Evaluation of the Seal Integrity for a Hydrocarbon Reservoir: The Niger Delta as Case Study

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***Abstract* -A typical seal rock in a Niger Delta reservoir was studied to describe its seal integrity. The brittleness index of the seal interval was estimated by first describing some elastic properties of the seal interval, Young's modulus and Poisson's ratio to be specific. These measures were estimated by measuring the p- and s-wave velocity from well logs obtained from a field in the Niger Delta. Comparing these velocities with depth showed a general trend of increasing velocity with depth. A mean brittleness index of 0.20 was estimated for the seal interval of one of the wells. This is indicative of a high seal integrity, as seal rocks with brittleness index less than 0.60 are considered to have good seal integrity.**

Index Terms: **Seal, Seal Integrity, Young's Modulus, Poisson's Ratio, P-wave, S-wave, Brittleness Index**

I. INTRODUCTION

Ranked as one of the major hydrocarbon provinces in the world, the Niger Delta basin is characterized by thick sedimentary deposits and prominent geological features favorable for petroleum generation, migration and entrapment[1]. It is the largest basin in the West African continental margin and is noted among the major prolific deltaic oil and gas accumulations[2]. Hydrocarbons are largely trapped in sandstones and unconsolidated sands in the pyroclastic Agbada Formation, which consists of multiple vertically-stacked reservoir sequences. However, the traps and structures pose great challenges in mapping because of their complexities largely in structural deformations[3, 4]. Historically, relatively little attention has been focused on seals, which are of critical importance, especially in areas with a proven history of breached hydrocarbon accumulations[5].

The top seal occurs above the reservoir and forms a barrier to the vertical migration of hydrocarbons. Seal integrity describes the mechanical properties of a seal rock. An understanding of the petroleum system is a huge part of modern petroleum exploration, requiring an understanding of each of the major elements of the system.

Seal integrity, which is a function of lithology and regional stresses, can be considered as the seal rock propensity to develop structural permeability[6] and is related to the presence or absence of fluid conducting fractures[7]. Seal integritycan be measured in a laboratory or evaluated qualitatively by core examination, bore-hole imaging and petrographic studies[5, 8].

According to Kivior et al.[7], Seal integrity can be estimated from geophysical well logs by taking the mean brittle index, BRI, for each seal interval where well logs were available. One way to define the brittleness index is in terms of geomechanical properties of Young's modulus, E, and Poisson's ratio, υ. It is however important to note that a BRI value does not necessarily indicate the presence of open fluid conducting fractures and thus a brittle rock may retain a hydrocarbon column [9].

II. THE NIGER DELTA BASIN

The Niger Delta, also referred to as the Niger Delta Province, is an extensional rift basin located in the Niger Delta and the Gulf of Guinea on the passive continental margin near the western coast of Nigeria, with suspected or proven access to Cameroon, Equatorial Guinea and Sao Tome and Principe[1]. This basin is very complex and it carries high economic value as it contains a very productive petroleum system. The Niger Delta basin is one of the largest subaerial area of about 75,000 km^2, a total area of 300,000 km^2, and a sediment fill of 500,000 km^3[1]. The sediment fill has a depth between 9-12 km [10].

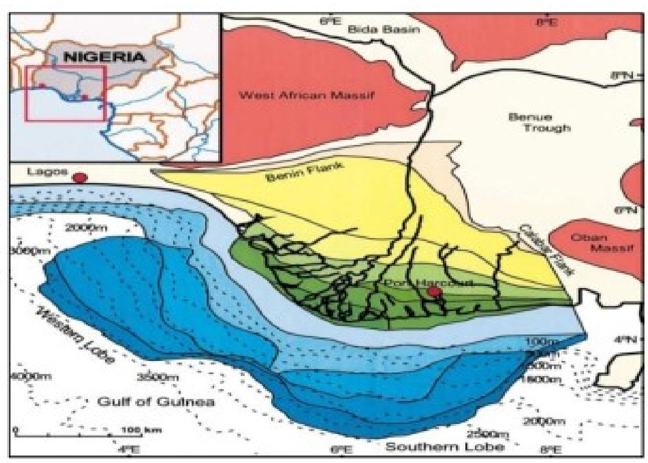

Fig.1: Map of The Niger delta[1]

Stratigraphically, the Niger Delta is made of three distinct lithostratigraphic layers; Benin, Paralic Agbada and pro-delta Marine Akata Formation representing prograding depositional facies distinguished mostly on the basis of sand-shale ratio[11, 12, 13, 14] as shown in Fig. 2 below.

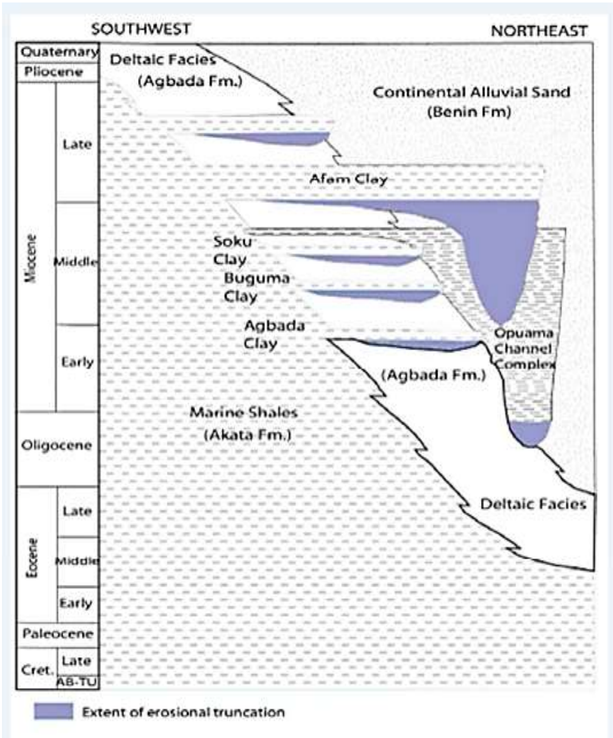

Fig. 2: Stratigraphic columns showing the three Formations of the Niger Delta[12]

III. METHODOLOGY

The data that will be used for this research are well log data includingGamma ray logs, Resistivity logs, Soniclogs and Density logs. With the aid of gamma ray logs and resistivity logs, a hydrocarbon bearing formation will be identified from a geo-physical well log obtained in the Niger Delta. The accompanying shaley formation above this formation will then be delineated for evaluation of its seal integrity.

Adopting the empirical model described by Waters et al. [15], the brittleness index of the seal interval of interest will be evaluated as;

$$BRI = 0.5\left(\left(\frac{E - E_{min}}{E_{max} - E_{min}}\right) - \left(\frac{\upsilon - \upsilon_{max}}{\upsilon_{min} - \upsilon_{max}}\right)\right) \qquad 1$$

Where

E = Young's modulus at each depth location along well path.

υ = Poisson's ratio at each depth location along well path.

E_{min} = Minimum vertical Young's modulus in interval of interest

E_{max} = Maximum vertical Young's modulus in interval of interest;

υ_{min} = Minimum vertical Poisson's ratio in interval of interest

υ_{max} = Maximum vertical Poisson's ratio in interval of interest.

There is an existing relationship between v_s, v_p and the elastic moduli. According to the existing literatures [16, 17, 18], the dynamic Young's Modulus, E_{dyn}, can be obtained from elastic wave velocities estimated from well logs such that;

$$E_{dyn} = \frac{\rho V_S^2(3V_P^2 - 4V_S^2)}{(V_P^2 - V_S^2)} \qquad 2$$

Where

ρ = Bulk density as described from density log, kg/m^3.

V_P = p-wave velocity, km/s.

V_S = s-wave velocity, km/s.

The p-wave velocity, V_P, will be obtained by estimating the inverse of the interval transit time, Δt, as obtained from sonic logs [19, 20, 21].

The s-wave velocity, on the other hand, will be obtained using Greenberg and Castagna [22] correlation for shales;

$$V_{S-shale} = (0.76969V_P - 867.35)\ m/s \qquad 3$$

Therefore, for the purpose of consistency, the obtained V_P from sonic travel time will be multiplied by 1000000 as there will be a conversion from $ft/\mu s$ (the unit of velocity obtained from sonic travel times which is usually in $\mu s/ft$) to ft/s and then divided by 3.2808 (since $1m/s = 3.2808ft/s$) converting to m/s.

According to Burshtein [23], dynamic Poisson ratio, μ_{dyn}, can be obtained using the resonance method above or the pulse test method involving the use of sonic velocities, but the later gives more accurate results. The pulse test method, as applied by Fjar et al. [24], Archer and Rasouli [16] and Davies et al. [25]is described as;

$$\mu_{dyn} = \frac{V_P^2 - 2V_S^2}{2(V_P^2 - V_S^2)} \qquad 4$$

Where

V_P = p-wave velocity, km/s.

V_S = s-wave velocity, km/s

As mentioned earlier, the seal integrity will be evaluated by taking the mean brittleness index of the seal interval of interest.

IV. RESULTS AND DISCUSSION

A.Results

The delineated reservoirs and seal intervals are shown in Fig. 3;

The estimated variables needed for a proper description of brittleness index and the estimated brittleness index are shown in *Table I* below, with a comparison between p- and s-wavevelocities as they relate to depth, as seen in Figs. 4 and 5.

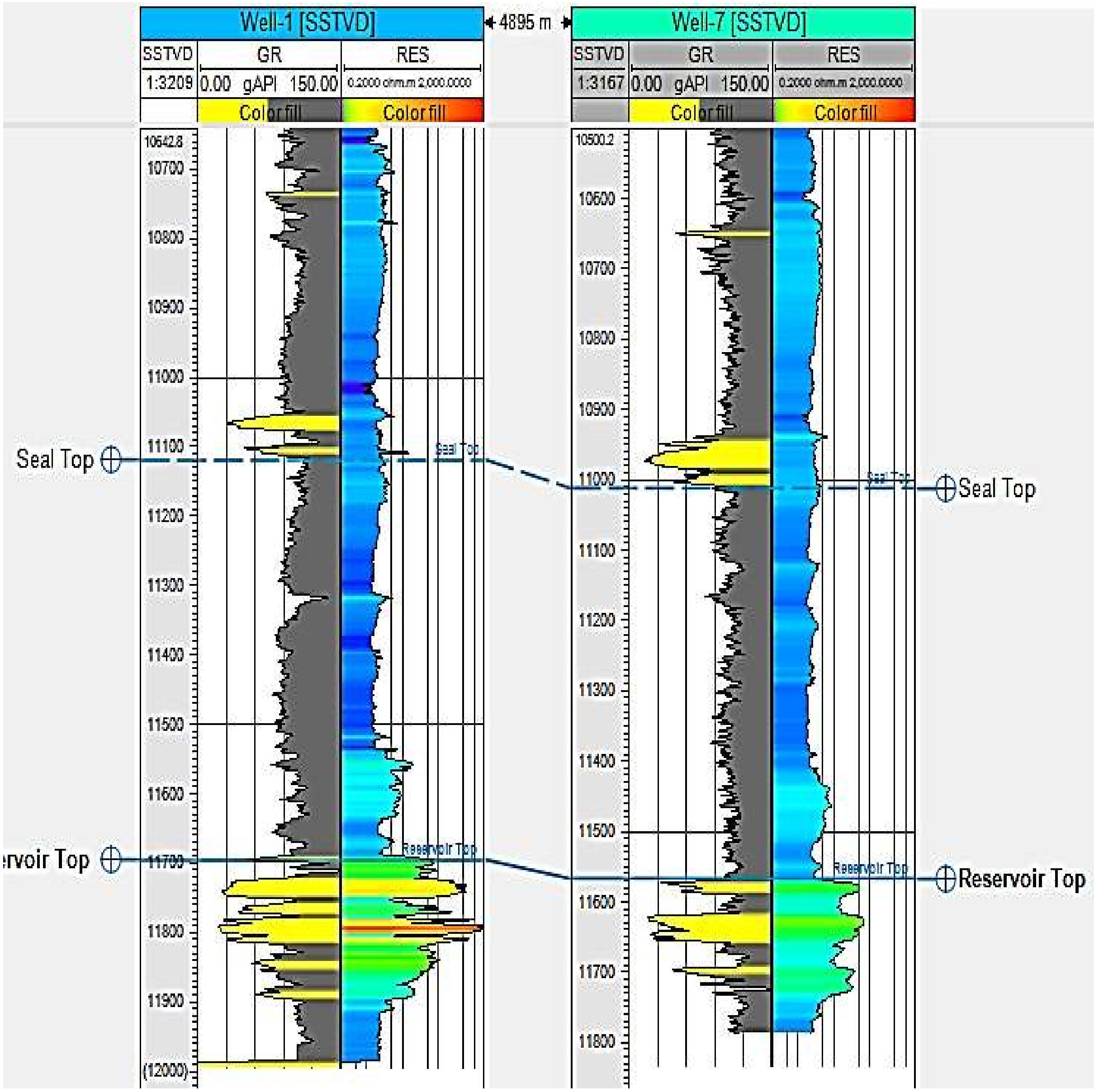

Fig.3: Delineated Reservoir and Seal intervals

Table I: Computed values of formation density, p-wave velocities, s-wave velocities, Young's modulus, Poisson's ratio and brittleness index for Well-1 within the seal interval

DEPTH	DENSITY	SONIC TRANSIT TIME	P-WAVE VELOCITY, V_P	S-WAVE VELOCITY, V_S	YOUNG'S MODULUS, E_{dyn}	POISSON'S RATIO, v_{dyn}	BRITTLENESS INDEX, BRI
(ft)	(kg/m^3)	$(\mu s/ft)$	(m/s)	(m/s)	(MPa)		
11120.00	2189.00	88.98	3425.53	1769.25	18063.39	0.31809	0.23
11125.00	2192.00	90.10	3382.95	1736.47	17464.37	0.32113	0.22
11130.00	2240.00	90.86	3354.65	1714.69	17428.74	0.32317	0.21
11135.00	2241.00	88.96	3426.30	1769.84	18504.11	0.31804	0.24
11140.00	2292.00	88.35	3449.96	1788.05	19292.08	0.31637	0.26
11145.00	2243.00	87.60	3479.49	1810.78	19332.22	0.31429	0.26

11150.00	2173.00	90.06	3384.45	1737.63	17334.64	0.32103	0.21
11155.00	2212.00	80.98	3763.94	2029.72	23602.10	0.29499	0.39
11160.00	2436.00	61.34	4969.09	2957.31	52228.86	0.22578	1.00
11165.00	2240.00	90.71	3360.20	1718.96	17510.34	0.32277	0.21
11170.00	2385.00	89.15	3419.00	1764.22	19575.95	0.31856	0.25
11175.00	2343.00	89.19	3417.47	1763.04	19207.08	0.31867	0.25
11180.00	2394.00	87.32	3490.65	1819.37	20817.47	0.31351	0.29
11185.00	2426.00	87.08	3500.27	1826.77	21256.92	0.31283	0.29
11190.00	2351.00	88.59	3440.61	1780.85	19639.64	0.31703	0.26
11195.00	2383.00	85.51	3564.54	1876.24	21951.56	0.30838	0.32
11200.00	2355.00	88.47	3445.28	1784.45	19747.54	0.31670	0.26
11205.00	2322.00	86.09	3540.52	1857.76	20996.81	0.31004	0.30
11210.00	2340.00	85.14	3580.03	1888.16	21812.54	0.30732	0.32
11215.00	2417.00	85.63	3559.54	1872.40	22179.42	0.30873	0.32
11220.00	2361.00	85.67	3557.88	1871.12	21637.84	0.30884	0.31
11225.00	2414.00	88.96	3426.30	1769.84	19932.58	0.31804	0.26
11230.00	2370.00	85.04	3584.24	1891.40	22163.19	0.30703	0.33
11235.00	2398.00	89.15	3419.00	1764.22	19682.65	0.31856	0.25
11240.00	2343.00	92.49	3295.53	1669.19	17331.50	0.32747	0.19
11245.00	2345.00	93.25	3268.67	1648.51	16944.41	0.32944	0.18
11250.00	2329.00	92.77	3285.58	1661.53	17079.64	0.32820	0.18
11255.00	2394.00	94.77	3216.25	1608.16	16510.09	0.33332	0.16
11260.00	2378.00	96.26	3166.46	1569.84	15671.28	0.33705	0.13
11265.00	2415.00	95.40	3195.01	1591.82	16337.45	0.33491	0.15
11270.00	2390.00	94.05	3240.87	1627.11	16850.11	0.33149	0.17
11275.00	2423.00	94.11	3238.80	1625.52	17051.35	0.33165	0.17
11280.00	2415.00	93.96	3243.97	1629.50	17073.46	0.33126	0.17
11285.00	2402.00	96.87	3146.52	1554.50	15538.94	0.33856	0.13
11290.00	2410.00	95.23	3200.71	1596.21	16388.43	0.33448	0.15
11295.00	2370.00	97.86	3114.69	1530.00	14879.28	0.34098	0.11
11300.00	2416.00	96.93	3144.58	1553.00	15601.09	0.33871	0.13
11305.00	2407.00	97.83	3115.65	1530.73	15125.28	0.34091	0.11
11310.00	2400.00	98.14	3105.81	1523.16	14940.77	0.34166	0.11
11315.00	2365.00	99.03	3077.89	1501.67	14333.32	0.34380	0.09
11320.00	2367.00	99.23	3071.69	1496.90	14259.42	0.34428	0.09
11325.00	2431.00	99.00	3078.83	1502.39	14746.62	0.34373	0.10
11330.00	2434.00	99.46	3064.59	1491.43	14562.06	0.34483	0.09
11335.00	2346.00	103.40	2947.81	1401.55	12479.03	0.35396	0.03
11340.00	2402.00	102.40	2976.60	1423.71	13161.95	0.35168	0.05
11345.00	2410.00	102.50	2973.69	1421.47	13166.58	0.35191	0.05
11350.00	2285.00	104.10	2927.99	1386.29	11905.20	0.35553	0.02
11355.00	2304.00	105.70	2883.67	1352.18	11450.53	0.35908	0.00
11360.00	2348.00	104.10	2927.99	1386.29	12233.44	0.35553	0.02
11365.00	2366.00	105.00	2902.89	1366.98	12003.78	0.35753	0.01

11370.00	2423.00	90.49	3368.37	1725.25	19071.21	0.32218	0.23
11375.00	2337.00	95.15	3203.40	1598.28	15930.89	0.33428	0.15
11380.00	2351.00	88.24	3454.26	1791.36	19857.45	0.31606	0.26
11385.00	2366.00	90.92	3352.44	1712.99	18374.75	0.32333	0.22
11390.00	2358.00	88.71	3435.96	1777.27	19623.85	0.31736	0.26
11395.00	2343.00	93.15	3272.18	1651.22	16982.18	0.32918	0.18
11400.00	2360.00	95.84	3180.34	1580.53	15752.68	0.33601	0.14
11405.00	2298.00	97.00	3142.31	1551.25	14807.66	0.33888	0.12
11410.00	2271.00	96.04	3173.72	1575.43	15066.61	0.33651	0.13
11415.00	2259.00	100.30	3038.92	1471.68	13178.87	0.34681	0.07
11420.00	2326.00	98.07	3108.02	1524.86	14510.72	0.34149	0.10
11425.00	2301.00	99.34	3068.29	1494.28	13816.07	0.34454	0.08
11430.00	2369.00	99.22	3072.00	1497.14	14275.76	0.34425	0.09
11435.00	2194.00	99.51	3063.05	1490.25	13106.50	0.34494	0.07
11440.00	2206.00	100.30	3038.92	1471.68	12869.67	0.34681	0.06
11445.00	2379.00	101.80	2994.14	1437.21	13270.82	0.35031	0.06
11450.00	2379.00	95.89	3178.68	1579.25	15855.35	0.33613	0.14
11455.00	2378.00	93.65	3254.71	1637.77	16972.72	0.33047	0.18
11460.00	2349.00	95.17	3202.73	1597.76	16002.91	0.33433	0.15
11465.00	2357.00	94.75	3216.93	1608.69	16264.87	0.33327	0.16
11470.00	2410.00	90.96	3350.96	1711.85	18693.18	0.32344	0.22
11475.00	2325.00	92.75	3286.29	1662.08	17060.83	0.32814	0.18
11480.00	2347.00	94.08	3239.84	1626.32	16531.72	0.33157	0.17
11485.00	2429.00	97.08	3139.72	1549.26	15613.88	0.33908	0.13
11490.00	2312.00	96.99	3142.63	1551.50	14902.39	0.33886	0.12
11495.00	2187.00	103.40	2947.81	1401.55	11633.26	0.35396	0.02
11500.00	2222.00	102.80	2965.02	1414.79	12031.74	0.35260	0.03
11505.00	2278.00	101.40	3005.95	1446.30	12859.87	0.34938	0.05
11510.00	2327.00	101.30	3008.92	1448.59	13175.74	0.34915	0.06
11515.00	2264.00	101.50	3002.99	1444.02	12742.77	0.34961	0.05
11520.00	2311.00	101.90	2991.20	1434.95	12853.15	0.35054	0.05
11525.00	2335.00	100.80	3023.85	1460.07	13419.97	0.34798	0.07
11530.00	2269.00	102.30	2979.51	1425.95	12470.20	0.35145	0.04
11535.00	2354.00	103.20	2953.52	1405.95	12596.07	0.35351	0.03
11540.00	2345.00	101.10	3014.87	1453.17	13357.18	0.34868	0.06
11545.00	2332.00	101.90	2991.20	1434.95	12969.95	0.35054	0.05
11550.00	2222.00	103.70	2939.28	1394.99	11714.84	0.35463	0.02
11555.00	2175.00	102.90	2962.14	1412.58	11742.33	0.35282	0.03
11560.00	2325.00	100.70	3026.85	1462.39	13402.51	0.34775	0.07
11565.00	2354.00	99.78	3054.76	1483.87	13948.81	0.34559	0.08
11570.00	2369.00	90.30	3375.46	1730.70	18757.05	0.32167	0.23
11575.00	2351.00	98.59	3091.63	1512.25	14438.47	0.34275	0.10
11580.00	2275.00	97.43	3128.44	1540.58	14469.78	0.33993	0.11
11585.00	2115.00	98.01	3109.92	1526.33	13218.33	0.34134	0.09

11590.00	2355.00	78.28	3893.76	2129.64	27483.62	0.28659	0.47
11595.00	2120.00	84.87	3591.42	1896.93	19933.83	0.30654	0.30
11600.00	2332.00	84.03	3627.32	1924.56	22528.50	0.30410	0.34
11605.00	2341.00	83.37	3656.04	1946.66	23103.47	0.30216	0.36
11610.00	2284.00	84.06	3626.03	1923.57	22043.44	0.30418	0.34
11615.00	2357.00	84.68	3599.48	1903.13	22298.05	0.30599	0.33
11620.00	2432.00	81.99	3717.57	1994.03	25104.18	0.29805	0.40
11625.00	2439.00	82.91	3676.32	1962.28	24432.71	0.30080	0.38
11630.00	2404.00	82.88	3677.65	1963.30	24105.59	0.30071	0.37
11635.00	2451.00	80.60	3781.68	2043.37	26481.60	0.29382	0.43
11640.00	2445.00	81.90	3721.66	1997.17	25312.75	0.29778	0.40
11645.00	2410.00	80.98	3763.94	2029.72	25714.76	0.29499	0.42
11650.00	2431.00	84.23	3618.71	1917.93	23333.84	0.30468	0.35
11655.00	2394.00	80.73	3775.59	2038.69	25755.15	0.29422	0.42
11660.00	2430.00	82.76	3682.98	1967.41	24461.57	0.30035	0.38
11665.00	2483.00	82.08	3713.50	1990.89	25555.36	0.29832	0.40
11670.00	2427.00	83.24	3661.75	1951.06	24053.38	0.30177	0.37
11675.00	2457.00	81.95	3719.39	1995.42	25395.43	0.29793	0.40
11680.00	2371.00	83.55	3648.16	1940.60	23263.50	0.30269	0.36
11685.00	2393.00	86.57	3520.89	1842.65	21310.37	0.31140	0.30
11690.00	2136.00	89.26	3414.78	1760.98	17471.75	0.31886	0.22
11695.00	2256.00	96.16	3169.76	1572.38	14912.56	0.33681	0.13
11700.00	2212.00	98.40	3097.60	1516.84	13662.83	0.34229	0.09
AVERAGE VALUE OF BRITTLENESS INDEX							***0.20***

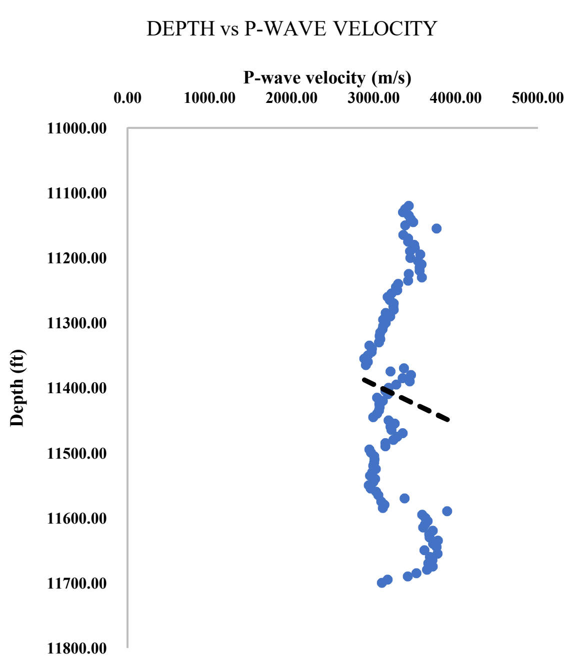

Fig. 4: A plot of depth against p-wave velocity

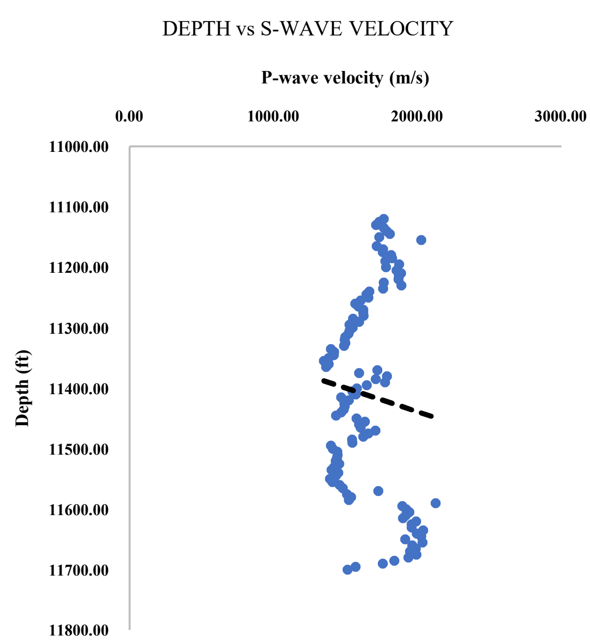

Fig. 5: A plot of depth against s-wave velocity

B.Discussion

Two well logs (Well 1 and Well 7) from an oil field in the Niger Delta were analyzed to identify a typical reservoir and its associated seal. From the associated gamma ray log and resistivity log, a hydrocarbon reservoir and seal were delineated, as seen in Figure 5. The seal interval was within 11120-11700ft.

A plot of p- and s-wave velocities against depth showed a general increase in velocity with depth which could be attributed to better consolidation of the seal rock deeper in the formation [26].

Digitizing Well 1 at 5ft interval, the brittleness index was estimated for the seal interval. The results, including a description of Young's modulus and Poisson's ratio for the sealing interval, are presented in Table 1. The average or mean brittleness index computed for the seal interval was 0.20. This indicates that the reservoir seal under consideration has a high seal integrity as described byMathia et al. [27].

V. CONCLUSIONS

With an aim to define the seal integrity of a seal rock in a Niger Delta petroleum system, the brittleness index of the seal rock was quantitatively described at different well intervals in a geophysical well log from an oil field in the Niger Delta. Aiding in this description were estimates of certain elastic moduli (Young's modulus and Poisson's ratio) and the p- and s-wave velocities at the seal interval within the well of interest. The followings conclusions were arrived at;

- There was a general increase of p- and s-wave velocities with depth within the seal rock possibly attribute to increased consolidation of the rock matrix with depth.
- With an estimated brittleness index of 0.20, the seal rock was considered to have a high seal integrity. Wettability of the reservoir rock had an effect on the estimated wetting phase relative permeability.

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REFERENCES

[1] Tuttle, M.L., R.R. Charpentier, and M.E. Brownfield, *The Niger Delta Petroleum System: Niger Delta Province, Nigeria, Cameroon, and Equatorial Guinea, Africa*. 1999: US Department of the Interior, US Geological Survey.

[2] Haack, R.C., P. Sundararaman, J.O. Diedjomahor, H. Xiao, N.J. Gant, E.D. May, and K. Kelsch, *Niger Delta Petroleum Systems, Nigeria, in M.R. Mello and B.J. Katz, eds.* AAPG Memoir, 2000. **73**: p. 213-231.

[3] Sorkhabi, R. and Y. Tsuji, *The place of faults in petroleum traps.* AAPG Memoir, 2005. **85**: p. 1-31.

[4] Opara, A.I., *Prospectivity evaluation of "Usso" field, Onshore Niger Delta Basin, using 3-D seismic and well log data.* Petroleum Coal, 2010. **52**(4): p. 307-315.

[5] Kaldi, J. and C. Gibson-Poole, *Storage Capacity Estimation, Site Selection and Characterisation for CO2 Storage Projects. CO2CRC Report No. RPT08-1001, Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), Canberra, Australia (March 2008)*. 2008.

[6] Sibson, R.H., *Structural permeability of fluiddriven fault-fracture meshes.* Journal of Structural Geology, 1996. **18**(1): p. 31-42.

[7] Kivior, T., J. Kaldi, and S. Lang, *Seal potential in cretaceous and late Jurassic rocks of the vulcan sub-basin, North West Shelf Australia.* The APPEA Journal, 2002. **42**(1): p. 203-224.

[8] Lou, N., T. Zhao, and Y. Zhang, *Calculation method about brittleness index in Qijia Oil field tight sandstone reservoir Daqing China.* IOSR Journal of Engineering, 2016. **6**: p. 14-19.

[9] Ingram, G.M. and J. Urai, *Top-seal leakage through faults and fractures: the role of mudrock properties.* Geological Society, London, Special Publications, 1999. **158**(1): p. 125-135.

[10] Fatoke, O.A. and J.P. Bhattacharya, *Controls on depositional systems and sequence stratigraphy of the Pliocene-Pleistocene strata of eastern Niger delta, Nigeria.* Search Discovery Article, 2010. **10220**.

[11] Short, K. and A. Stauble, *Outline of geology of Niger Delta.* AAPG bulletin, 1967. **51**(5): p. 761-779.

[12] Doust, H. and E. Omatsola, *Niger delta.* American Association of Petroleum Geologists Memoir, 1989. **48**: p. 201-238.

[13] Kulke, H. and H. Zantop, *Regional Petroleum Geology of the World. Part I: Europe and Asia. Part II: Africa, America, Australia and Antarctica.* Economic Geology the Bulletin of the Society of Economic Geologists, 1995. **90**(5): p. 1354.

[14] Ameloko, A.A. and A.O. Omali, *Reservoir Characterization and Structural Interpretation of Seismic Profile: A Case Study of Z-Field, Niger Delta, Nigeria.* Journal of Petroleum coal, 2013. **55**(1): p. 37-43.

[15] Waters, G., R. Lewis, and D. Bentley. *The effect ofmechanical properties anisotropy in the generation of hydraulic fractures in organic shales SPE 146776.* in *SPE Annual Technical Conference and Exhibition held in Denver, Colorado, USA*. 2011.

[16] Archer, S. and V. Rasouli, *A log based analysis to estimate mechanical properties and in-situ stresses in a shale gas well in North Perth Basin.* Journal of Transactions on Engineering Sciences, 2012. **81**: p. 163-174.

[17] Eyinla, D.S. and M.A. Oladunjoye, *Estimating geo-mechanical strength of reservoir rocks from well logs for safety limits in sand-free production.* Journal of Environmental Earth Science, 2014. **4**(20): p. 38-43.

[18] Jamshidian, M., M. Mansouri Zadeh, M. Hadian, S. Nekoeian, and M.J.G.E. Mansouri Zadeh, *Estimation of minimum horizontal stress, geomechanical modeling and hybrid neural network based on conventional well logging data–a case study.* Journal of Geosystem Engineering, 2017. **20**(2): p. 88-103.

[19] Asquith, G.B., D. Krygowski, and C.R. Gibson, *Basic well log analysis*. Vol. 16. 2004: American association of petroleum geologists Tulsa, OK.

[20] Rider, M.H., *The geological interpretation of well logs.* 1986.

[21] Schon, J., *Basic Well Logging and Formation Evaluation-eBooks and textbooks from bookboon. com*. 2015, bookboon. com.

[22] Greenberg, M. and J.J.G.p. Castagna, *Shear-wave velocity estimation in porous rocks: Theoretical formulation, preliminary verification and applications 1.* Journal of Geophysical Prospecting, 1992. **40**(2): p. 195-209.

[23] Burshtein, L.S., *Determination of poisson's ratio for rocks by static and dynamic methods.* Journal of Mining Science, 1968. **4**(3): p. 235-238.

[24] Fjar, E., R.M. Holt, A. Raaen, R. Risnes, and P. Horsrud, *Petroleum related rock mechanics*. Vol. 53. 2008: Elsevier.

[25] Davies, D.H., O.A. Davies, and O.I. Horsfall, *Determination of Geomechanical Properties of a typical Niger Delta Reservoir Rock Using Geophysical Well Logs.* Asian Journal of Applied science Technology, 2019. **3**(1): p. 222-233.

[26] Behn, M.D. and P.B. Kelemen, *Relationship between seismic P-wave velocity and the composition of anhydrous igneous and meta-igneous rocks.* Geochemistry, Geophysics, Geosystems, 2003. **4**(5).

[27] 27. Mathia, E., K. Ratcliffe, and M. Wright. *Brittleness Index-A Parameter to Embrace or Avoid?* in *Unconventional Resources Technology Conference, San Antonio, Texas, 1-3 August 2016*. 2016. Society of Exploration Geophysicists, American Association of Petroleum.