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An Assessment of the Causes of Wellbore Instability and Stuck Pipe Occurrences in an Offshore Field, Niger Delta, Nigeria

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Abstract

Wellbore instability and consequential stuck pipe issues are a common challenge associated with offshore drilling. Usually, the effect of wellbore instability is an increase in non-productive time, possible loss of tools and costly drilling operations. Hence, there is a need for wellbore stability analyses before and during drilling operations. In "Agaza Field", offshore Niger Delta, wellbore instability problems were encountered at various depths between 3,696-4,270 ft.; 5,000-5,425 ft. and 7,600-8000 ft. intervals. Sixty-five ditch-cutting samples and composite log plots obtained from both wells were and analyzed to determine the clay swelling potential and the cationic exchange between the formation and the drilling fluid as well as causes of formation instability. Agaza-1 well showed evidence of tight hole at intervals between 4,200 and 7,600 ft. In Agaza-2, there were indications of wellbore stresses from 1,908 ft. to 2,030 ft. However, deeper than 4,225ft depth, high fluctuation of pore pressure coincided with wellbore instability between 4,810 ft. and 5,200 ft. The principal clay minerals present within the formations are Illite, Smectite and Smectite/Illite interlayered types. Result of the cation exchange analysis showed that high concentration of calcium and sodium in the shale is responsible for high dissociation of the constituent minerals hence making the shales unstable. Analysis has shown that samples at some intervals from both wells are associated with high swelling potential while average cation exchange value is 40 meq/100g. Therefore, the primary cause of wellbore instability and stuck pipe within the studied intervals are attributed to high swelling and reactivity over time due to fluid-formation interaction.

Keywords: Clay cationic exchange, Clay swelling potential, Offshore drilling challenges, Reactive shales.

1. Introduction

One of the major objectives in any drilling operation is to drill to total depth (TD), for efficient logging and data acquisition, bearing in mind safety and optimum productive time. Operations involved in the exploration and production of hydrocarbons are more frequently confronted with complications associated with wellbore instability and stuck pipe. Shale is often responsible for wellbore stability problems during drilling operations. It is estimated that in most Basins 75% of the drilled formations are shales and 90% of wellbore stability problems occurred in shales (Steiger and Leung 1992). This challenge is common within the Niger Delta basin where deviated wells are becoming an increasingly common technology used in drilling operations for enhancing productivity. Also, most of the world's remaining oil and gas prospects will be more challenging to drill than those in the past (Rohani, 2012). Hence, wellbore stability studies should be taken into consideration in the planning stage of well operations to minimize drilling challenges.

The inability to properly mitigate wellbore instability issues can result to well suspension and aborted drilling operations thereby incurring losses worth millions of dollars. Osisanya (2011) is of the opinion that wellbore instability is caused by a combination of mechanical and physico-chemical mechanisms; in such cases, there is no simple solution for wellbore instability. Zeynali, (2012) opines that mechanical interactions are time independent phenomena, which are directly linked to the appropriate selection of mud weight. On the contrary, physico-chemical processes are time dependent (Osuji et al., 2008; Zeynali, 2012) and related to the interaction between shales and water based muds (WBMs). It is therefore necessary, to address these cases with careful rock characterization and mud weight optimization. This study therefore seeks to investigate the causes of wellbore instability and stuck pipe within an offshore field in the Niger Delta Basin from a physico-chemical standpoint. As this will invariably enable proposing a technique suitable for early prediction and possible mitigation of wellbore instability.

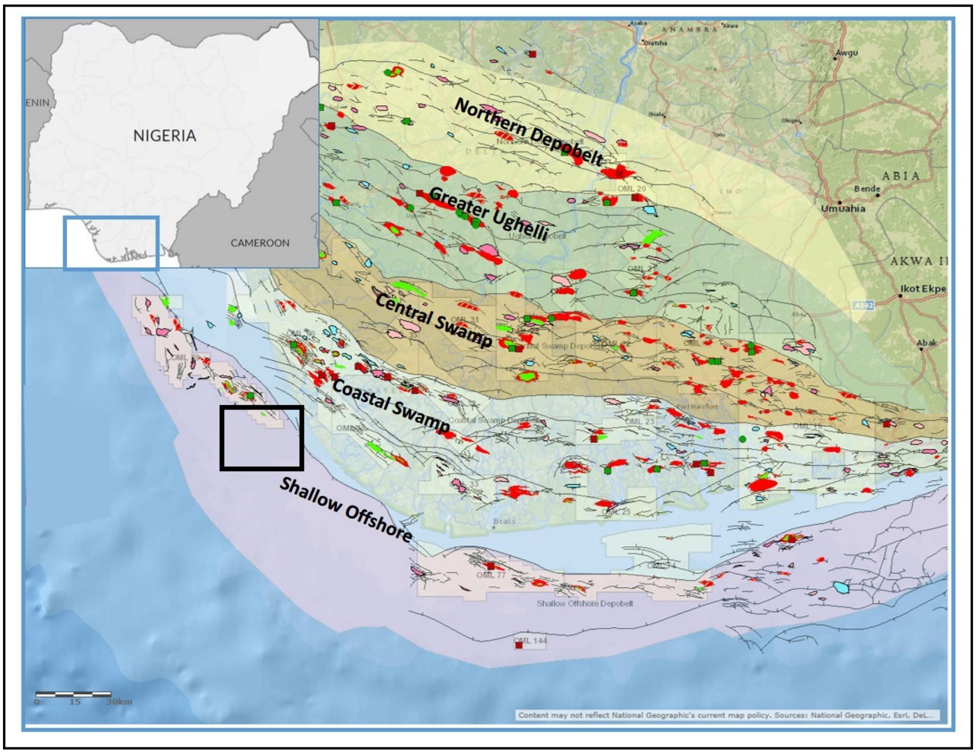

Fig. 1: map of Nigeria inset; showing a depobelt map of the Niger Delta and the study area (Ejedawe, 1981).

2. Regional tectonic and stratigraphic setting of the Niger Delta Basin

The Niger Delta, situated on the passive western margin of Africa, is one of the largest modern deltaic systems in the world. The Delta is a progradational complex largely shaped by wave and tidal processes. The Dahomey Basin borders it to the west; the Abakaliki Fold Belt and Calabar Flank are at the eastern margins of the Basin, while its northern and southern limits are the Anambra Basin and the Gulf of Guinea, respectively. During the breakup of the South American and African plates in the Late Jurassic (Burke et al., 1972) the development of a passive continental margin on the coast of West Africa began forming the Niger Delta.

From the Eocene to the present, the delta has formed depobelts that together make up one of the largest regressive deltas in the world with an area of some 300,000km^2 (Kulke, 1995) and a sediment thickness of over 10 km in the basin depocenter (Kaplan et al., 1994). The Niger delta is made up of the Akata, Agbada and Benin lithostratigraphic diachronous units. These units have been known to contain prodelta shales (with occasional turbiditic sands), paralic clastics and continental sands respectively.

3. Materials and methods

The causes of instability were determined using composite well logs, swelling potential tests and cation exchange results.

Clay swelling potential: Agaza-1 and Agaza-2 were sampled and logged. Sixty-five ditch-cutting samples collected from shale shakers were utilized for the formation swelling potential determination using the Holtz and Gibbs (1956) method. Swelling volume of the sample was noted after it came to rest and left for 24 hours and 96 hours for shallow intervals and depths greater than 6000ft respectively. Similar procedures were employed for samples collected from Agaza-2 however, samples deeper than 5000ft were allowed for 168 hours as a simulation of the delay in drilling operations due to Top Drive System failure. The water based drilling fluid was used as a solvent. The percentage of the volume expansion indicates the water-sensitivity of shales.

The free swelling potential is given by:

$$:FS = \frac{V - V_o}{V_o} * 100 \quad \text{(equation 1)}$$

Where

FS = the free swell, in percentage (%)
V= the sample volume after swelling in cm^3, and
V_o= the volume of dry sample. $10cm^3$

Cation Exchange Analysis: The degree of cation exchange between the formation and drilling fluid was gotten using EDTA (ethylenediaminetetraacetic acid) titrimetric and flame photometry method for the calcium/magnesium ions and the potassium/sodium ions respectively. Cationic exchange capacity (CEC) measurements are usually in milliequivalent per 100 g of clay (meq/100 g) and values are often > 20 meq/100 g for reactive clays and 10–20 meq/100 g for moderately reactive clays. Recall that the CEC of a typical Smectite is between 60 and 120 meq/100 g; Illite is between 10 and 40 meq/100 g (Stephens et al., 2009).

4. Results and analysis

4.1 Well program and drilling plan

Agaza-1 was initially programmed for a straight wellbore to a depth of 11,000 ft. as a wildcat, however, it was drilled to a depth of 10,090 ft. MD (10,083 ft. TVD) due to certain instability issues. The first hole instability problem was encountered while drilling from 4,270 ft. to a casing point of 5,000 ft. The second instability problem was encountered while drilling a shale interval from 5,420-5,995 ft. in an effort at pulling out of hole (POOH). Third instability issue was caused by presence of cavings causing tight hole at a depth of 7630 ft. Mud weight was raised from 9.0 to 10.3 ppg., yet no success until the mud was treated with lubricants. The unstable hole caused issues with logging and subsequently resulting in a loss of the well velocity tool at a depth of 7900 ft. fishing attempts proved abortive and the well was sidetracked in the second attempt with kick-off-point (KOP) at 7000 ft. Leak-off-test (LOT) was finally carried out at 7900 ft. with equivalent mud weight (EMW) of 15.5 ppg. Finally, pore pressure obtained from DCX exponent was 8.3-9.9 ppg. as no further issues were encountered.

Agaza-2 is an appraisal well and was programmed as a deviated well to a total depth of 15,002 ft. unfortunately, due to wellbore instability problems the actual depth drilled was 10,842 ft. (MD). The first borehole instability issue was between 1,908-2,030 ft. within the $17^{1/2}$ well section was due to washouts and erosion as indicated by the $17^{1/2}$" directional MWD-LWD assembly. High sand traps and mud pits were observed which resulted in breakdown and dilution from 9.4 to 9.1 ppg. The second and major instability issue was encountered within the $12^{1/4}$ borehole section. There was a considerably long exposure time due to power failure on the rig after drilling up to 10,756 ft. (MD). In an attempt to POOH after the delay, the drill string was stuck between 4,810 and 5,208 ft. (MD). Several fishing attempts proved futile. Eventually the fishing tool became stuck. Finally, the well was then suspended without reaching the proposed depth due to the circumstantial stuck pipe incident.

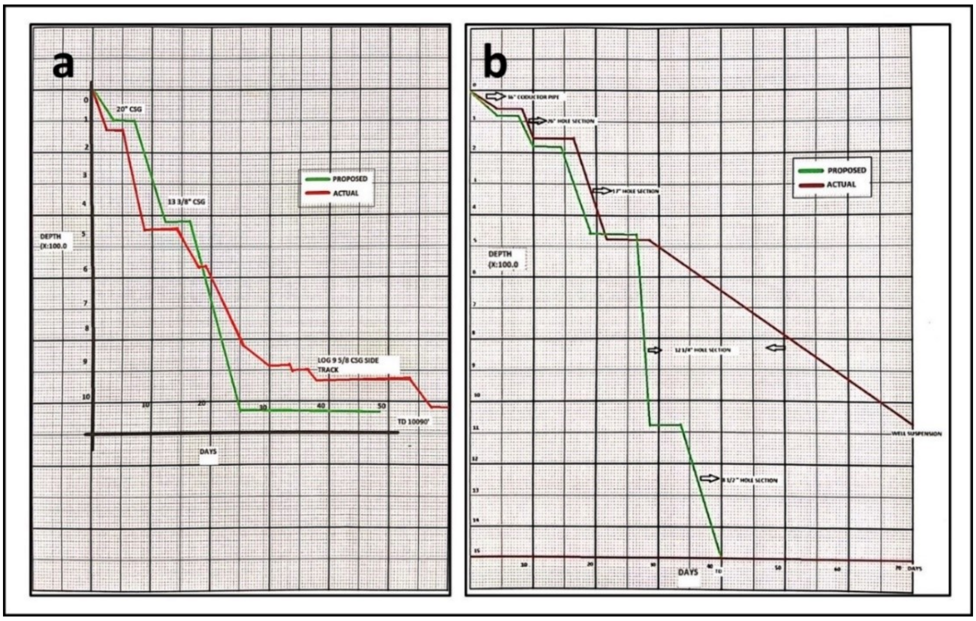

Fig. 2: Drilling plan plot of depth (1=1000ft) vs time; a) Agaza-1 b) Agaza-2 (proposed path in green; actual path in red).

4.2 Composite Well Log Analysis and Lithologic Description

The composite well logs were used to delineate areas with abnormal pore pressure and wellbore conditions. The torque (TRQ) increase was used especially to identify intervals experiencing stresses at the wellbore wall (Fig. 3b & c). The first wellbore instability occurrence in Agaza-1 coincides with an increase in several parameters including rate of penetration (ROP), standpipe pressure (SPP), equivalent circulating density (ECD) and rotations per minute (RPM) (Fig. 3b). The composite pressure plots for Agaza-2 show only a noticeable increase in TRQ at around 5,750 ft.

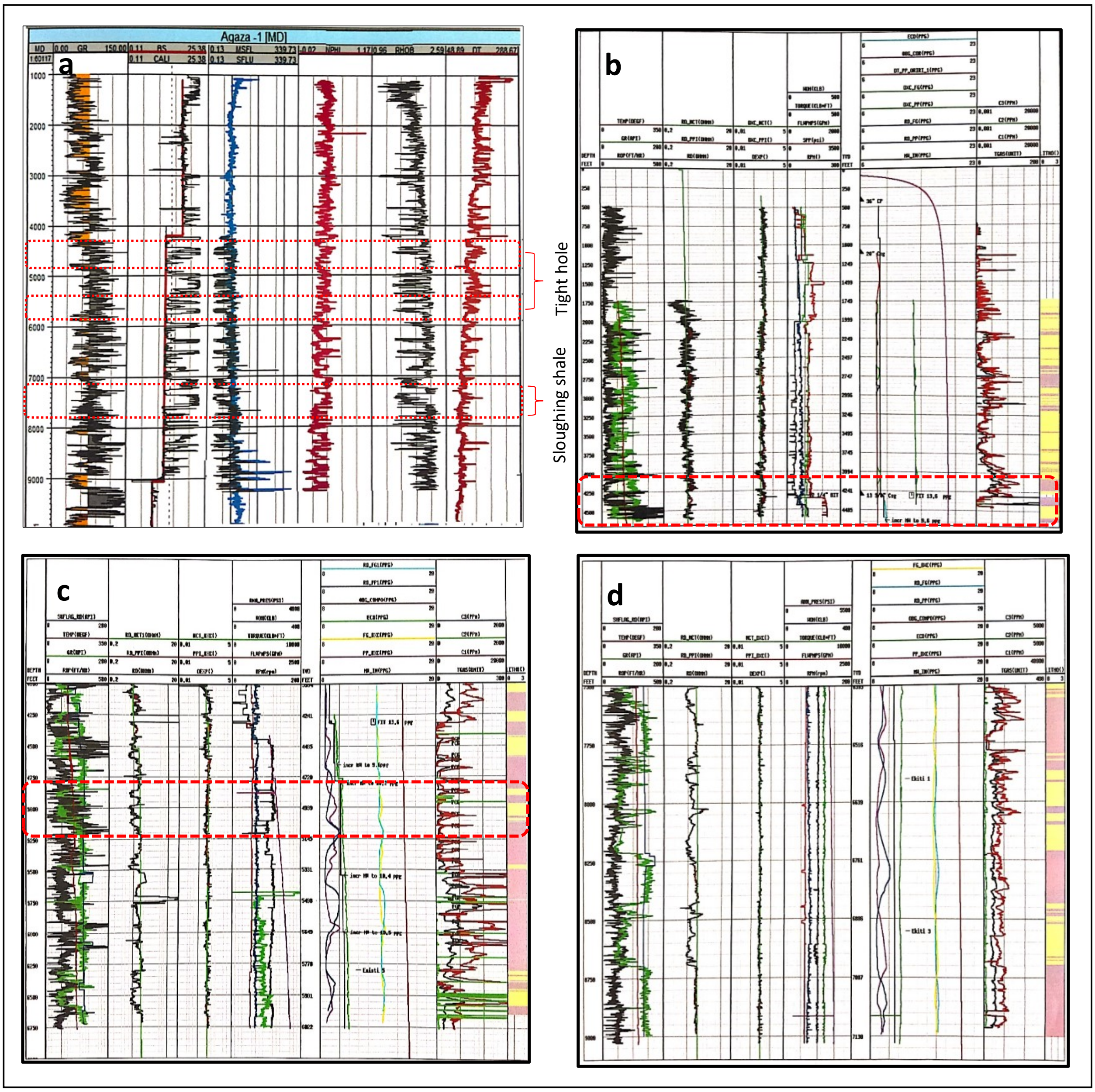

Fig. 3: a) Well log suites used in this study showing intervals of unstable formations; note increase in wellbore size from caliper log. Composite pore pressure plots for Agaza-1 (b) and Agaza-2 (c&d); unstable intervals showing high torque; depth interval: a) 500-4500 ft.; b) 4200-6766 ft.; c) 7500-9000 ft.

4.3 Lithologic Description

The lithologies encountered within the field were sandstones and shales. The sandstones are brown, fine to medium occasionally coarse-grained and mostly moderately sorted. Below the sandstones are intercalations of shale and sandstone (Figure 4b). The shale is light grey, soft, firm in part, amorphous, washable, non-calcareous with presence of lignite.

At greater depths of about 8700 ft., shale percentage was around 90% with minor sandstone intercalations (Figure 4e).

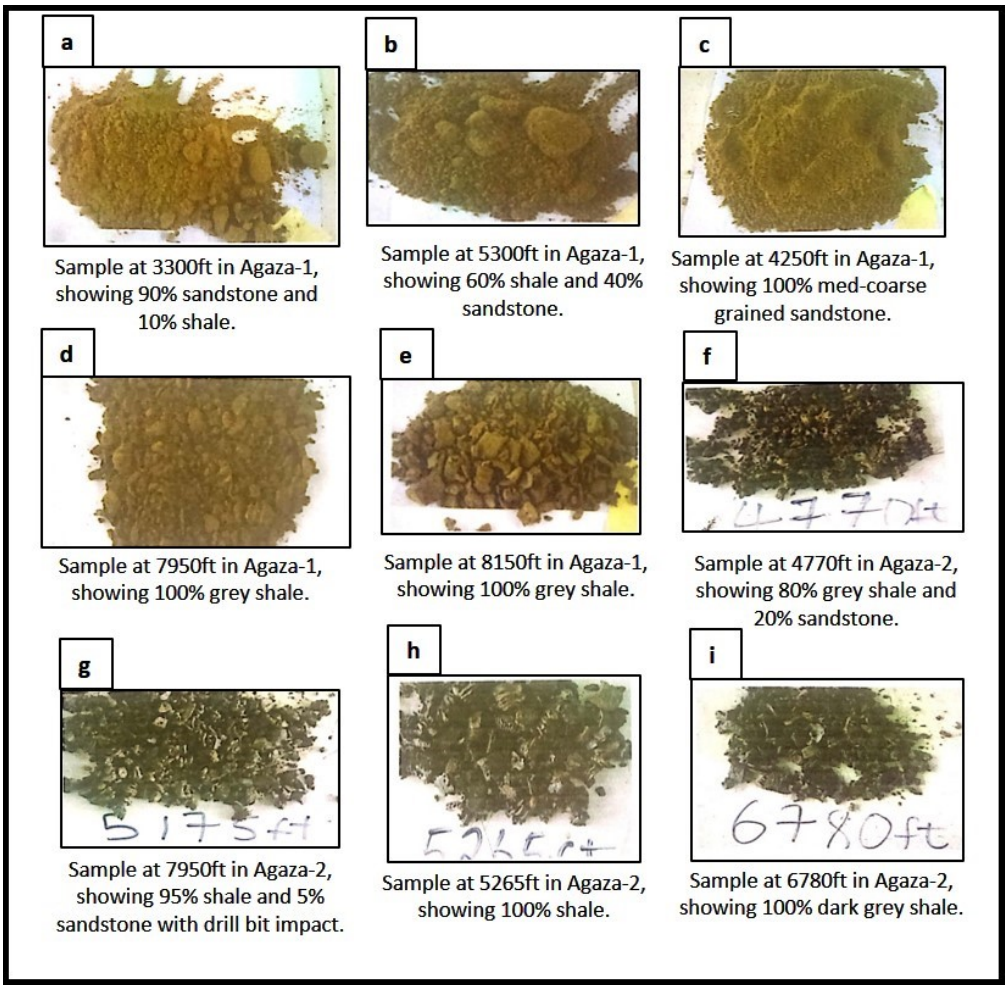

Fig. 4: Lithologic description done on samples gotten from the shale shakers for Agaza-1 (a & b) and Agaza-2 (c & d) wells.

4.4 Cationic exchange

The CEC test results from the two wells were used to determine the dominant clay minerals in order to correlate these with swelling potential tests carried out at those depths.

Agaza 1

Within this well, three main clay mineral types were found the Smectite, Smectite/Illite and the Illite minerals (TABLE 1). Agaza-1 well contains mainly the mixed Smectite/Illite interlayered clay types. The average CEC of the samples is 44 meq/100g. The Smectite content within the well was 3%, while Smectite/Illite and Illite had 58% and 39% respectively.

Agaza 2

Within this well, only the Illite and Smectite/Illite clay mineral types were found (TABLE 1). Agaza-2 well contains mainly the Illite clay types. The average CEC of the samples is 36 meq/100g. Although not readily hydrated and dispersible, the average CEC values show that the illite minerals are generally reactive. The percentages of the clay minerals were 18% and 82% for Smectite/Illite and Illite respectively.

Table 1: Wells Agaza-1 and Agaza-2 cation exchange capacities at various depths; NB: I-Illite, S-Smectite S/I-Smectite/Illite.

Depth	Agaza-1						Agaza-2					
	K (ppm)	Ca (ppm)	Na (ppm)	Mg (ppm)	CEC	Clay Type	K (ppm)	Ca (ppm)	Na (ppm)	Mg (ppm)	CEC	Clay Type
5100	800	4440	3400	1080	33.25	I	450	6630	1400	624	39.50	I
5200	750	5160	3000	1032	36.32	I	700	8760	4000	1476	57.89	S/I
5300	500	4140	1600	432	25.58	I	700	5360	3100	672	34.19	I
5400	450	8840	800	192	46.95	S/I	1000	8980	2700	996	55.70	S/I
5500	400	8120	1200	168	43.02	S/I	1050	6910	1400	281	39.58	I
5600	500	7160	2400	624	42.28	S/I	650	3550	2100	201	21.09	I
5700	800	9080	4000	1476	59.75	S	850	5980	3400	758	38.39	I
5800	900	6180	3500	672	38.80	I	800	3130	1900	790	24.28	I
5900	650	8960	3700	804	53.16	S/I	1000	5560	2900	549	34.93	I
6000	800	9280	3700	296	50.91	S/I	1050	2980	1900	1139	27.08	I
6100	800	9220	2700	366	51.20	S/I	900	7950	4000	767	48.44	S/I
6200	800	7900	1400	281	43.89	S/I	1000	5480	2100	313	32.57	I
6300	500	5640	2100	201	31.15	I	850	7900	2700	909	49.25	S/I
6400	650	7240	3400	458	41.68	I	800	5760	2700	796	37.48	I
6500	600	8650	1900	790	51.37	S/I	1150	4890	2200	251	29.49	I
6600	850	7800	2900	549	45.75	S/I	900	5450	1400	205	31.26	I
6700	900	5450	1900	1139	39.04	I	1050	6310	2500	458	38.05	I
6800	900	7320	4000	767	45.29	S/I	1050	5780	3100	790	38.17	I
6900	850	6850	2100	313	39.03	I	800	5000	1700	549	31.62	I
7000	600	8650	2700	909	52.36	S/I	800	5990	2900	1219	42.15	S/I
7100	700	7770	2700	796	47.27	S/I	950	6050	1400	807	39.41	I
7200	900	6000	2200	251	34.39	I	750	7590	2600	743	46.06	S/I
7300	750	7210	1400	205	39.68	I	950	5760	1900	780	37.73	I

7400	950	8880	2500	458	50.65	S/I	700	3950	2400	932	29.31	I
7500	800	7570	4100	790	46.48	S/I	500	5760	1800	743	36.27	I
7600	650	6780	1700	549	40.14	I	500	5760	1800	743	36.27	I
7700	700	7950	2900	1219	51.70	S/I	900	3160	3400	1080	27.10	I
7800	850	8190	2400	807	49.85	S/I	650	4120	3100	1032	30.86	I
7900	600	9100	2600	743	53.23	S/I	950	5080	1700	432	31.40	I
8000	750	7865	1900	780	47.74	S/I	500	7280	900	192	39.28	I
8100	500	5960	2400	932	38.84	I	750	7240	2200	168	39.52	I

4.5 Swelling Potential

Essentially, swelling is determined by the type and amount of mineral particularly clay in the shale. In the majority of siliciclastic rocks, swelling minerals are represented by the mixed-layered mineral Illite-Smectite (Srodon, 2009). Shale reactivity is mainly a function of clay mineral surface area. Generally, higher surface area indicates higher reactivity. For example, shale with more Smectite (750m^2/gm) absorbs more water than Illite (80m^2/gm) or Kaolinite (25m^2/gm). The clay minerals that create problems associated with reactive formations are Kaolinite, Smectite, Illite, and Chlorite. Illite are naturally non-swelling clays, however, cationic replacement of potassium by sodium or calcium induces swelling.

The swelling test results of the samples from both wells are shown in Table 2.

Table 2: Agaza-1 and Agaza-2 free swell percentages

Depth	**Agaza-1**				**Agaza-2**			
(ft.)	**Initial Vol (Vo) cm3**	**Final Vol (V) cm3**	**Diff Vol cm3**	**Free Swell %**	**Initial Vol (Vo) cm3**	**Final Vol (V) cm3**	**Diff Vol cm3**	**Free Swell %**
5100	8.00	8.20	0.20	2.50	9.00	9.50	0.50	5.56
5200	13.50	13.50	0	0	15.00	15.80	0.80	5.33
5300	9.00	9.00	0	0	11.00	11.40	0.40	3.64
5400	8.00	8.27	0.27	3.38	12.00	13.70	1.70	14.17
5500	6.00	6.50	0.50	8.33	2.00	2.30	0.30	15.00
5600	15.00	15.80	0.80	5.33	5.00	5.40	0.40	8.00
5700	20.00	21.50	1.50	7.50	16.00	17.20	1.20	7.50
5800	10.00	10.82	0.82	8.20	15.00	15.80	0.80	5.33
5900	18.00	18.80	0.80	4.44	16.00	17.00	1.00	6.25
6000	15.00	15.40	0.40	2.67	11.00	11.95	0.95	8.64
6100	9.00	9.15	0.15	1.67	11.00	11.86	0.86	7.82
6200	14.00	15.40	1.40	10.00	6.00	6.50	0.50	8.33

6300	16.00	16.30	0.30	1.88	14.00	14.70	0.70	5.00
6400	19.70	19.90	0.20	1.02	20.00	21.00	1.00	5.00
6500	4.00	4.06	0.06	1.50	10.00	11.00	1.00	10.00
6600	1.80	1.80	0	0	18.00	18.80	0.80	4.44
6700	9.00	9.41	0.41	4.56	13.00	13.50	0.50	3.85
6800	5.00	5.40	0.40	8.00	18.50	18.80	0.30	1.62
6900	2.00	2.40	0.40	20.00	12.20	12.59	0.39	3.20
7000	12.00	14.30	2.30	19.17	5.50	5.89	0.39	7.09
7100	16.00	17.75	1.75	10.94	15.00	15.66	0.66	4.40
7200	13.50	14.20	0.70	5.19	16.00	16.84	0.84	5.25
7300	15.00	15.40	0.40	2.67	16.00	16.05	0.05	0.31
7400	11.00	11.20	0.20	1.82	19.90	20.10	0.20	1.01
7500	16.00	17.00	1.00	6.25	18.90	19.40	0.50	2.65
7600	15.00	15.80	0.80	5.33	5.50	5.55	0.05	0.91
7700	16.00	17.00	1.00	6.25	26.00	26.12	0.12	0.47
7800	12.50	12.80	0.30	2.40	14.00	14.09	0.09	0.65
7900	15.00	15.40	0.40	2.67	16.00	16.20	0.20	1.25
8000	11.00	11.10	0.10	0.90	19.90	20.00	0.10	0.50
8100	12.20	12.40	0.20	1.64	11.00	11.20	0.20	1.82

5. Discussion

5.1 Cationic exchange

The high CEC values show that the clay minerals are reactive and seem to have played a considerable role in the tight-hole and sloughing issues found in the Agaza-1 well (TABLE 1).

In Agaza-2 however, open-hole time during drilling operations, induced the hydratable nature in the Illite by cation replacement, thereby causing sloughing and caving (Figure 3b). The study shows that the main clay types seen within the area were consistent with those documented by Osisanya (2011).

5.2 Effects of high clay swelling

The results from the clay swelling potential shows that upon adsorption of water from the drilling fluid, the clays hydrate and swell. Agitation within the wellbore during drilling then disintegrates the swollen pockets into individual plates or smaller pockets of plates.

Furthermore, results show that Agaza-1 well contains clay minerals with high swelling potential within the intervals of 6,800 – 7,700 ft. (TABLE 2). This is most likely the cause of the sloughing and cavings around that depth. One depth interval showed high swelling potentials within the Agaza-2 well. From a depth of 5,100 to 6,500 ft., the average free swell percentage was 8.45% (TABLE 2). The stuck pipe occurrence within 4,800-5,200ft can therefore be attributed to the swelling of the shales.

6. Conclusion

Assessment of cation exchange and shale swelling potential within the Agaza field showed that the shales contain mainly Illite, Smectite and Smectite/Illite mixed-layered clay minerals with high free swell percentages. Careful examination proves that the instability problems within the Agaza field could have resulted from hydrating and swelling shales. Cutting samples analysis showed high swelling potentials causing sloughing and caving around these unstable intervals. Agaza-2 contained mainly Illite, which had undergone cation replacement due to excess open-hole exposure and became unstable as a result. The critical instability problems caused stuck pipe issues, loss of tools and subsequently well abandonment.

The possible remediation techniques include the use of polymer based mud systems for spudding. Inhibitive water based mud is also ideal to use after spud mud as they can minimize clay swelling when they contain potassium (K+). At deeper sections, a well formulated oil based mud is ideal for improving hole stability when drilling troublesome shales, high deviation wells and high temperature/high pressure wells. Good drilling practices are also advised in order to reduce the occurrence of wellbore instability. Time of exposure of the formation to the drilling fluid should be minimized to lower the risk of instability issues.

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