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Research Article

Experimental Investigation on the Effect of KCL and Bentonite on Shale Stability

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Abstract

Shale is considered most of the time as a troublesome formation due to the problems caused while drilling using water based muds. Additionally, the shale composition which varies from one type to another has complicated the effort of developing appropriate water based mud. In light of maintaining a stable wellbore, there is need to formulate an adequate drilling mud and investigate the shale swelling and borehole instability problems associated with shale-fluid interaction. This study presents results of experimental investigation conducted on the swelling behavior of shales under static and dynamic conditions. The investigation was carried out using clean Okolobra 2 and Okolobra 5 shale samples from a Niger Delta well obtained at different depths. Dynamic swell meter was used to measure the swelling strain as a function of time at different temperatures (85, 150, and 200°F). Three types of drilling fluids were used during the investigation. Bentonite based fluids composed of varying concentrations of bentonite, barite, salt, and the KCl polymeric additives were prepared. Swelling test was conducted using cylindrical wafer (disks) of Okolobra 2 and Okolobra 5 shales. The wafers were made by compacting powder samples of both shales. The Okolobra 2 exhibited more interaction and swelling on exposure to aqueous fluids while the Okolobra 5 shales showed less swelling. Increasing temperature and fluid agitation intensify shale swelling and instability problems. This indicted that in addition to the interaction between the water molecules and shale particles, the movement of water molecules in the fluid affects the process of shale swelling.

Keywords: *wellbore instability, shale swelling, swelling inhibitor additives, Mud-Shale Interaction, Oil based mud (OBM), water based mud (WBM), agitation, bentonite, KCl-Polymer.*

1. Introduction

Instability in the wellbore is one of the primary causes of delays in drilling operations and in some cases; it even leads to suspension of wells prior to reaching the target depth. This is mainly experienced in shale sections and is believed to be the unfavorable interactions between the shale and drilling mud (Chenevert, 1970). Since the drilling operations is capital intensive, drilling engineers do not want to spend longer time on site than necessary because every minute on the rig floor is equivalent to some dollars; thus, this has necessitated a lot of authors trying to present a more acceptable method of wellbore stability analysis.

The primary causes of shale instability are related to the movement of water/ions into or out of shale, in-situ stress state conditions, well types (vertical or directional), well trajectories (inclination and azimuth), rock properties (strength, Poisson ratio, modulus of elasticity, permeability) and thermal effects. This movement causes change in mechanical and physiochemical properties of the shale, and can lead to wellbore instability problems. Although interactions between the shale and drilling mud which include chemical, physical, hydraulic, mechanical, thermal, arid electrical phenomena, are very complicated (Mody *and* Hale., 1993).

Over the years, with much experience and considerable research, the drilling operations have been continuously plagued by the various hole problems encountered in shale formation. These problems are not specific to a particular region but a worldwide problem whenever a shale formation is encountered. Thus, in order to effectively and efficiently drill shale formation, we need to understand the wide variations in clay chemistry which makes the solution to shale instability difficult. The oil and gas industry is developing new generation of drilling fluid additives to battle shale swelling and reduce environmental impact of drilling operation. The development of effective clay swelling inhibitors which are able to meet today's environmental regulations is therefore an area, which attracts a large amount of

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*Corresponding author: **Okotie Sylvester** research attention from both the academia and industry. The development of new clay swelling inhibitor additives is particularly challenging in identifying materials, which are biodegradable but can also remain stable when exposed to typical wellbore temperatures and pressure.

2. Drilling Mud Selection

The drilling fluid has several functions which enhance the drilling operation. It must be selected/designed proper in such as way that the physical and chemical properties of the fluid perform the desired functions. Hence, a special consideration must also be adopted when selecting the fluids (Dosunmu and Ogunrinde, 2010; Xiaoqing and Lihui, 2009) such as:

- The drilling fluid environmental impact
- The cost of the fluid
- The effect of the drilling fluid on production from the reservoir

Due to the various desirable rheological properties that oil exhibit, the oil base mud (OBM) have a lot of advantages over the conventional water base mud. The composition of a typical OBM is given as: about 3% of Clays and sand, Salt about 4%, 9% Barite, 30% Water, Oil 50-80% with oil as the dominant or continuous phase. Since the oil is component to the formation, during drilling the filtrate will not have much damage the reservoir as compare with other foreign fluid such as water (Sachez et al, 1999). OBM is preferred to WBM especially in hot environment and salt beds where formation compositions can be dissolved in WBM.

Water-based muds (WBMs) are usually the mud of choice in most drilling operation carried out in sandstone reservoir; however some unconventional drilling situations such as deeper wells, high temperature/pressure formation, deepwater reservoir, alternative shale-sand reservoir and shale resource reservoir require use of other mud systems such as oil based mud to provide acceptable drilling performance (Dosunmu and Ogunrinde, 2010; Xiaoqing and Lihui, 2009; Fadairo et al, 2012).

One of the primary well control is the drilling muds which help to remove drill cuttings from wells with the following functions: bit cooling and lubrication, Hole cleaning, suspend cuttings during circulation stoppage, Pressure control, maintain the stability of the wellbore, control corrosion and formation damage, Transmission of hydraulic energy to Bottom Hole Assembly, enhances cementing operations, Minimize environmental impact, prevention of loss circulation and formation of mud cake which seal permeable zones.

3. Brief Literature Review

Charlez and Heugas (1991) stated that during drilling operation, wellbore instability is the monumental source of concern, causing waste of drilling time and unnecessary costs. This serious problem mainly occurs in shales (principally clays), which represent about 75% of all formations drilled in industry. The remaining 25% are composed of other minerals such as sand, salt, etc. The wellbore instability is due to the dispersion of the clay into ultra fine colloidal particles and this has a direct impact on the drilling fluid properties. Chen (2002) pointed out that wellbore instability problems is estimated to cost the oil industry about 1 billion US dollars each year. Thus, oil-based drilling fluids which contain elevated levels of salt can address this problem; however, excessive costs and environmental requirements limit their use.

Conventional water-based muds (WBMs) that are used to drill through water sensitive shale formations cause a high degree of wellbore instability. Consequently, oil-based muds (OBMs) were adopted to solve the wellbore instability problems due to their superior shale stabilization properties (Patel et al., 2007). Unfortunately, high costs, environmental restrictions, cutting and used mud disposal difficulties, and safety have largely limited the use of OBMs. All over the world, restrictions on the types of drilling fluids used are continually being evaluated with respect to their environmental compatibility. Consequently, WBMs that have the ability to effectively reduce shale instability problems have once again come under the limelight to replace the OBMs.

In order to see the effect of chemical potentials on shale swelling, Chenevert (1970) performed experiments after matching the water activity of the aqueous component of oil-based muds and the shale samples. As a result of balancing the water activity of OBMs with those of shale samples, the swelling was minimized. Tests conducted at lower chemical activity of the liquid portion of drilling fluid than the once in shale, showed more reduction in shale swelling to the point that the movement of water was in the opposite direction which is known as the shrinkage state rather than swelling. In general, increasing salt content in drilling fluids has a tendency to minimize the swelling of shale, and vice versa.

4. Challenges of Wellbore Instability

Wellbore instability is one of the most serious problems in the oil and gas industry. It can lead to delays in the drilling process, increase in drilling cost, and in some cases even to abandonment of the well. The most common failures or problems associated with shale instability using conventional water based mud are bit balling, stuck pipe, caving, sloughing, and increased torque and drag. These problems can grow into massive expenses due to lost non-productive time. These expenses are further compounded by mud treatment cost, difficulties in running casing and poor cement jobs. However, shales make up about three fourths of drilled formation and over 90% of the wellbore instability problems that occur in shales. Even though shale stability has been studied for several decades, it is still a serious problem in not only the petroleum industry but also in the mining and construction industries. Before any measures are taken to address this problem, it is crucial that potentially problematic formations and the mechanisms of wellbore instability be identified. Once the mechanisms are understood, well planning, drilling fluid design, and drilling operation strategies can be implemented to ensure wellbore stability. Due to the unique mechanical and physicochemical properties of shales, it is well- recognized that wellbore instability in shales is a complicated problem.

5. Objectives of Study

The study is basically on the instability behaviour of clays when exposed to oil and water-based drilling fluid systems. The main objectives of the study are:

- To deliver a detailed review on fundamental of shale instability (swelling), water based mud, shale-fluid interactions, inhibitors, and temperature effect on swelling of shale.
- Better understanding swelling behavior of clays under high temperature and dynamic conditions.
- To evaluate the performance of different mud system (Bentonite, KCl and oil base mud) on shale stability.

6. Materials/equipment used

The materials used for this study are: two shale samples, mortar and pestle, distilled water, diesel oil, Weighing balance, Retort, Hamilton Beach Mixer, Mud balance, Round bottom flask, API filter press, variable speed rheometer and pH meter. The functions of these additives are given in table 1.

Table 1: Additives and their functions

Additive	Function (S)
Bentonite (Gel)	Control of viscosity and filtration
Barite	Weighting agent
Soda Ash (sodium carbonate)	Calcium precipitant and pH reducer in cement contaminated mud
Water and Diesel Oil	Base fluid
XCD	Control of viscosity and filtration
Par R	Viscosifier and fluid loss control
Par L	Viscosifier and fluid loss control
Caustic soda (sodium hydroxide)	pH control
KCl	Control borehole stability

7. Formulation of a Bentonite Mud

335grams of water was measured and poured into the Hamilton mixing cup. 4.5grams of Bentonite was added and prehydrated for 25 minutes under stirring condition. After 25 minutes, 0.25grams of xanthan gum, 0.5grams of Pac-R, 0.8grams Pac-L respectively were added to the mixing cup. This with prehydrated bentonite was stirred for 18 minutes before 0.25grams of Soda ash was added and stirred for another 12 minutes. Then 14.0 grams of barite was finally added and the mixture was stirred further for another 20 minutes for homogeneity before taking the rheological readings and (10 seconds/minutes) gel strength using VG meter.

The mixing procedure was repeated using the ground sample of shale. Different weights of the shale, KCl and polymer by weight of the formulated mud were added. The rheological readings and (10 seconds/minutes) gel strength values were recorded as well. The plastic viscosity and Yield Point values were evaluated as applicable.

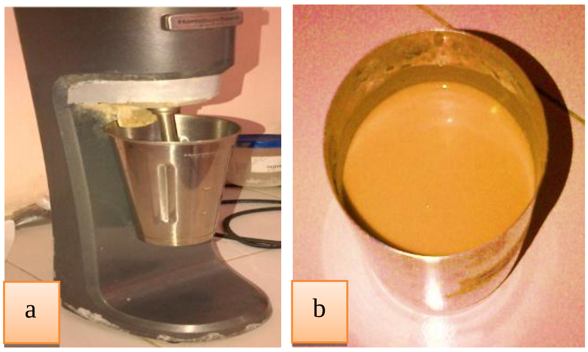

Figure 1: (a) Hamilton mud mixer (b) formulated water-based mud

8. Shale Samples

The shale samples used for this study were gotten from a geology analysis laboratory of a field previously been drilled in Okolobra (2 & 5) field in the Niger Delta region of Nigeria.

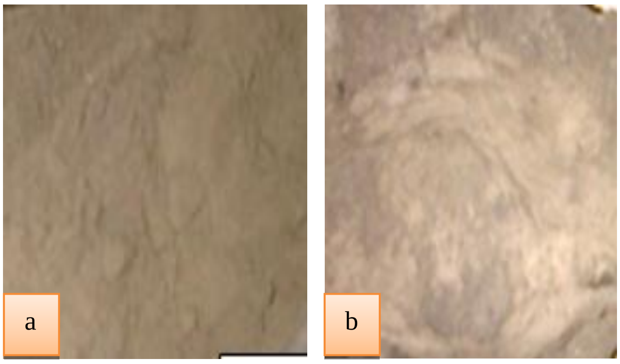

Figure 2: (a) Okolobra 2 shale sample (b) Okolobra 5 shale sample

9. Shale Test Sample Characterization

Okolobra 2 shale sample was cored at a depth of 8750 ft and transported in plastic polythene bags to the geology lab where it was stored in cardboard boxes. The second sample was obtained from Okolobra 5 and was cored at a depth of 9000 ft. These samples were cored and preserved using the water-based mud used to drill the wells. The shale samples were prepared by grinding them to fine powder of less than 0.01mm using a mallet, mortar and pestle. All instruments were cleaned with acetone to remove any trace amounts of previous shale samples. After grinding, the shales were placed in an oven at 60^0C (140^0F) for 24 hours to remove moisture present in the shale. The two shale samples were characterized using the following methods:

1. Mineralogy analysis – Fourier Transform Infra-Red Spectrometer
2. Native moisture content – Oven
3. Cation exchange capacity – Methylene blue test

Shale mineralogy analysis is used to identify the type and relative amounts of minerals present in shale samples. X-Ray diffraction analysis (XRD) and Fourier Transform Infra-Red Spectrometry are common techniques of analysis utilized. It is also important to note that the composition of the pore fluid, and CEC of Okolobra 5 was not available during the period of study.

10. Experiment 1 (Bentonite-Shale Interaction)

- Measure 100ml of the bentonite into a 250ml beaker
- Immersed a sample of the shale cuttings into the mud and monitor for 6hrs.

(a) Kcl Polymer System

- Treat the water with soda ash
- Prehydrated bentonite in fresh water at a concentration of not more than 10ppb
- Then add the KCl at 3% by volume
- Add the polymer; polypac R and the weighting agent (Barite)

11. Experiment 2 (Kcl Polymer Mud-Shale Interaction)

- Measure 100ml of the KCl polymer into a 250ml beaker
- Immersed a sample of the shale cuttings into the mud and monitor for 6hrs.

12. Oil-Based Mud System

Mixing procedure

- Prior to mixing the synthetic base mud, mix the $CaCl_2$ brine in a separate beaker
- Fill the mixing beaker with the required volume of synthetic base fluid
- Add the viscosifier with maximum possible shear applied
- Add the lime, if required and shear the system for 15 to 20min
- Add the primary and secondary emulsifier and mix for 15 to 20mins
- Add the weighting agent
- Slowly add the $CaCl_2$ brine over a period of 20 to 30min and continue mixing for as long as practicable
- Add the fluid loss additive
- Add the barite to weight up the mud to the desired density
- Add rheological modifier if needed
- Continue to mix for at least one more hour and then make a full mud check.

13. Experiment 3 (Oil Base Mud-Shale Interaction)

- Measure 100ml of the oil base mud into a 250ml beaker
- Immersed a sample of the shale cuttings into the mud and monitor for 6hrs.

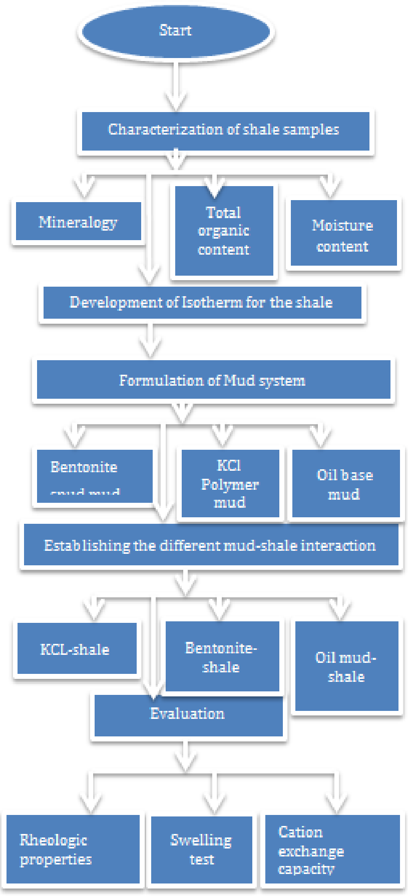

Figure 3: Experimental flow chart

14. Results

14.1 Shale Characterization: Mineralogical Test Results

Mineralogical compositions of the samples were determined using FTRI test. The mineralogy results for Okolobra 2 and Okolobra 5 shales are shown in Table A1 in appendix A. The results of Okolobra 2 analysis obtained at a depth of 8750 ft indicate that it is composed from 25 75% quarts, 4.97% calcite, 7.98% dolomite, and almost 44.38% clay minerals (illite 5.72%, smectite 24.39%, kaolinite 3.87%, and mixed clays 10.4%). Also, it contains some other non-clay minerals such as Orthoclase Feldspar, Albite, Anhydrite, and Aragonite. The Okolobra 2 shale contains substantial amount of smectite and expected to have high swelling.

The Okolobra 5 shale sample that was obtained at a depth of 9000 ft was made up of 65.94% clay minerals (31.37% Illite, 12.56% Smectite, 3.87% Kaolinite, 6.31% Chlorite), 18.42% Quartz, 10.30% Orthoclase Feldspar, 2.94% Siderite, 3.47% Apatite, 1.62% Oglioclase Feldspar. Also, it had small amounts of Albite (0.99%) and Anhydrite (0.57%). The presence of 12.56% smectite group indicates the possibility of hydration and swelling in aqueous solution. According to the classification of O'Brien and Chenevert (1973), the sample falls under the second class that exhibit high content of illite and distinguished to be soft and fairly dispersive.

14.2 Results for Native Moisture Content (NMC)

Table 2: Native moisture content and cation exchange capacity

Parameters	Okolobra 2	Okolobra 5
Native moisture content (% wt)	13.2	21.8
Cation exchange capacity (Meq/100gm of solid)	3.47	5.2

14.3 Swelling Test

Shale swelling test is one of the methods used to quantify shale-fluid interaction. The level of swelling differs from shale to shale and the type of the fluid. The shale swelling theory brought its essential concept to explain the surface interaction between different phases. There is a general agreement that the increase in adsorbed molecules is affected by many physic-chemical factors such as water activity and pressure. Furthermore, the structure of the clay minerals gives enough space for adsorption to occur. It is important to know that the clay content of shale is used to evaluate its adsorptive tendencies due to hydrophilic nature of clay minerals.

14.4 Experiments with Okolobra 2 Samples

Extensive swelling tests were conducted on Okolobra 2 samples. Several types of drilling fluids were tested. For all the experiments 1.25-in. diameter and 0.36-in. thickness wafers were used (Figs. 4 & 5) present swelling of Okolobra 2 shale sample with bentonite mud (WBM) and WBM + 3.5% KCl + 4.5% polymer at static and dynamic conditions respectively. A similar test using mineral oil (oil base mud) didn't show measurable swelling in all the test conducted. The maximum swelling was observed with bentonite mud because of its complete inability to inhibit the clay sample from swelling.

Table 3: Swelling of Okolobra 2 shale after 6hrs

Fluid type	without agitation			with agitation		
	85^{0}F	150^{0}F	200^{0}F	85^{0}F	150^{0}F	200^{0}F
bentonite mud (WBM)	55	65	68	55	65	68
WBM + 3.5% KCl + 4.5% polymer	45	58	64	50	60	68
oil base mud	no swelling was observed, shale found stable even at extended time					

Table 4: Swelling of Okolobra 5 shale after 6hrs

Fluid type	without agitation			with agitation		
	85^{0}F	150^{0}F	200^{0}F	85^{0}F	150^{0}F	200^{0}F
bentonite mud (WBM)	13	15	16	13	15	16
WBM + 3.5% KCl + 4.5% polymer	8	9	9.5	8	8.5	10
oil base mud	no swelling was observed, shale found stable even at extended time					

Table 5: Swelling of Okolobra 2 + WBM + 3.5% KCl + 4.5% polymer at different temperature

Time(hrs)	1	2	3	4	5	6
85^{0}F	25	32	32.3	32.35	32.3	32.3
150^{0}F	25	35.38	39	40	40	40
200^{0}F	25	35.6	40	42.4	43	43

Table 6: Swelling of Okolobra 2 + WBM at different temperature

Time(hrs)	1	2	3	4	5	6
85^{0}F	24	32	40	45	51	55
150^{0}F	25	34	43	50	56	63
200^{0}F	25	35.6	43.4	52	62	68

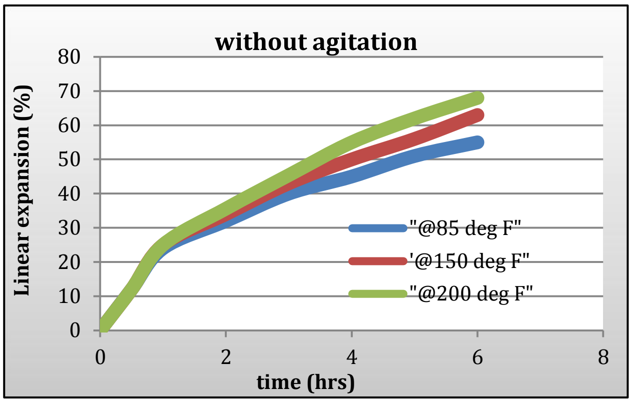

Figure 4: Swelling data of Okolobra 2 shale with (WBM) at different temperatures (75, 150, and 200°F) with agitation

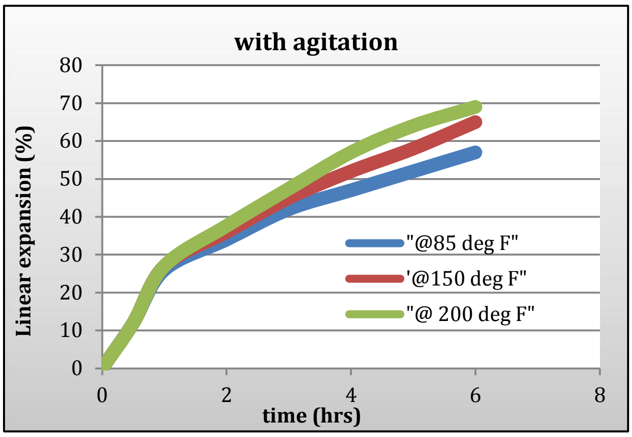

Figure 5: Swelling data of Okolobra 2 shale with (WBM) at different temperatures (75, 150, and 200°F) with agitation

Results presented in (Fig 4 & 5) show the effects of temperature and agitation on the swelling of the samples. The swelling rate (the slope of the curves) tends to reduce with time and eventually becomes approximately constant indicating the presence of two swelling regimes (transient and steady state swelling regimes). The swelling curves show similar trend both under static and dynamic conditions. As expected the swelling tendency increases with temperature for both static and dynamic cases. The agitation has as light effect on the swelling observed after 6 hours.

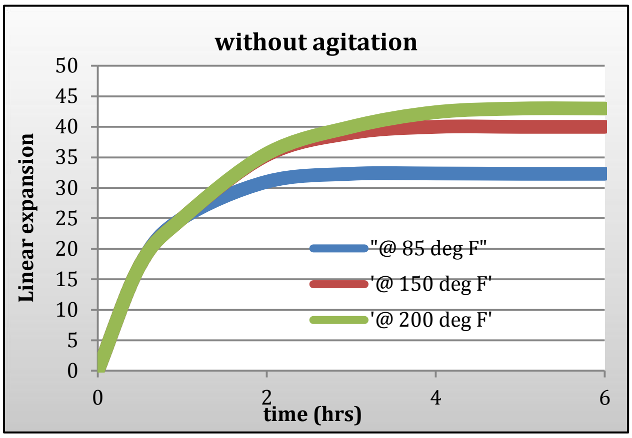

Figure 6: Swelling data of Okolobra 2 with (WBM+ %KCl + % polymer) at different temperatures (75, 150, and 200°F) without agitation

Furthermore, comparison was performed (Fig. 6 & 7) between static and dynamic swelling cases with Okolobra 2 shale sample using (WBM+3.5% KCl + 7% polymer). Like the experiments with bentonite mud, the swelling rate showed reduction with time. However, the swelling curves display three regimes (transient, steady state and ultimate swelling regimes). In ultimate swelling regime, the swelling rate approached to zero. The temperature effect was minimal in the transient and steady state regimes. Moderate differences are shown in the ultimate swelling regime. In both static and dynamics cases, the swelling increased with temperature. Again, the agitation slightly increases the overall swelling that occurs after 6 hours of exposure. Consistent with the swelling measurements obtained using WBM, agitation tends to increase slightly the overall swelling observed after 6 hours.

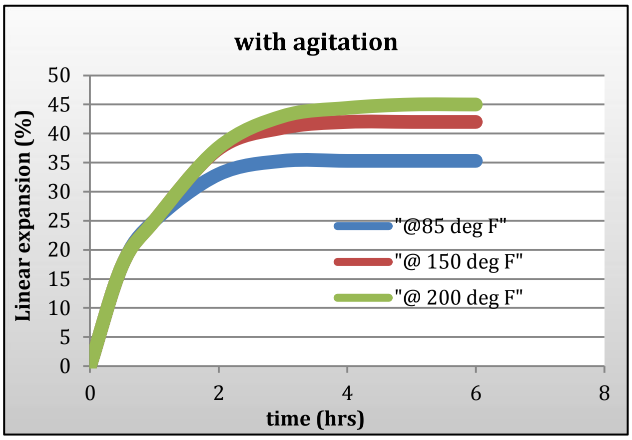

Figure 7: Swelling data of Okolobra 2 with (WBM+ %KCl + % polymer) at different temperatures (75, 150, and 200°F) with agitation

14.5 Result of stability test of drilling mud (WBM & OBM) and shale interaction

Table 6: stability test for WBM and shale interaction

Mud type	Cutting type	Observation	Time
Bentonite (WBM)	shale	observed that shale sample is taking water	1hrs
		Swollen and shale soft	2hrs
KCl-Polymer @ 3.5% wt	shale	the shale cutting was observed to be fairly stable	2hrs
KCl-Polymer @ 5-6% wt		the shale cutting was stable	4hrs

The table 6, shows that the result obtained for the stability test for shale when interacted with water base mud, it was observed that the swelling and softening of the shale for both bentonite, KCl-Polymer at 3.5% wt, KCl-Polymer @ 5-6% wt gradual increase with time.

Table 7: Stability test for OBM and shale interaction

Mud type	Cutting type	Observation	Time
Oil base/synthetic base mud	shale	cutting was found to be stable	2hrs
		the shale cutting was stable even to an extended time	4hrs

For the case of oil base/synthetic mud, there was no significant swelling and softening of the shale cutting even in extended time of the experiment.

Conclusion

- Okolobra 2 exhibits more reactivity and swelling on exposure to aqueous liquids while the Okolobra 5 shales show less swelling and reactivity.
- Increasing temperature exacerbate shale swelling and instability problems.
- Dynamic conditions favor shale swelling and reactivity. This indicted that in addition to the interaction between the water molecules and shale particles, the movement of water molecules in the fluid influences the process of shale swelling. As a result dynamic condition and higher temperature facilitate the swelling process by enhancing the molecular movement in the fluid. The rheology of the fluid plays a major role in determining the molecular movement. Fluids with high viscosity have a tendency to hamper molecular movement; and hence swelling.

Hence, studies that consider high-temperature and high- pressure conditions may be useful to examine shale swelling under simulate real borehole conditions. Further investigation on the effect of agitation can be valuable to better understand the relationship between the molecular transport in the fluid and shale swelling.

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Appendix A

Table A1: mineralogical composition of the shale samples

Mineral Name	Okolobra 2 Shale (%)	Okolobra 5 Shale (%)
Quartz	25.75	18.42
Calcite	4.97	0.00
Dolomite	7.98	0.00
Orthoclase feldspar	10.71	10.30
Oglioclase feldspar	0.00	1.62
Albite	3.84	0.99
Anhydrate	2.65	0.57
Siderite	0.00	2.94
Apatite	0.00	3.47
Aragonite	0.08	0.00
Pyrite	0.00	0.00
Illite	5.72	31.37
Smectite	24.39	12.56
Kaolinite	3.87	3.12
Chlorite	0.01	6.31
Mixed clays	10.04	0.01

Table A2: Composition of interstitial pore fluid for Okolobra 2 shale (cations)

Cations	Concentration (meq/100g)
potassium	0.695
magnesium	0.402
sodium	1.598
calcium	1.012

Table A3: Composition of interstitial pore fluid for Okolobra 2 shale (anions)

Anions	Concentration (meq/100g)
chloride	1.101
carbonate	0.00
bicarbonate	6.633
sulfate	0.210

Table A4: Exchangeable bases for Okolobra 2 shale

Cation	Exchangeable bases (meq/100g)
potassium	0.704
magnesium	4.401
sodium	0.618
calcium	23.019