

GEOPRESSURE PREDICTION AND INTENSITY CHARACTERIZATION BASED ON FUZZY INFERENCE SYSTEM IN BARBADOS FIELD OF THE NIGER DELTA, NIGERIA

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ABSTRACT

In the paper we present a method of characterizing overpressure intensity in an oil field from wireline log with fuzzy inference system using well logs from Barbados field in the Niger Delta area of Nigeria. The method employs pressure coefficients obtained from the ratio of the pore pressure and the hydrostatic pressure as input into the fuzzy system. The lithostatic and hydrostatic pressures were derived from sonic and density log equations while the Hunt and Shi classifications were used to characterize the overpressure intensity, although with a slight modification. The plot of sonic log with depth in the wells followed a typical stepped-tiered configuration having a maximum of three episodes of abnormal pressure. The distribution of pressure coefficient (PC) increases from the left flank to the right flank of the field. Mild overpressure with PC values of 1.28, 1.35 and 1.53 were observed at shallowest depth and 1.33, 1.36 and 1.32 at intermediate depths. Strong overpressure with maximum PC values of 2.04, 2.46, 3.60 and 3.75 were observed in Barbados wells 1, 2, 3 and 4 respectively at greater depths. The result from this study has proven to be a dependable tool in the characterization of overpressure intensity as well as serve as a guide for predicting overpressure behavior in adjacent areas. Further work on pressure coefficient (PC) computation in the vicinity of well kicks, caving, loss of drilling mud, or possibly full blowout is welcomed from other workers.

Keywords: Barbados field, characterization, fuzzy, overpressure, inference, intensity

INTRODUCTION

Abnormal formation pressures are usual occurrences in both offshore and onshore rocks of most sedimentary basins of the world and has received worldwide attention in recent times. This is due to environmental, physical and human hazards associated with this phenomenon. The occurrence and magnitude of overpressure have profound effects on the activities in the oil and gas sector. Some of these hazards associated with this phenomenon include influx, kicks, cavings, blowouts and fracturing, hence resulting in loss of lives and money. Over the years, several researchers have reported cases of abnormally high formation pressure from various fields across the world [1-7]. The report

of overpressure development in the Niger Delta dates back to the early 1960s when [8] investigated formation pressure using log-derived shale properties. [9] employed vertical seismic profile techniques (VSP) to predict overpressure in the Niger Delta. Workers in the Nigeria's Niger Delta include [10-12]. At the commencement of the millennium, other workers have reported same occurrences [13-16]. All these researchers came up with novel empirical and non-empirical methods for the estimation of pore pressure in the various fields where they worked. Some of these methods have been found to be relevant in several parts of the world.

In recent times, several workers have also described the occurrence of overpressure in Nigeria. [17] employed the use of temperature and pressure data in overpressure detection. They also used velocities associated with 3D seismic data to affirm that disequilibrium compaction, gas generation, thermal expansion and clay diagenesis all contribute to overpressure generation at great depths. Also, [18] observed that chemical compaction process (according to [19]) in the form of kerogen transformation and hydrocarbon generation in the Akata Formation, is responsible for fluid overpressure, seepage forces and the rapid migration of fluid volume in the outer thrust belt of the Niger Delta. [20] reported overpressure occurrence in the Esenam field of the Niger Delta, and observed that the deeper part of Agbada Formation is overpressured primarily due to disequilibrium compaction. Predicting overpressure occurrence in oil and gas exploration is one of the most important activity because it is critical to exploration, drilling and production of hydrocarbons [21]; more importantly is the challenge of predicting the intensity of overpressure. This study considers the intensity of overpressure as a measure of overpressure strength based on the degree of damages it causes. Therefore, the aim of this research is not just to predict the occurrence of overpressure but to predict the intensity of overpressure. The intensity of overpressure is widely believed to have several effects on the subsurface rock and has been found to be associated with the ratio of the pore pressure to the hydrostatic pressure generally referred to as pressure coefficient [22, 23]. A slight increase in pressure above hydrostatic (with pressure coefficient greater than 1.27) according to [22] which has been described as mild overpressure by certain workers [23, 24] may result in well kicks when there are uncontrolled influxes of formation fluids into a borehole. As the intensity increases, caving may develop - a situation of greater pore pressure in low permeability rocks, which causes the rocks to stress relieve or cave into the borehole. Loss of drilling mud may also occur due to rupturing of formation as a result of rise in mud weight to control the formation pressure at the bit with consequential running out of the mud into the well bore on its own. There is also the possibility of a full blowout when the drilling fluid is fully displaced from the well and the formation fluid exits the well. There is also the possibility of encountering strongly overpressure intervals (having pressure coefficient greater than 1.8 which has been described as hard overpressure by some workers [25] when the hydrostatic pressure in the borehole exceeds the fracture gradient of exposed formations [26]. This could fracture mudstone formation and drive sandstone intrusion into the mudstone, thereby causing the formation of the sand injectites [27]. Slightly over-pressured intervals may be exploited for hydrocarbon prospect because oil generation and maturation sometimes result in overpressure [12]. Overpressure may also trigger hydrocarbon migration from the source rock to the traps [12], [28], [29]. All these overpressure effects come with various intensities. Based on these findings, this study desire to attempt a characterization of overpressure intensities using pressure coefficient estimates as a single input into a fuzzy inference system (FIS.).

Classification of pressure coefficient based on [22, 23] were employed but with a slight modification. This was done in order to make the PC more fuzzified so as to accommodate more possibilities (which are likely possibilities) while the classification assisted in formulating the needed fuzzy rule for characterizing the intensity of overpressure and presenting a clue on how the intensities of overpressure varies with depth and also serve as a guide for drilling activities in oil and gas fields in the future.

LOCATION OF STUDY AREA

The Niger Delta basin of Nigeria lies roughly between latitudes 4°N and 6°N and longitudes 3°E and 9°E (Figure 1). It is located in the southern part of Nigeria and bounded to the northwest and west by the West African shield, which ends at the Benin hinge line and to the east by the Calabar hinge line. To the northern part of the basin is the Anambra basin and Abakaliki anticlinorium. To the immediate south of the area is the Gulf of Guinea that extends into the Atlantic Ocean (Figure 1).

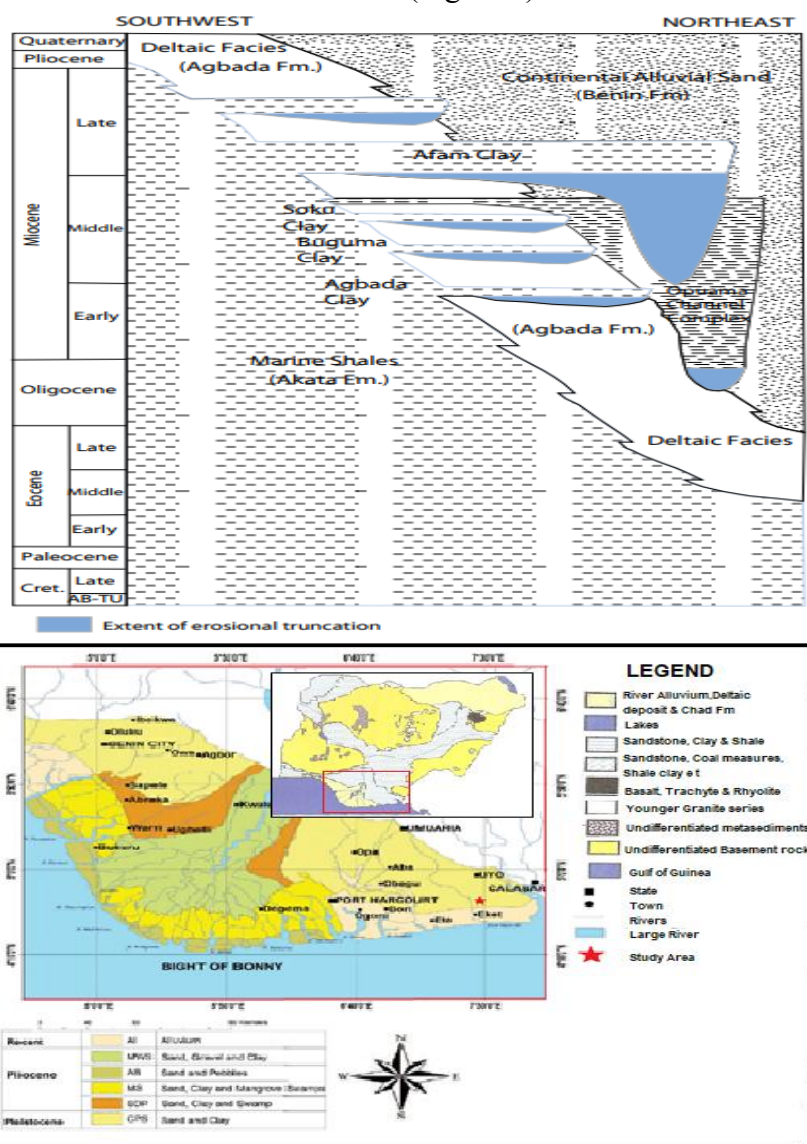


Figure 1. Geologic map of the Nigeria (inserted) showing the lithostratigraphy and the location of the study area (modified from [30, 31]).

Stratigraphically, the Niger Delta is made up of three major units - the Akata, Agbada and Benin Formations. The Akata Formation, the oldest stratigraphic unit at the base of the delta is of marine origin and consists essentially of thick shale sequences acting as potential source rock, and sometimes turbidite sand acting as potential reservoirs in deep water environments. Small amounts of clay and silt materials exist within the Akata Formation [30]. The Akata Formation which is under-compacted in much of the delta is overlain by the Agbada Formation, a paralic sequence of alternating sand and shale rich materials. It is the reservoir of the bulk of the known hydrocarbon accumulation in the Niger Delta. Previous studies reveal that the Benin Formation is the uppermost and youngest. The stratigraphic unit and is essentially made up of about 2000 m thick continental alluvial deposits of the Eocene to Recent. The location of the site under study is situated onshore towards the eastern part of the Niger Delta Basin. The exact location, coordinates and description of the field under investigation has been made confidential due to the agreement reached with the oil and gas servicing company that released the data for the project. Also, the names of the wells in the field has been made informal due to the confidentiality of the data.

MATERIALS AND METHODS

Materials used for this work include four composite suite of well logs and seismic data procured from an oil prospecting company with each of the logs comprising neutron porosity, gamma ray, sonic log, deep induction log and bulk density log. The first phase involved preliminary log corrections and the generation of the sonic-depth plot for each of the wells under investigation. Zones on the sonic-depth plots where deviation from the normal compaction trend exist were delineated as overpressured zones. The depths to these overpressured tops were marked and selected. Clean shale intervals were selected from the delineated overpressure zones using the [34] volume of shale equation for Tertiary rock given by:

$$V_{sh} = (0.083 \times 2^{3.7 \cdot IGR} - 1) \quad (1)$$

where V_{sh} is the volume of shale and IGR is the gamma ray index. The overburden stress S_v was estimated using the expression given by

$$S_v = 0.434 \int_0^z \rho_z dz \quad (2)$$

where S_v is the overburden stress (psi/ft), ρ_z is the bulk density of rock at any depth of investigation and 0.434 is conversion factor that converts g/cc to psi/ft. The overburden stress was later converted to its MPa equivalent using appropriate conversion factors. In this work, the bulk density log was used directly for the lithostatic pressure estimation in wells. However, in wells that had no bulk density log, the bulk density log was generated from the [35] equation given by

$$\rho_{b_{log}} = 2.75 - \left[2.11 * \frac{\Delta t_{log} - \Delta t_{max}}{\Delta t_{log} + \Delta t_{fl}} \right] \quad (3)$$

where $\rho_{b_{log}}$ is the bulk density log from well logs, Δt_{log} is the sonic log reading from wireline logs, Δt_{max} , the sonic log value of the matrix and Δt_{fl} the sonic log for the mud filtrate used. Hydrostatic pressure on the other hand was estimated by using the expression given as:

$$P_{hydr} = 0.433 * z * \rho_f \quad (4)$$

where z is depth in feet, ρ_f is density of fluid and P_{hyd} is the hydrostatic pressure (psi).

The hydrostatic pressure was later converted to its MPa equivalent using appropriate conversion factor. For this research, a water density value typical of the West African environment of 1.025 g/cm³ (0.433 psi/ft) [36] was used as the average formation water density. The magnitude of the deviation from normal compaction trend in these zones was used to estimate the pore pressure, after local calibration using the [11] expression given as:

$$P_{\text{por}} = S_v - (S_v - P_{\text{hydro}}) \left(\frac{\Delta t_n}{\Delta t_{\text{log}}} \right)^{3.0} \quad (5)$$

where P_{por} is pore pressure; S_v is the lithostatic stress; P_{hyd} is hydrostatic pore pressure; and the subscripts n and log refer to the normal and measured sonic (Δt) at each depth. The choice of exponent of 3.0 has been found to be most appropriate for use in the Niger Delta [37] where overpressure has been due to under-compaction. The pressure coefficient (PC) was estimated from the ratio of the calculated pore pressure using the [11] expression and the hydrostatic pressure. The pressure coefficients obtained served as apriori information in characterizing the overpressure intensity in the overpressure zones using standard methods. [38] observed that overpressure situations within the subsurface commence at pressure coefficient above 1.27 and that strong overpressure (hard overpressure according to [39] is associated with pressure coefficient greater than 1.8. Hence, the pressure coefficient value of 1.27 may be regarded as slight overpressure while pressure coefficient estimates that ranges between 1 and 1.27 should correspond to intervals of near hydrostatically pressured rocks. A slight modification of this classification was introduced between the slight overpressure and strong overpressure that may be regarded as moderately over-pressured interval and this correspond to PC value of 1.54. This was found by averaging the 1.27 (near hydrostatic pressure limit) and 1.8 (strongly overpressure) limit. This point of 1.54 was assumed to marked the commencement of a moderately overpressure condition. Based on these conclusions, using the pressure coefficient ranges as input variable, a series of fuzzy membership function (fuzzy crisp) were developed for this study to define the fuzzy-based inference rules. A number of fuzzy learning sets were developed for the characterization of the intensity of overpressure distribution in the overpressure zones in the study area using the Mamdani type of fuzzy inference system within the MATLAB fuzzy logic toolbox with the following format:

- If (Pressure Coefficient = Less than or equal to 0.99), then (Pressure Status = Below Hydrostatic),
- If (Pressure Coefficient = Greater than 0.99 and less than or equal to 1.26), then (Pressure Status = Near hydrostatically-pressured),
- If (Pressure Coefficient = Greater than 1.26 and less than or equal to 1.54), then (Pressure Status = Slightly pressured),
- If (Pressure Coefficient = Greater than 1.54 and less than or equal to 1.8), then (Pressure Status = Moderately pressured), and
- If (Pressure Coefficient = Greater than 1.8), then (Pressure Status = Hard or Strongly pressured).

The fuzzy inference rules were followed by fuzzy aggregation (coding), de-fuzzification and subsequent modelling of the codes with depth at the overpressured zones in all wells in the field. The hydrostatic pressure (P_{hydr}) and pore pressure (P_{por}) values were selected around the vicinity of abnormal pressures and developed within the corresponding depths. (Table 1 to 3).



Table 1. Summary of Pressure Coefficient Computation from the Ratio of Pore Pressure and the Hydrostatic Pressure in Zone 1

Barbados Well 1						Barbados Well 2						Barbados Well 4					
Depth (m)	P _{hyd.} (MPa)	P _{por.} (MPa)	PC	Avg PC	PS	Depth (m)	P _{hyd.} (MPa)	P _{por.} (MPa)	PC	Avg PC	PS	Depth (m)	P _{hyd.} (MPa)	P _{por.} (MPa)	PC	Avg PC	PS
1500	15.78	13	0.84	0.88	BH	1300	15.09	12.57	0.83	0.88	BH	1230	15.09	11.19	0.74	0.85	BH
1510	21.04	19	0.92		BH	1310	20.35	18.97	0.93		BH	1240	19.66	18.90	0.96		BH
1520	26.30	27	1.05	1.05	NP	1320	32.98	41.91	1.27	1.35	SP	1250	32.22	35.70	1.11	1.20	NP
1530	27.35	27	1.00		NP	1330	32.91	42.46	1.29		SP	1260	32.90	39.70	1.21		NP
1540	29.46	27	0.93		NP	1340	32.22	44.64	1.39		SP	1270	31.46	38.41	1.22		NP
1550	31.56	36	1.13		NP	1350	33.05	46.67	1.41		SP	1280	31.66	39.77	1.26		NP
1560	32.61	38	1.16		NP	1360	34.33	48.17	1.40		SP	1290	30.90	46.94	1.52		SP
1570	33.67	43	1.27	1.28	SP	1370	34.43	57.57	1.67	1.73	MP	1300	33.05	50.67	1.53	1.53	SP
1580	33.60	43	1.27		SP	1380	42.08	72.29	1.72		MP	1310	47.31	72.42	1.53		SP
1590	33.74	44	1.30		MP	1390	33.74	59.10	1.75		MP	1320	33.72	59.38	1.76	1.77	MP
1600	42.08	71	1.69	1.69	MP	1400	41.23	72.98	1.77		MP	1330	41.23	73.67	1.79		MP
1610	42.15	78	1.85		HP	1410	41.49	77.81	1.88	1.88	HP	1340	41.49	79.19	1.91	1.91	HP

Keys: P_{hyd.}: Hydrostatic Pressure, P_{por.}: Computed Pore pressure; PC: Pressure Coefficient. Av. PC: Average of Pressure Coefficient; PS: Pressure Status; BH: Below Hydrostatic; NP: Near hydrostatic pressured; SP: Slightly pressured; MP: Moderately pressured; Strongly (Hard) pressured



Table 2. Summary of Pressure Coefficient Computation from the Ratio of Pore Pressure and the Hydrostatic Pressure in Zone 2

Barbados Well 1						Barbados Well 2						Barbados Well 3						Barbados Well 4							
Depth (m)	P _{hyd.} (MPa)	P _{por.} (MPa)	PC	Avg PC	PS	Depth (m)	P _{hyd.} (MPa)	P _{por.} (MPa)	PC	Avg PC	PS	Depth (m)	P _{hyd.} (MPa)	P _{por.} (MPa)	PC	Avg PC	PS	Depth (m)	P _{hyd.} (MPa)	P _{por.} (MPa)	PC	Avg PC	PS		
2300	26.30	25	0.93	0.97	BH	2130	25.62	23.90	0.93	0.96	BH	1900	18.72	34.24	1.83	1.98	HP	2260	32.61	30.34	0.93	0.95	BH		
2310	31.49	30	0.95		BH	2140	26.66	25.12	0.94		BH	1910	18.79	34.44	1.83		HP	2270	32.98	30.69	0.93		BH		
2320	31.50	30	0.95		BH	2150	27.36	26.01	0.95		BH	1920	19.08	35.12	1.84		HP	2280	33.01	30.72	0.93		BH		
2330	31.56	30	0.97		BH	2160	28.11	27.03	0.96		BH	1930	21.21	39.53	1.86		HP	2290	33.05	30.76	0.93		BH		
2340	31.49	31	0.97		BH	2170	31.48	30.81	0.98		BH	1940	21.28	39.29	1.85		HP	2300	33.08	30.93	0.93		BH		
2350	31.53	31	0.97		BH	2180	31.53	30.77	0.98		BH	1950	21.43	39.66	1.85		HP	2310	40.01	38.28	0.96		BH		
2370	31.83	31	0.97		BH	2190	31.91	30.93	0.97		BH	1960	22.21	41.26	1.86		HP	2320	40.05	38.45	0.96		BH		
2380	31.90	31	0.98		BH	2200	31.86	31.15	0.98		BH	1970	27.72	51.66	1.86		HP	2330	40.08	38.97	0.97		BH		
2390	31.95	31	0.98		BH	2210	31.95	30.48	0.95		BH	1980	28.50	53.17	1.87		HP	2340	40.10	39.79	0.99	1.16	NP		
2400	32.01	31	0.98		BH	2220	32.00	31.18	0.97		BH	1990	28.69	53.79	1.88		HP	2350	40.14	40.34	1.01		NP		
2410	32.03	31	0.98	BH	2230	31.97	31.26	0.98	BH	2000	28.83	54.43	1.89	HP	2360		40.23	44.83	1.11	NP					
2420	32.07	32	0.99	1.0	NP	2240	32.14	28.37	0.88	BH	2010	28.97	55.12	1.90	HP		2370	40.27	48.03	1.19	NP				
2430	32.08	32	1.00		NP	2250	34.14	34.17	1.00	1.09	NP	2020	29.10	60.48	2.08		HP	2380	40.49	48.32	1.19		NP		
2440	32.08	32	1.01	1.33	NP	2260	32.08	32.94	1.03		1.36	NP	2030	30.00	62.76		2.09	HP	2390	40.62	49.15		1.21	NP	
2450	32.86	41	1.26		SP	2270	32.10	40.59	1.26	NP		2040	30.72	64.72	2.11		HP	2400	41.14	50.24	1.22		NP		
2460	32.91	42	1.28	1.53 5	SP	2280	32.91	42.15	1.28	1.88	MP	2050	30.90	65.41	2.12		HP	2410	40.28	50.43	1.25		NP		
2470	33.52	48	1.44		SP	2290	32.83	45.38	1.38		MP	2060	31.45	66.90	2.13		HP	2420	41.04	51.38	1.25	NP			
2480	34.32	52	1.53	1.93	MP	2300	33.56	47.56	1.42	1.88	MP	2070	32.18	68.96	2.14		HP	2430	41.15	54.46	1.32	1.32	SP		
2490	34.42	53	1.54		MP	2310	34.43	62.68	1.82		HP	2080	33.05	71.03	2.15		HP	2440	41.24	66.14	1.60	1.60	MP		
2500	34.57	66	1.92		HP	2320	34.57	66.94	1.94		HP	2090	33.45	72.48	2.17		HP	2450	40.38	72.76	1.80	1.81	HP		
2510	35.32	67	1.91		HP								2100	34.57	75.52		2.18	HP	2460	40.52	73.17	1.81		HP	
2520	35.38	68	1.93		HP																				
2530	35.41	69	1.96	HP																					



Table 3. Summary of Pressure Coefficient Computation from the Ratio of Pore Pressure and the Hydrostatic Pressure in Zone 3

Barbados Well 1						Barbados Well 2						Barbados Well 3						Barbados Well 4						
Depth (m)	P _{hyd.} (MPa)	P _{por.} (MPa)	PC	Avg PC	PS	Depth (m)	P _{hyd.} (MPa)	P _{por.} (MPa)	PP C	Avg PC	PS	Depth (m)	P _{hyd.} (MPa)	P _{por.} (MPa)	PC	Avg PC v.	PS	Depth (m)	P _{hyd.} (MPa)	P _{por.} (MPa)	PC	Avg PC	PS	
2870	20.00	23	1.15	1.15	NP	2810	20.69	14.07	0.68	0.80	BH	2940	33.30	74.06	2.22	3.60	HP	2750	59.09	46.68	0.79	0.79	BH	
2875	20.87	30	1.42	1.47	SP	2813	22.41	17.48	0.78		BH	2950	33.91	80.36	2.37		HP	2755	48.92	48.43	0.99		1.10	NP
2880	23.77	37	1.51		SP	2815	24.69	19.75	0.8		BH	2960	34.54	88.28	2.56		HP	2760	47.46	54.10	1.14			NP
2885	27.45	42	1.58	1.64	MP	2818	26.90	23.13	0.86		BH	2970	34.81	93.79	2.69		HP	2765	47.89	55.55	1.16		NP	
2890	30.48	50	1.64		MP	2820	27.24	23.97	0.88		BH	2980	35.85	101.88	2.84		HP	2770	46.71	59.56	1.28	1.35	SP	
2895	34.22	59	1.71	MP	2830	27.59	28.97	1.05	1.14	NP	2990	36.06	107.83	2.99	HP		2775	48.78	65.86	1.35	SP			
2900	34.72	63	1.81	HP	2840	29.24	32.75	1.12		NP	3000	36.67	115.85	3.16	HP		2780	52.39	74.39	1.42	SP			
2910	35.25	66	1.86	HP	2850	29.59	36.98	1.25	NP	3010	37.37	122.28	3.27	HP	2790		51.54	80.41	1.59	1.56	MP			
2920	35.77	67	1.87	HP	2860	31.03	41.72	1.34	1.45	SP	3020	37.78	136.66	3.62	HP		2800	43.71	87.86		2.01	3.75	HP	
2930	35.80	67	1.88	HP	2870	31.38	46.83	1.49		SP	3030	37.24	149.48	4.01	HP		2810	46.57	101.05	2.17	HP			
2940	36.02	68	1.89	HP	2880	32.83	49.76	1.52		SP	3040	35.57	158.53	4.46	HP	2820	40.51	108.97	2.69	HP				
2950	36.21	69	1.9	HP	2890	33.94	52.34	1.54	1.67	MP	3050	34.17	170.10	4.98	HP	2830	35.49	121.38	3.42	HP				
2960	37.88	71	1.88	HP	2900	33.97	53.03	1.56		MP	3060	34.47	184.37	5.35	HP	2840	29.52	136.36	4.62	3.75	HP			
2970	38.30	72	1.88	HP	2910	34.32	54.63	1.59	MP	3070	33.99	199.77	5.88	HP	2850	27.38	149.21	5.45	HP					
2980	38.72	80	2.06	HP	2920	34.49	55.48	1.61	MP							2860	26.79	157.23	5.87		HP			
2990	39.14	81	2.07	HP	2930	35.14	61.90	1.76	MP															
3000	39.56	83	2.09	HP	2940	35.38	62.00	1.75	MP															
3010	39.98	86	2.15	HP	2950	35.56	62.91	1.77	MP															
3020	40.40	89	2.2	HP	2960	35.98	64.28	1.79	MP															
3030	40.82	91	2.22	2.04	HP	2970	36.40	80.96	2.22	2.46	HP													
3040	41.24	94	2.27		HP	2980	36.82	87.26	2.37		HP													
3050	41.66	96	2.3		HP	2990	37.24	95.17	2.56	HP														

Keys: P_{hyd.}: Hydrostatic Pressure, P_{por.}: Computed Pore pressure; PC: Pressure Coefficient. AV: Average of Pressure Coefficient; PS: Pressure Status; BH: Below Hydrostatic NP: Near Hydrostatic pressured; SP: Slightly pressured; MP: Moderately pressured; HP: Hardly (Strongly) pressured

The fuzzy inference engine is one of the soft computing techniques that has found application in geosciences. Just like every other soft computing technique, fuzzy logic is tolerant of imprecision, accommodate partial truth and takes a value between a completely true value and a completely false value [32]. At the end, a set of data is made to mimic human reasoning. The concept was introduced by [33] as a method for handling imprecise and inexact data. All forms of predictive data fall into two major categories viz YES or NO, TRUE OR FALSE. This is similar to conclusions of an average probability statistical series in that it gives results in form of mutually exclusive events that takes the form of HEAD or TAIL. However, like probability, a fuzzy set recognizes both extremes but unlike probability, it attempts to express the degree of both extremes. The basis of operation of fuzzy logic is similar to that of a typical mathematical set operation such as union, intersection and complement, intersection [31]. It is usually carried out using a set of arguments coupled by logical operators verbally formulated as:

- IF the condition (or conditions) is/are fulfilled, THEN the consequence has to be True.
- IF the condition (or conditions) is/are NOT fulfilled, the consequence has to be False

Hence, the reason why workers describe fuzzy logic as a soft computing IF/THEN rules.

THEORETICAL BACKGROUND OF FUZZY SYSTEM

The fuzzy system when applied, the rules respond in different combinations with different conclusions. For instance, the suitability of an orange for consumption can be expressed by taking into consideration three important variables. These may include variables such as size (S), colour (C) and taste (T), each of which represent a variable within the fuzzy system. In terms of size, it could be expressed as small or large (statistical mutually exclusive event) while in terms of colour, it could be expressed as either ripe or unripe (statistical mutually exclusive event). In terms of taste, it could be expressed as either sweet or sour (statistical mutually exclusive event). Hence, the suitability of the orange for consumption could follow this fuzzy rule:

- IF the orange is large, sweet and it is yellow in colour, THEN = Consumable
- IF the orange is small, sour and green in colour, THEN = Not Consumable

However, in nature, there are several possibilities between the two extremes of consumable and non-consumable, all of which possess characteristic size, colour and taste. These include such possibilities such as SLIGHTLY Consumable, FAIRLY Consumable, MODERATELY Consumable, FAIRLY Not Consumable, SLIGHTLY Not Consumable etc. These conclusions could be as a result of certain characteristics of each of the variables that are not too precise and exact and so, makes the entire data fuzzy in nature.

In basic mathematics, all predictions fall within 0 and 1. Between these two extremes are possibilities that are feasible in nature; and so fuzzy logic finds application in geoscience field because measurements of geologic parameters or geophysical measurements are not exact. Rather, they occur in the form of range of values. For instance, a hand specimen of any rock when subjected to magnetic susceptibility measurement, for instance, cannot have similar value on all the faces. Rather, the values measured would occur in the form of a range of values. This fuzziness of geologic data makes it possible for designing a set of rules that does not only recognize the two extremes but also conclude possibilities that exist between the two extremes. Two types of pressure situations exist in sedimentary basins. These are underpressure and overpressure situations. Pronounced underpressure

condition rarely occur in nature, although a few has been reported in certain basins across the world especially in certain sedimentary basins of North and South America, China, Russia, mainland Europe and the Norwegian Barents shelf and Svalbard [33]. Also, they rarely occur in conjunction with overpressure but sometimes, the pressure within the subsurface could be slightly below hydrostatic condition. However, overpressure situations are prevalent; and so, the application of fuzzy inference engine becomes a useful tool in elucidating the intensity of the vast possibilities that occur between below hydrostatic and very strong overpressure conditions. At the end, it is able to conclude the degree of the overpressure situation whether the subsurface layers are mildly overpressured, moderately overpressured or strongly overpressured since these extremes exhibit different pressure coefficients (PC) ranges.

PRESENTATION AND DISCUSSION OF RESULTS

In this study, Figure 2 shows the input and output membership function used for overpressure characterization while Figure 3 represent the diagram employed for the fuzzy rule generation, the input membership function and the output membership function. Figure 4 is the typical stepped-tiered overpressure configuration plot displayed in Barbados Field of the Niger Delta. Figure 5 is a display of the variation of the PC with depth in the four wells on the seismic data. Table 1, 2, and 3 represents the summaries of pressure coefficient computation from the ratio of pore pressure and the hydrostatic pressure in zones 1 to zone 3 at specific depths (in meters) in Barbados Field. The overpressured intervals were delineated in the four wells (Barbados well 1 to Barbados well 4) with the exception of well 3 where only two over-pressured intervals were delineated. There exist no abnormal geopressure in the vicinity of the shallowest zone in Barbados well 3. In zone 1, these over-pressured intervals were delineated at intervals between 1500 to 1610 meters in Barbados well 1, 1300 to 1410 meters in Barbados well 2 and 1230 to 1340 meters in Barbados well 4. However, in zone 2, overpressure intervals were selected at depths of 2300 meters to 2530 meters in Barbados well 1 with overpressure top at 2300 meters and 2130 to 2320 meters in Barbados well 2 with overpressure top at 2130 meters and 1900 to 2100 meters in well 3 with overpressure top at 1900 meters. However, in Barbados well 4, overpressure interval in this zone was delineated at a depth of 2260 meters and extends to a depth of 2460 meters with overpressure top at 2460 meters. In zone 3, the three stepped-tiered overpressure intervals were selected at depths of 2870 to 3060 meters (Barbados well 1), 2810 to 3000 meters (Barbados well 2), 2940 to 3070 (Barbados well 3) and 2750 to 2860 meters (Barbados well 4).

In all the zones, abnormal pressured conditions were detected within the fairly thick and thick shale layer, some within the intercalated regions in the Akata Formation of the delta while thickest shale were encountered with depth within the Agbada Formation. Generally, pore pressure in “Barbados” field was observed to increase rapidly with depth as the lithofacies also increases in thickness. Strongly over-pressured intervals at shallow depths are found in relatively thinner shale intervals while very strongly over-pressured intervals are found at greater depth where thick shale intervals exist. This imply that the deeper formations are hydraulically isolated from shallower ones. Also, pressure coefficient (PC) increases gradually with relatively lower PCs are found at relatively shallower depths but with high PC values found at greater depths. Also, the thickness of strongly over-pressured intervals increases with depth and also increases in value.

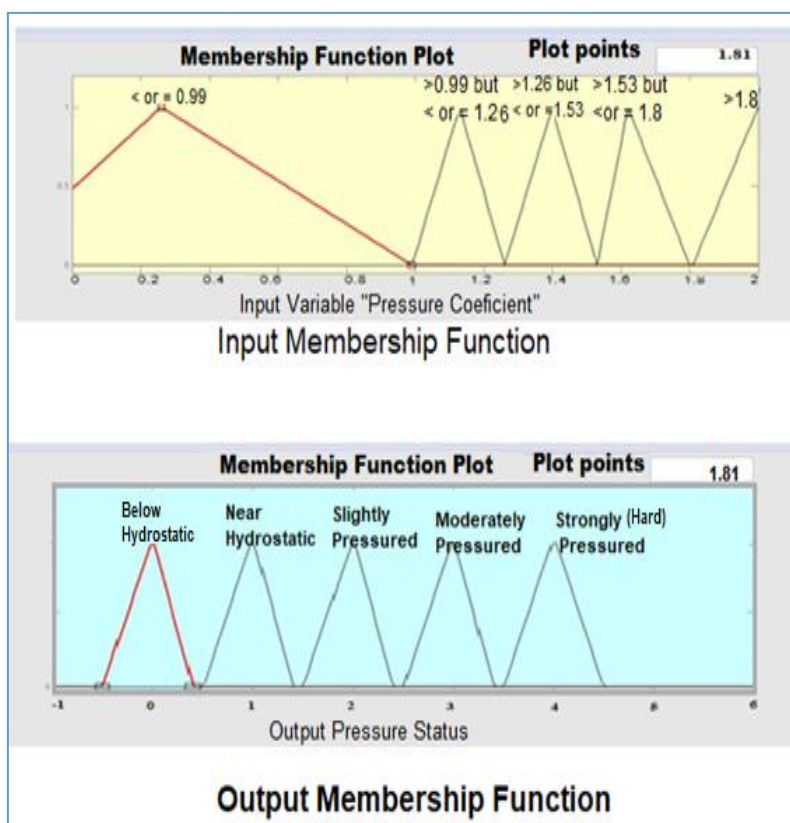


Figure 2. Input and Output Membership Function used for Overpressure Characterization.

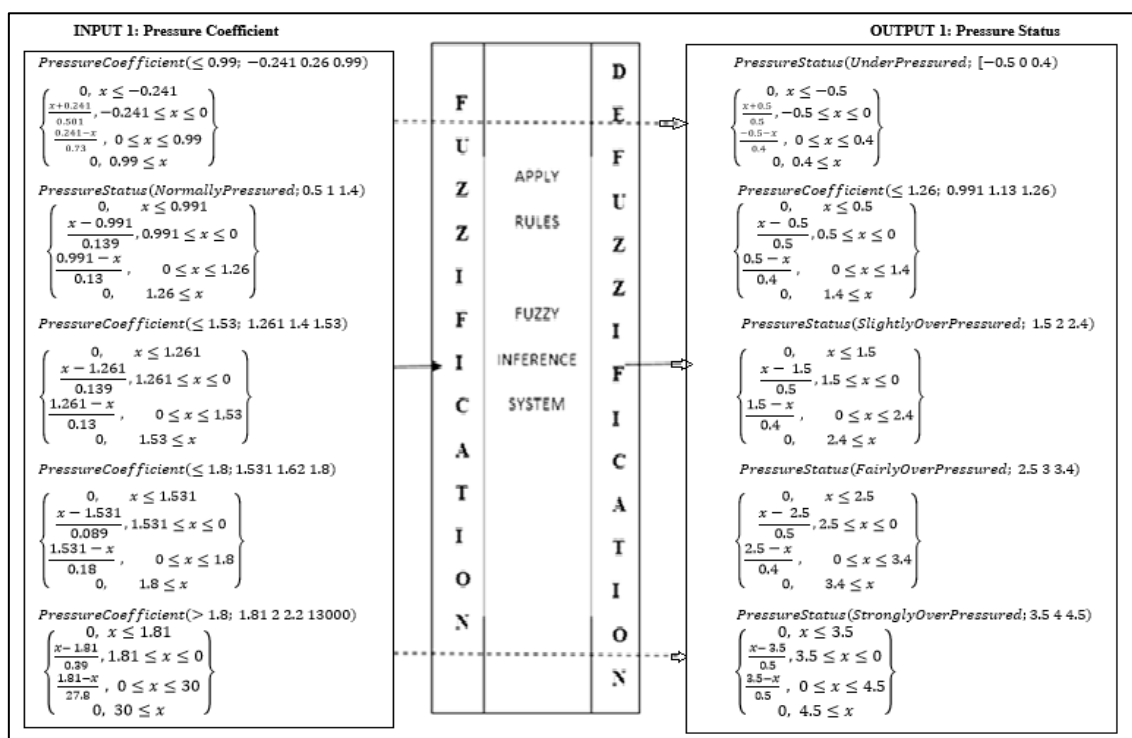


Figure 3. Input Functions Fuzzification and Defuzzification and the Corresponding Output Function.

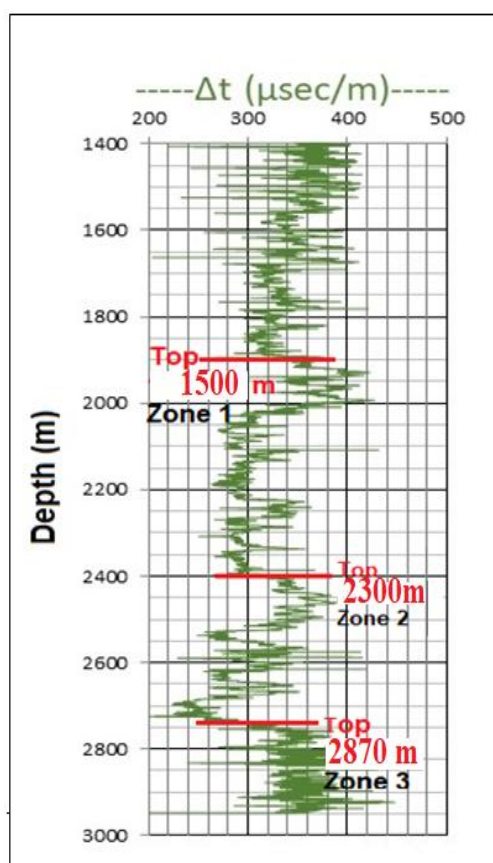


Figure 4. A typical stepped-tiered Overpressure Configuration in "Barbados" Field, Niger Delta, Nigeria

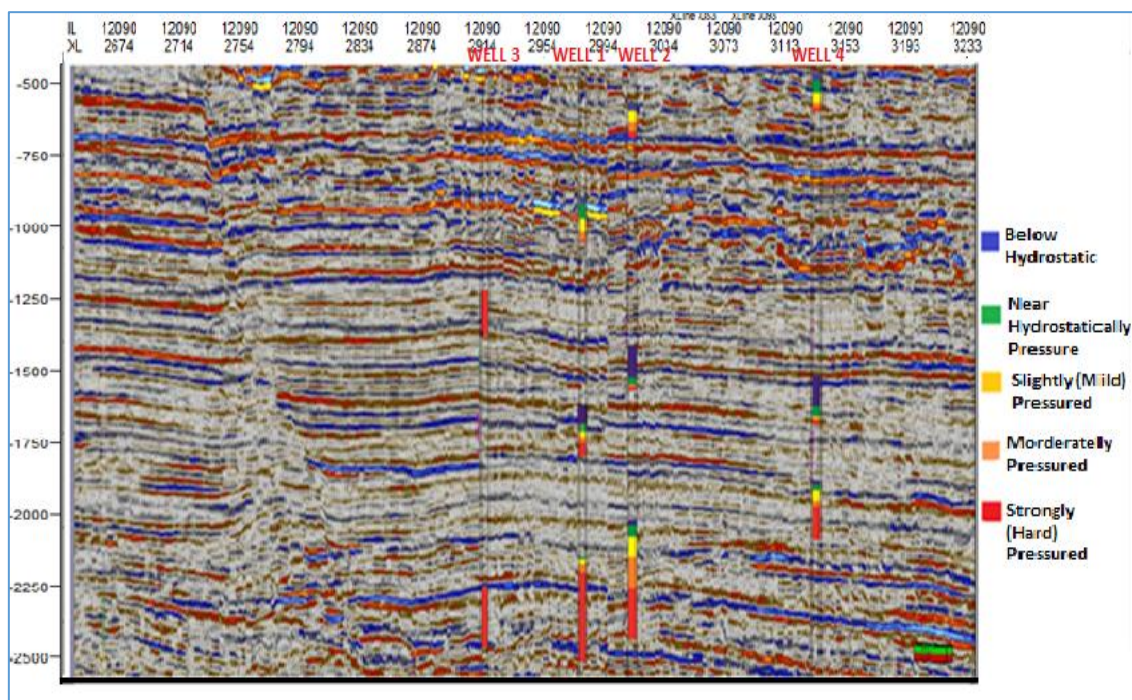


Figure 5. Fuzzy Characterization of Pressure Status in Overpressure Zone 1,2,3 in Barbados 1,2,3 and 4

In all the wells, there exist three intervals of overpressure defined by a typical stepped-tiered triple overpressure system except in Barbados well - 3 where there are only two intervals of overpressure. Figure 4 shows the general pattern of pressure configuration observed in the field and depth to overpressure tops. The results obtained from modelling of the pressure status in the overpressure zones in Barbados - well 1, Barbados – well 2, Barbados – well 3 and Barbados - well 4 are as shown in Figures 5. The overpressure in the three zones shows three important characteristics, all of which are summarized in Tables 1, 2 and 3.

Generally, virtually all geopressure conditions were found to occur within shale beds either intercalated within sand-bearing layers or occurring as single thick layer below the sequence of rocks in the basin. However, as the thickness of the shale increases with depth with no evidence of sand intercalation, the geopressure increases in intensity.

The distribution of the pressure coefficient (PC) was not uniform in all parts of the studied section of the basin. At shallow depths, low overpressure intervals are “sandwiched” between zones of slight and moderate over-pressured throughout the studied intervals. Within the sand-shale intercalations, the geopressure increases steadily in intensity.

The pressure coefficients at shallow depth were observed to be less than the pressure coefficient at greater depth, just as the thickness of hard (strongly) over-pressured intervals increases with depth. This indicates the fact that pressure coefficient also increases with depth – an indication that intensity of overpressure increases with depth.

In zone 1 at shallowest depths, overpressure intervals in this zone in all the wells exhibit various degree of geopressure characteristics. The only exception is Barbados well 3 where there exist no evidence of geopressure condition. Geopressure condition only commences at intermediate depth in Barbados well 3. In wells 1, 2 and 4, slightly pressured intervals occur within certain lithofacies having pressure coefficient values ranging from as low as 1.27 in Barbados – well 1 to 1.35 in Barbados well 2 and 1.53 in Barbados – well 4 (Table 1). However, in zone 1, moderately pressured intervals with PC values of 1.49, 1.73 and 1.77 were observed in wells 1, 2 and 4 respectively. Although, intervals of normal pressure, near hydrostatic geopressure exist, they are not much pronounced but thin compared to other zones. Strongly over-pressured shale beds are also present but relatively thin. These all range in PC value from 1.85 in Barbados well 1 to 1.88 in Barbados well 2 and 1.91 in Barbados well 4. At shallowest intermediate depths (Zone 1), intervals of pressure slightly lower than hydrostatic were encountered in three Barbados wells 1, 2 and 4. None exist in Barbados well 3. Also, nearly hydrostatic condition (normal pressure) and slightly pressured intervals (layers) exist but the layers were observed to be thin while moderately over-pressured zones exist within thicker layers (Figure 5), having average pressure coefficient that range from 1.59 in Barbados - well 1 to 1.63 in Barbados well 2, 1.66 and 1.72 in Barbados - well 4.

In the intermediate zone 2, the PC value observed in well 3 was very high, having PC value around 2.14, indicating strong overpressure with no evidence of other geopressure conditions. Similar behavior was observed at greater depth in well 3. At other wells in over-pressured zones 2 and 3, the zones are dominated by a specific overpressure type.

At greater depths, strongly pressure coefficients were observed in zone 3 which correspond to the third overpressure zones. The pressure coefficient ranges from 2.10 in well 1 to 2.42 in well 2, 2.68 in well 3 and 2.98 in well 4 respectively. However, there were evidences of thin low-pressure zones at greater depths. This is expressed with PC

values of 0.73 in well 2 and 0.94 in well 4 (Table 2). The degree of overpressure was observed to increase gradually from well 1 located at the north-western border of the studied area to wells 4 located to the eastern border of the studied area. Also, the thickness of strongly over-pressured intervals increases with depth and also increases from the north-western part to the eastern part.

In over-pressured zone 3, wells 2 and well 4 showed thin layer of pressure with questionable characteristics as they exhibit pressure below normal at earlier portion of the zone. Thick interval of strong (hard) overpressure were observed in overpressure zone 3 in all the wells. This indicates that the highest-pressure coefficient value is located at greater depth in this zone. The pressure coefficient values in the zone were observed to be as high as 2.04 in Barbados - well 1 to 2.46 in Barbados - well 2, 3.60 in Barbados - well 3 and 3.75 in Barbados – well 4 (Table 3). In such zone and at such a depth, under-compaction does not appear to be the only main pressure mechanism. In certain cases, a combination of a number of factors such as presence of a regional fault causing a thick regional seal coupled with hydrocarbon cracking and expulsion may be responsible for generating such a strong overpressure. [39] described this as hard overpressure.

IMPLICATION FOR HYDROCARBON EXPLORATION

The overpressure configuration and regime in the four wells is similar. They all revealing a stepped-tiered pressure configuration, a configuration typical of Niger Delta environment. The pressure in the reservoir rocks is near normal in all the wells but abnormal in some of the source lithofacies. Previous drilling practice in the Niger Delta Basin showed that the near hydrostatically pressured areas are favoured hydrocarbon accumulation when compared with the high or strongly overpressure area; an important guide for subsequent exploration of the basin.

The overpressure models showed that the overpressure distribution is not uniform (see Figure 5). Some distinctly low overpressure areas were observed sometimes in the vicinity of high overpressure intervals. However, drilling through the slightly overpressured intervals might not pose much challenge as proper and appropriate use of mud would combat the effect of the slight overpressure as drilling progresses.

The pressure coefficient gradually increases from top to bottom and is exemplified by the overpressure status grading downwards into highly pressured regions at greater depths, an indication that the hydrocarbon generated in this deeper section can be driven by the strong overpressure and migrate along the faults into the shallow, low overpressure area. Thus, the low overpressure belt is favourable for hydrocarbon accumulation.

CONCLUSIONS

In this study, overpressure was detected and its intensity characterized from well log using the fuzzy inference system approach. The result showed that the investigated area exhibits abnormal pressure development with a typical stepped-tiered overpressure configuration identified by triple overpressure, where three episodes of overpressure give rise to three overpressure zones.

The distribution of pressure coefficients was not uniform in the studied area. The pressure coefficient estimate increases gradually down into the subsurface rock; with intermittent occurrence of low and medium pressured intervals sandwiched between sand intervals at

the intercalated section of the Akata Formation of the Niger Delta region and intermediate depths. Higher values were found concentrated towards the deeper parts of the wells while lower values occur at shallower depths. On the average, the PC values in Barbados – well 1 and Barbados – well 2 were less than those in Barbados – well 3 and Barbados – well 4. This indicates that the geopressure occurrence in Barbados field increases from the left flank of the field to the right flank of the field. Past exploration examples in the Niger Delta show that near normal pressure zones are favourable for hydrocarbon accumulation, and strongly over-pressured zones ($PC > \text{than } 1.8$) are unfavorable for hydrocarbon accumulation.

Lastly, the fuzzy inference system result obtained in this study has been a useful and dependable tool in overpressure characterization and modeling. Although the fuzzy inference system has been useful in characterization of different overpressure intensities, further work on pressure coefficient (PC) computation from measurements of hydrostatic pressure and pore pressure in the vicinity of well kicks, caving, loss of drilling mud, or possibly full blowout is welcomed from other authors. We strongly believe result from such adventure will not only help to tie a range of PCs to a specific hazard but also go a long way towards addressing these unwanted hazards associated with drilling activities and manage them effectively.

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