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On the Compaction and Viscous Behavior of Deep-Water Reservoirs

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Abstract

There have been many studies on reservoir compaction where different mechanisms being suggested as the reasons behind the integrity of unconsolidated reservoirs during production. Theory of poroelasticity is often used to evaluate the likelihood of compaction under these circumstances, but it is often failed to explain the creep behavior of unconsolidated formations. In this study, attempts are made to have a closer look into the compaction mechanism of deep-water sandstone reservoirs. The results obtained indicated that depending on the type of clays, confining pressure and the loading rate, sandstone may exhibit a viscoelastic or viscoplastic behavior during compaction. The results of this study suggest that detailed analysis of clays is required for correct simulations and to answer questions related to geomechanical responses of unconsolidated sandstones under different stress conditions.

1. INTRODUCTION

Pore fluid extraction during continuous production from hydrocarbon reservoirs, under certain circumstances, may result in large strain and deformation of the reservoirs which could be followed by compaction, surface subsidence and significant changes of petrophysical properties (Settari, 2002; Hol et al., 2015). Subsidence of hydrocarbon fields and compaction of reservoirs in Long Beach, California (Colazas and Strehle, 1995), Venezuela (Finol and Sancevic, 1995), and the North Sea (Hermansen et al., 2000) are few examples showing how reduction of the pore pressure may reduce the production rate and severely damage the downhole and surface facilities.

Although there are many carbonate and consolidated sandstone reservoirs which host oil and gas reserves (Chilingar et al., 1972; Jiang et al., 2008), many unconsolidated sandstone formations have been drilled for their promising petrophysical properties and the significant amount of hydrocarbon in place (Graham et al., 2003; Brignoli and DiFederico, 2004; Fortin et al., 2005; Dautriat et al., 2009; Crawford et al., 2011). Time-dependent compaction of these reservoirs is a widely observed phenomenon (Hettema et al., 2002) which may follow a viscous creep deformation mechanism (Mallman and Zoback, 2007; Hagin and Zoback, 2004a). As such, compaction that often takes place within weeks or months in conventional reservoirs, may continue after the production for decades (Mallman and Zoback, 2007; Morton and Bernier, 2010).

Several authors have studied time-dependent deformation of unconsolidated sandstones in the laboratory under different stress conditions. For instance, Chang et al. (1997) conducted laboratory experiments on the room-dry unconsolidated sands and reported the creep strain as an intrinsic property of the solid frame. Hettema et al., (2000) argued that the significant changes in the stress path is the main reason behind the compaction observed in unconsolidated sands. Hagin and Zoback (2004a, b) performed a series of hydrostatic compaction, triaxial compression and ultrasonic pulse measurements on the unconsolidated sands of California and observed a viscoelastic behavior which was attributed to the presence of clays. Crawford et al., (2008, 2011) attempted to determine the compressibility of unconsolidated sands through a series of hydrostatic compaction tests and observed plastic deformation in the matrix structure. Zhnag and Buscarnera, (2017) did a study on the rate-dependent rheological behaviour of poorly consolidated sandstone reservoirs and argued that the Perzyna-type viscoplastic formulation can be used to predict the behaviour of sands under compaction. However, it seems that the mechanism behind the compaction of unconsolidated sands is not fully understood. The aim of this paper is to investigate the mechanism of compaction in unconsolidated deep-water sandstone reservoirs through a series of uniaxial, triaxial compression and compaction tests. A case study from Western Australia is also presented to evaluate the effect of different clays on the viscous behavior of sandstone under different loading conditions.

2. Reservoir Compaction

Withdrawal of oil and gas from high porosity loose and unconsolidated formations is often resulted in compactions and damages to production, completions and surface facilities. Compaction, under these circumstances, is a function of reservoir pressure, compressibility, geometry (radius and depth), thickness and the support of overburden rocks. The amount of support, however, depends on the depth and geometry of the reservoir, and the contrast in mechanical properties between the reservoir and its surrounding formations. it is to be noted that many of the studies carried out in the past decades attempted to evaluate the amount of reservoir compaction by assuming that: 1) the reservoir is a homogenous and linear elastic medium with an elliptical shape, 2) strains applied are vertical, 3) no support is provided by the overburden (Morton et al., 2006; Crawford et al., 2011). However, assumption of a linear elastic or poroelastic behaviour from formations dominated by clays may not be realistic given the fact that the pore-fluid cannot be rapidly drained and mineral transformation may initiate a viscous behavior. This will be further discussed in the next section where compaction of unconsolidated sandstone reservoirs is presented in more details.

2.1. Sandstone Reservoirs

Sandstone reservoirs have been the subject of many studies and are often divided into different categories based on their physical and mechanical properties as given in Table 1. Compaction in sandstone as a quartz-rich rock is induced due to mechanical or chemical processes (Bjørlykke, 2003). In the mechanical process, the effective stress reorients, breaks and consequently creates a very dense pack of sandstone. This means that mechanical compaction has the potential to reduce the porosity from about 40% down to 25% in clean, well sorted, quartz rich sandstones. The chemical compaction, on the other hand, is often referred to as the precipitation of quartz which enhances the cement strength once the temperature reaches 60°C to 80°C (Bjørlykke and Egeberg, 1993). Compactions in sandstone reservoirs is linked to the magnitude of in-situ stresses and temperature of subsurface layers but cannot be easily predicted due to the variation of composition, texture and packing of the rock.

Table 1. Physical characteristics of sandstone formations (Modified after Fjaer et al., 2008)

Rock Type	Density (g/cc)	Effective Porosity (%)	Young Modulus (GPa)	Poisson's Ratio	Bulk Compressibility (1/Pa)	UCS (MPa)
Very Unconsolidated	1.5-1.7	25-40	$9 \times 10^{-6} - 9 \times 10^{-5}$	> 0.45	0.02-0.15	> 1
Weakly Cemented	1.9	15-35	4×10^{-4}	0.45	0.004-0.00252	1-5
Consolidated	2.18	5-30	1-5	0.38	0.001-0.006	5-75
Tight	2.0-2.7	0-5	5-15	<0.45	0.0004-0.002	75-240
Clay Dominated	2.3-2.8	2<	58-10150	0-0.3	10-100	290-35000

For instance, poorly sorted sands compact more rapidly than well sorted sands while coarse grained sands compact faster than fine grained sands. In the meantime, mineralogically immature sands compact quicker than mineralogically mature sands (Fawad et al., 2011). Clay mineral transformations might also be the reason behind the compaction in sandstone reservoir with a huge impact on permeability. It should be noted that in sedimentary basins with a source of potassium (usually K-feldspar or mica), kaolinite and smectite become unstable and transform to Illite and/or chlorite (Peltonen et al., 2008). For instance, illitisation of kaolinite and the quartz cementation are the most significant cause of compaction in many deeply buried reservoirs located in the North Sea (Maast, 2013).

2.2. Time Dependent Deformation

According to many studies carried out in the past decades, compaction in unconsolidated/poorly consolidated sandstone is initiated by fluid withdrawal during production where the theory of poroelasticity can be used to model the reservoir and changes induced in the reservoir characteristics due to the alteration of in-situ stresses (Walsh, 2002). However, reservoir deformations may not cease after the stoppage of production and continue for days or months. Creep strain, under these circumstances, would be the subject of interest where the theory of viscoelasticity or viscoelasticity is considered for the reservoirs modeling (Hagin and Zoback, 2004; Zhnag and Buscarnera, 2017). Viscoelasticity under these circumstances is referred to the behavior under which the materials undergoes a time dependent deformation but can totally recover to its initial state upon unloading. A viscoplastic sandstone, on the other hand, is gone through a time dependent deformation after reaching its elastic limit and may never recover upon unloading. It appears that depending on geological settings, composition, differential stress, type of clays in the matrix, and many other parameters, sandstone may exhibit a viscoelastic or viscoplastic deformation (Mallman and Zoback, 2007). These behaviors and the reason(s) behind them, however, have not been fully understood and will be further discussed in this paper.

2. Methodology and Approaches

2.1. Sandstone Samples

Sandstone samples used for the purpose of this study were obtained from a gas field located in the Northern Carnarvon Basin, Western Australia. The Carnarvon Basin is an epicontinental with the age of Late Paleozoic to Cenozoic underling the north-eastern continental margin of Australia (Russel et al., 2001). The results obtained from performing a series of XRD, thin section and NMR tests on the samples indicated that clay in the sand could reach to 50% and the samples were laminated and bioturbated in part with the porosity of 25 to 38% and permeability in the hundreds of mD range. Table 2 gives the mineralogical compositions of sandstone samples taken from different reservoir intervals. These four samples were chosen since they had different percentage of kaolinite and illite/smectite clays. Given the fact that presence of clays is known to be the reason behind the creep strain of unconsolidated sandstones (Hagin and Zoback, 2004a), these samples might be useful to identify the type of clays inducing time dependent compactions in sandstone.

Uniaxial, Triaxial and Strain Compaction (USC) tests were performed on the samples. Plugs were end-lathed to produce a sample that meets the ISRM standards and then saturated with brine (i.e. 27000 ppm NaCl salinity) either outside or inside the cell according to the core condition. Weak samples were frozen and then saturated under a nominal confining pressure of 100 KPa.

Table 2. Composition of the samples taken from the reservoir and used in this study

Samples	Quartz	K-feldspar	Plagioclase	Siderite	Total Carbonate	Kaolinite group	Illite+Smectite	SUM CLAY	CMC (meq/100g)	Grain Density
Sandstone	37	1	12	3	3	17	30	47	1.17	2.76
Sandstone	44	0	6	4	4	14	31	45	1.13	2.77
Sandstone	35	0	4	2	2	9	49	58	3.69	2.79
Sandstone	44	1	11	4	4	9	31	39	6.29	2.78

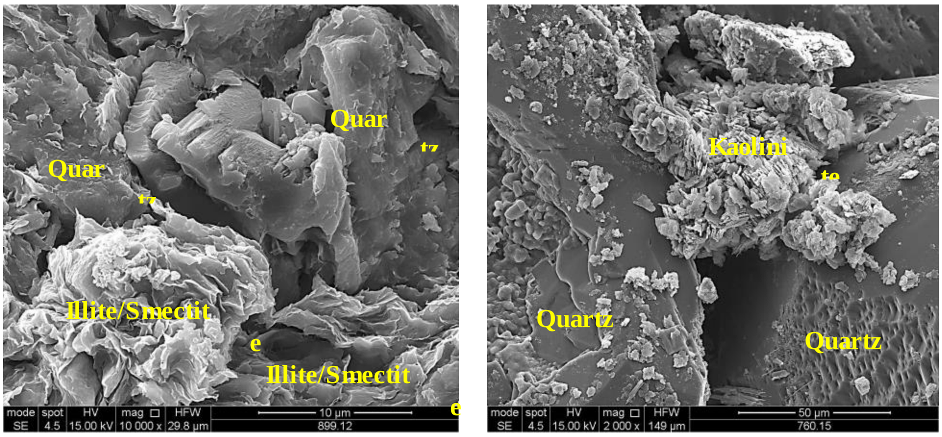


Figure 1. SEM images of the sandstone samples taken from the reservoir intervals

2.2. Experimental Studies

2.2.1. Uniaxial Compression Strength (UCS) Tests

To determine the elastic and Uniaxial Compressive Strength (UCS) of the samples, the standard recommendation practices of the ISRM, (1981) was used. Deformations were measured using linear variable differential transformers (LVDTs) and four cantilever radial gauges mounted onto stand-offs at mid-height around the circumference of the samples. Samples were jacketed with a flexible synthetic rubber membrane and placed between hardened steel platens such that the load can be transferred evenly over the end faces of the samples. Axial load was applied at a constant rate of 10^{-5}/sec until failure, or such that failure occurs within 15-20 minutes of the onset of loading.

2.2.2. Single Stage Triaxial Strength (SSTS) Tests

The standard practices recommended by the ISRM was followed to determine the triaxial compressive strength of the samples without pore pressure measurement (ISRM, 1983). Once installed, a cell pressure of 0.7 MPa was applied to allow the platens to contact the lapped end faces of the sample. Cell and pore pressures were then applied at a constant rate of 0.5 MPa/min. Upon stabilization, deviatoric load was applied at a constant average axial displacement rate. These tests were conducted under the confining pressure of 1, 5 and 10 MPa, respectively.

2.2.3. Uniaxial Strain Compaction (USC) Tests

To perform Uniaxial Strain Compaction Tests (USC), samples with the diameter and the length of 35mm and 60mm, respectively were used. Test plugs were then saturated in the cell with the formation water (brine with 27000 ppm NaCl salinity) synthesized using deionized water and grade salts following the procedures recommended by the Society of Core Analysts. The confining pressure and the pore pressure were increased at a controlled rate (2 MPa/min) until they reached the level of the anticipated pressure at the reservoir condition. The total axial stress was then increased at a controlled rate (0.5 MPa/min) to research the total vertical stress while maintaining the confining stress and pore pressure constant. Pre-test permeability was measured using the constant head method (under a constant pressure gradient) and the pore pressure was reduced at a controlled rate (0.08 MPa/min), in order to simulate depletion. The total axial stress was maintained constant while the uniaxial strain boundary conditions were established and measured during depletion. The total duration of the test was 9 days to monitor the viscous behavior of the samples. Figure 2 shows the loading path of the samples in the test.

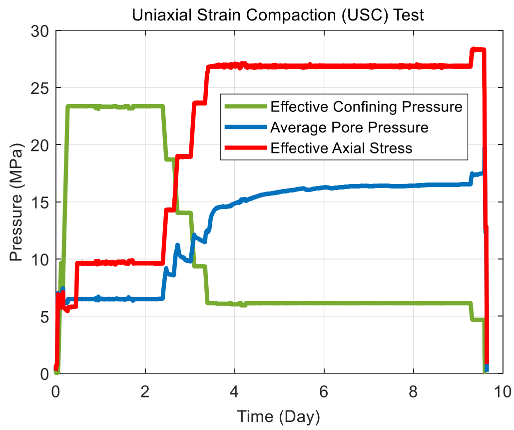


Figure 2. Loading path used to determine the compaction parameters of the samples

3. Results and Discussions

3.1. Uniaxial Compression Strength (UCS) Test

As it was mentioned earlier, in this study, attempts were made to evaluate the mechanical response of unconsolidated sandstone under different loading conditions. However, given the fact that samples do not have a strong cemented matrix, their response to unconfined or confined loading conditions might be quite different. The results obtained from performing a series of UCS tests on two samples with different clay compositions are shown in Figure 3 and reported in Table 2.

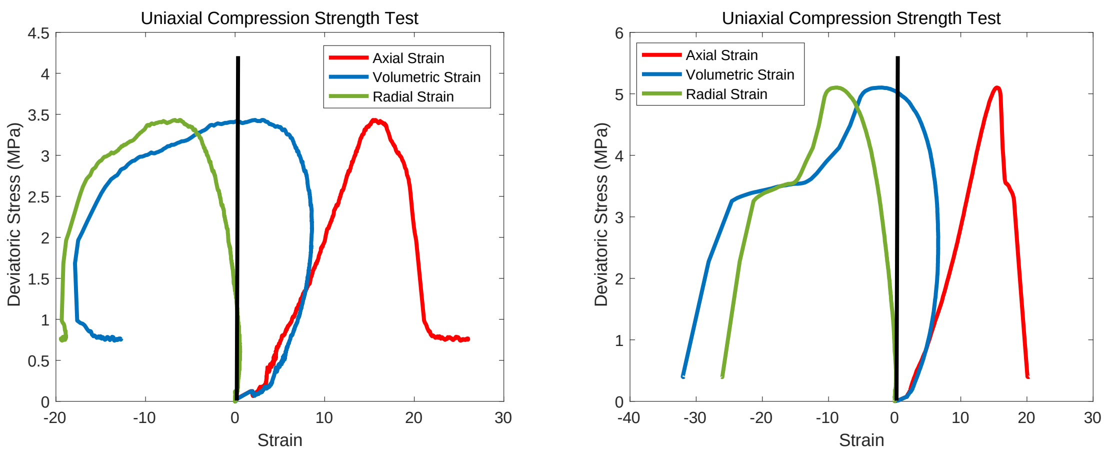


Figure 3. Stress-strain curves obtained from performing the UCS tests on the samples: Left) Smectite/illite dominated sandstone and right) kaolinite clay dominated sandstone

As it can be seen in Figure 3 and Table 3, both of the samples exhibited a ductile behavior with a very low Young's modulus and UCS but a high Poisson's ratio. This could be linked to the weak cemented matrix of the samples. However, the sample with kaolinite dominated clay revealed a higher strength then the sample with Smectite/illite which might be linked to the nature of clays. In fact, the sooner the clays deform, the lower the strength would be. It should be noted that the unconsolidated samples are not able to sustain the expansion induced by the axial load and as such rapid failure before reaching the boundary of plastic deformation is often observed under the UCS test condition.

Table 3. Density, size, elastic and strength parameters of the samples

Sample	Clay Domination	Diameter (mm)	Length (mm)	L/D Ratio	Dry Density (G/CC)	Wet Density (G/CC)	UCS (MPa)	Young Modulus (GPa)	Poisson's Ratio
1	Smectite/illite	26.05	51.79	1.99	1.701	1.956	3.4	0.3	0.35
2	Kaolinite	36.50	77.27	2.12	1.785	2.026	5.1	0.44	0.49

Figure 4. Type of failures induced in the samples under the UCS testing conditions

3.2. Single Stage Triaxial Strength (SSTS) Tests

Single stage triaxial strength (SSTS) tests were carried out on two set of samples under different loading conditions to evaluate the effect of the confining pressure on the behavior of sandstone samples. Figure 3 shows the stress-strain curves obtained under four confining pressures for two set of samples with different kaolinite and illite/smectite contents. Table 4 reports the loading condition as well as the elastic and strength parameters obtained.

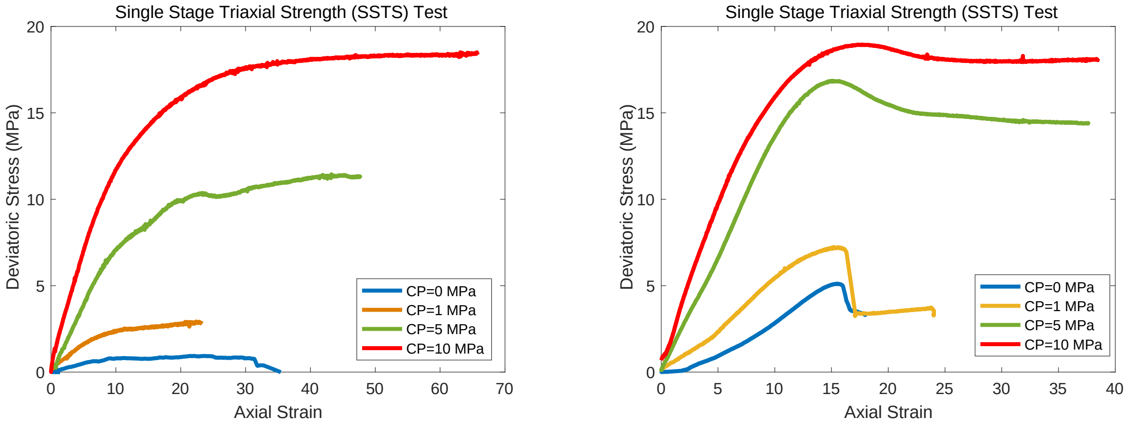


Figure 5. Stress-strain curves obtained from performing SSTS tests on the samples. Left) viscoelastic behavior observed in the sample with a higher percentage of illite/smectite and right) viscoplastic behavior observed in the sample with a higher percentage of kaolinite

Looking at Figure 5, it appears that confining pressure has a huge impact on the samples and can induce plastic or viscous deformation once reached 5 to 10 MPa. Under the low confining pressure, like the results obtained from the UCS tests, samples with kaolinite dominated clay are still failing like a brittle material (Figure 5 right) and there is no sign of any plastic deformations. Creep (viscous) deformation was, however, observed in the same sample once the confining pressure reaches 10 MPa within the first 8 hours of the test. It seems that creep strain in the unconsolidated sandstone can be experienced very fast within the first 10 hours of the test and it is a function of the pressure as mentioned by Hagin and Zoback (2004a). However, depending on the clay type and their percentage, samples may show viscoelastic (Figure 5 left) or viscoplastic (Figure 5 right) behaviors once the confining pressure reaches certain thresholds. In fact, samples loaded under a high confining pressure may reach to the strain softening state and go under a significant amount of axial strain without any increase in the magnitude of the deviatoric stress, if there is a significant amount of illite/smectite in the samples. On the other hand, samples with a remarkable amount of kaolinite are more viscoplastic even in the presence of other clays. It also appeared that the lower the Young's modulus is, the higher the likelihood of observing a viscoelastic behavior for unconsolidated sandstone. This is the same conclusion drawn by Chang and Zoback (2009) and Hagin and Zoback (2004a). Figure 6 depicts the condition and failure of the samples after the SSTS tests.

A significant inelastic behavior was also observed in the samples under the low confining pressure which might be linked to the closure of pore spaces in the samples. It should be noted that these pore spaces must be closed before initiation of any permeant damage in the solid framework. Given the low Young's modulus and high Poisson's ratio observed in the samples under the SSTS tests, it appears that creep (viscous) strain in unconsolidated sands is an intrinsic property of the solid frame. Creep and viscous behaviour of the sandstone is further discussed in the next section where compaction analysis was done.

Table 4. Elastic and strength parameters of the samples under SSTS testing conditions

Set of Sample	Confining Stress (MPa)	Axial Strength (MPa)	Young Modulus (GPa)	Poisson's Ratio	Cohesive Strength (MPa)	Friction Angle (Deg)
1	1	2.5	0.32	0.39	0.25	28.0
	5	12.8	1.4	0.24		
	10	18.9	1.6	0.39		
2	1	7.19	0.6	0.48	0.2	23.3
	5	16.8	1.8	0.22		
	10	18.8	1.6	0.29		

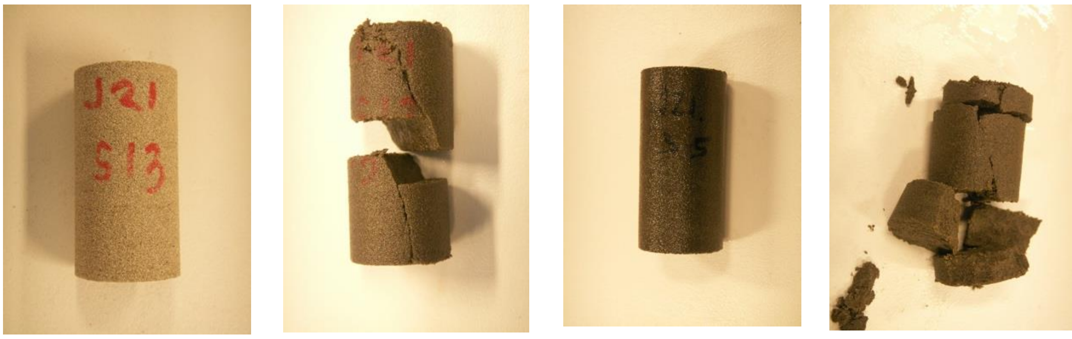


Figure 6. Type of failure induced in the samples under the SSTS testing conditions

3.3. Uniaxial Strain Compaction (USC) Tests

Uniaxial Strain Compaction (USC) tests were done on two set of samples as per the procedure explained earlier. Compressibility and the compaction parameters of the samples were obtained as per the ISRM suggested practice while the pore compressibility was obtained based on the approach presented by Zimmerman (1991). Table 5 summarises the results obtained from the compaction test.

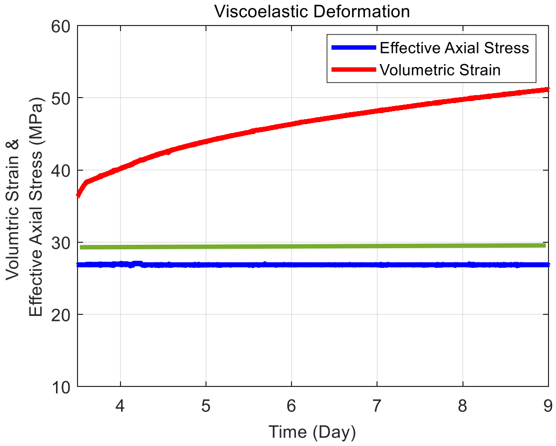
The results obtained indicated that the grain, bulk and pore compressibility of the samples are significantly low and the permeability may reduce by as much as 10 times during production. Regardless of the creep strain that might be observed in this field, it appears that the poroelastic response of the reservoir during fluid withdrawal may significantly reduce the petrophysical properties (porosity and permeability) of sandstone and decreases the production rate very fast. A proper production strategy and slow pore pressure reduction, under these circumstances, may help to prevent the compaction but may not totally resolve the issue in deep water sands.

The most important observation in the USC tests was the link between type of clays and viscous behavior of the samples. In fact, it was found that once the percentage of illite/smectite clays dominates and reaches 50%, a clear viscoelastic behavior is induced (Figure 12). However, as the amount of kaolinite increases, the samples exhibit a viscoplastic behavior preventing the solid framework to deform under the elastic conditions. Similar to the observations made during the triaxial testing, it was also found that the volumetric strain in all samples is a function of the confining pressure and the cumulative creep strain increases with pressure with a nonlinear trend. These observations suggested that grain rearrangement facilitated by the presence of clays and confining pressure (in-situ stress) might be the mechanisms behind the creep strain in the deep-water sandstone reservoir of this study. These are the same conclusion made by Chang and Zoback (2009) in their study on the Gulf of Mexico shale and Hagin and Zoback (2004a) in a study on the unconsolidated sandstone of Wilmington field. It seems that when the percentage of clays exceeds certain limits, shale and unconsolidated sandstone may exhibit similar viscous behaviors but the crucial rule of the confining pressure should not be neglected.

Table 5. Compaction based parameters obtained from the USC tests

Sample Number	**Sample 1**	**Samples 2**
Grain Compressibility (10^{-3}/MPa)	0.063	0.087
Bulk Compressibility (10^{-3}/MPa)	2.178	2.431
Pore Compressibility (10^{-3}/MPa)	5.716	6.422
Biot factor	0.97	0.96
Pre-test Permeability (mD)	56.3	139.5
Post-test Permeability (mD)	12.5	11.9

The effect of the loading should not also be ignored in the compaction related studies. According to the results obtained from this study, it was also observed that as the loading rate increases from 0.5 MPa/min to 1 MPa/min, viscoelastic deformation dominates but a viscoplastic response is revealed more once the loading rates reduces to 0.25 MPa/min. Nevertheless, the viscous deformation was experienced with a remarkable rate during the first 8 hours of the test but continues at a very slower rate throughout the entire observation time. This rate, however, approached an equilibrium state after 80 hours but the creep strain never stopped before unloading the samples. However, plotting the data in a log-log space, shown in the right side of Figure 7, indicated that the creep strain follows a power law function and may continue for a long period of time but its rate may decrease after the first two or three days of the test. Further studies are required to perform the test for a longer period to see if creep strain occurs indefinitely in unconsolidated sands.



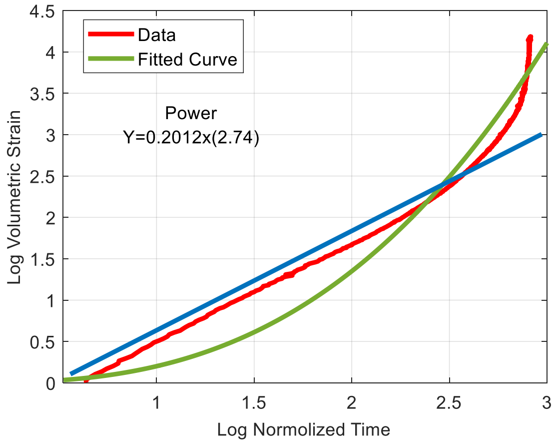


Figure 7. Left) Log-log plot of the creep strain data with a power-law function of time and right) time-dependent deformation in the viscoelastic sandstone observed as creep strain

4. Conclusions

In this study, a series of experimental tests were conducted on the unconsolidated sandstone samples to evaluate the likelihood of viscous deformation under the reservoir condition. It was found that time-dependent strain is a function of clay type, confining pressure and the loading rate. This deformation will also be largely unrecoverable regardless of the clay type presented in the rock matrix. Creep is initiated once the confining pressure is high enough as otherwise a conventional brittle failure is observed. However, the relationship between the creep strain and confining pressure appears to be nonlinear. Confining pressure and the loading rate could also be combined to distinguish the type of viscous behavior in sandstones with different types of clays. Although the results obtained seem to have sufficient accuracy, more studies should be carried out to ensure that the effect of clays on the sandstone rheological behavior is fully understood.

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