand production when the Modulus of strength ranges between 1.03 x 10^{10} Pa and 2.07 x 10^{10} Pa.

The standard deviation obtained in this study is averagely not high which implies a good precision of the computations made.

CONCLUSION

The study shows that well logs data of acoustic properties can be used in predicting shear wave velocities as well as from P-wave velocity. Also, the knowledge of these values can help us to estimate other rock geo-mechanical properties using appropriate model equations; from which the competency of the formation for hydrocarbon exploration safety can be inferred.

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