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Experimental Investigations to Study the impact of Pore Fluid Chemistry on Tight Sands Permeability

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Abstract: In this study tight sands samples from Kirthar fold belt area were obtained to investigate the impact of pore fluid composition on petro physical properties. The assumptions that the gas permeability is equivalent to liquid permeability could lead to an overestimation of aquifer encroachment if gas permeability values obtained during routine core analysis are given to the aquifer. Hence, such analysis necessitates making measurements using formation compatible brines (NaCl) and is essential to understand tight gas reservoirs productivity. This study conducted single phase gas and liquid flow properties of tight sandstone samples by conducting series of experiments. The intrinsic slip free gas permeability measured was ranged between 0.0012 m Darcy and 25mDarcy. The intrinsic gas permeability (slip corrected) was higher by factor of 1.25 to 20 than the permeability measured with water. Moreover, the permeability results showed that the changing brine (NaCl) composition has large sensitivity to those samples which were exhibiting very low absolute permeability less than 0.1mDarcy.

Keyword: stress sensitive properties, tight gas sandstones, Kirthar fold belt, Indus basin, gas and liquid permeability.

1. INTRODUCTION

Pakistan has a large potential of tight gas reservoirs (Shar, and Mahesar, 2016). Petrophysical analyses of tight gas reservoirs are very challenging. Understanding how presence of clay minerals, overburden stresses and different pore fluids affects such properties are critical steps for evaluating low-permeability reservoirs (Shar *et al*. 2016). Moreover, the brine permeability is important to consider for reservoirs which are associated with an active aquifer as it has a significant impact on aquifer encroachment, which controls water production and ultimate gas recovery. Several companies are involved to exploit the low permeability hydrocarbon resources. However, every exploration and production company is reluctant to invest money on such marginally profitable reservoirs. Hence this new experimental measurements of permeability of a tight gas sandstone of Kirthar fold belt explores their dependence on pore fluid chemistry, and petro physical controls in the perspective of gas production from such low permeability and marginally profitable reservoirs.

Role of porosity and permeability and their relation is important in reserves evaluation. Information about the extent and distribution of the water within interconnected pores of a reservoir rock is critical to understand the behaviour of reservoir rock. The water in pores could occur as a free water and capillary, or clay bound water (Leverett, 1941). Bound water takes account of the both water present either in form of the negatively charged on the rock grain surfaces, and it could possibly allied with the mineral charge by balancing the counter-ions (e.g. Leverett,1941).

There is an extensive investigation conducted about the impact of capillary bound water and their relationships for cores taken from several different North Sea reservoirs. These reservoirs were displaying very different clay mineralogy. But no single investigation of Pakistani reservoirs has been yet conducted to study the impact of pore fluid chemistry on petrophysical properties of tight rocks.

Hence we collected data and integrated with minerology by performing XRD to explain the influence of the different brine composition on rock structure and mineralogy have on the tight rock flow properties.

Generally, within rocks the quartz is the dominating mineral, some other minerals present such as detrital mica, detrital clay such asillite-smectite associated with minor feldspar and oxide phases (Armitage *et al*. (2010). Diagenetic controls and variations also plays significant role to alter claystoillite and chlorite, causes the development of patchy particles siderite, and growth of cementing materials, hence altering the rock petrophysical properties (Mondol *et al.* 2008). *Armitage et al.(2010)* provided that the variations in clastic rock are associated to the presence of clay minerals such as illite-muscovite within rocks and is affected by presence of varying quantities of other minerals such as chlorite and the extent of the quartz cementation. In which the

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quartz grain are coated with chlorite, which results in stopping the cementation of the quartz locally, hence the porosity in these sands remain stable presence of chlorite developed within the confined pore throats *constriction (*Worden and Morad, 2003). *Authors (*Mesri and Olson *(1971) reported that, clay permeability if plotted with porosity the relation between two shows that permeability increases by increasing porosity logarithmically.* Dewhurst *et al.* (1998, 1999) *showed that there is a large variation in porosity* and permeability data due to varying pore sizes and their distribution. Dewhurst *et al.* (1998,1999*)*reported that, the permeability was two orders magnitude high in lower clay samples than clay rich at same porosity values.

Moreover, many studies have shown that the absolute gas permeability of tight gas sand can exceed the absolute brine permeability by in excess of an order of magnitude (Jones and Owen, 1980 and Chowdiah, 1987). Indeed, it is well known that the absolute brine permeability can vary by an order of magnitude depending upon the brine composition **(Fig-1)**. Although, other studies have found that gas permeability and brine permeability are virtually identical for some tight gas sand samples (e.g. Rushing *et al*. 2004). The causes for the differences between gas and brine permeability yet not known. Although, it has been reported that fines migration or clay swellings could cause the differences in between gas and brine permeabilities (e.g. Brower and Morrow, 1986).

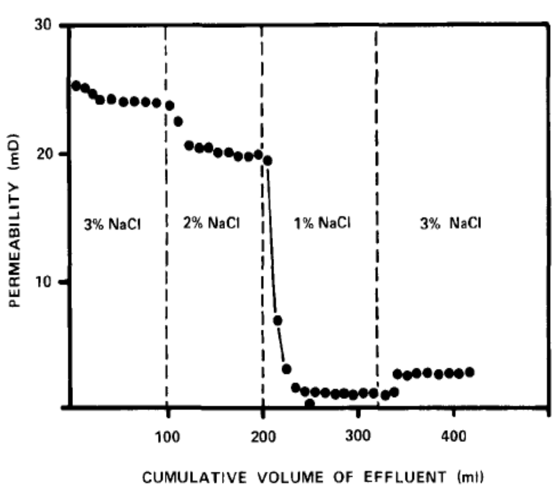

Fig.1 Pore fluid chemistry impact on the Spiney sandstone, Moray Firth Basin. The greater reduction in permeability could be seen, when it was measured using 1% NaClsolution.

The present study provides discussions about the differences between gas and brine permeability measured for Kirtar formations and the study investigations include:-

(i) The assumption that the gas permeability is similar to brine permeability could lead to an overestimation of aquifer encroachment if gas permeability values obtained during routine core analysis are used as input into simulation and modelling the water influx.

(ii) Differences in gas and brine permeability equivalency could point to errors in the measurement of gas permeability and/or brine permeability.

(iii) It is uncertain which absolute permeability value (k_g or k_b) to use when modelling the performance behaviour of such low permeability reservoirs.

We start by outlining the laboratory experimental details and then the study strategy is outlined in such that the experimental setup and the standards procedures we followed. Moreover, we provided an overview about the results to the reader; after that the results and their predictions were carefully presented and then preceded with a comparison of the permeability data to different brine chemistry. Results of present study suggested that particle mobility was not the case to affect tight sands permeability; hence we concluded that particle mobilization to fluid chemistry is only affecting those samples with higher permeability rather in low permeability particles clogging leading to decrease in permeability values.

2. EXPERIMENTAL METHODOLOGY AND SAMPLE ANALYSIS

Petrophysical measurements were investigated using the facility to measure the tight sands porosity (using helium porosimeter techniques), permeability (measured on plugs taken horizontal to the bedding section). The flow experiments were performed in Hassler type tri-axial core holders **(Fig-2)**. The long term experiments were conducted for permeability measurements using steady state experimental approach. The measurements made at room temperature of 25^0C and confining pressures up to 500 psi. Initially we measured gas permeability using helium and the brines were measured using the 5% (NaCl) brine. However water used for flow experiments was the deionized water; the brine and distilled water both were degassed before measurements. Prior to perform the petrophysical (porosity and permeability) measurements, cylinders samples of 2.52 cm (1 inch) diameter were cut having varying lengths (from 4 to 6.2 cm) using a diamond drilling machine. Tape water used as a coring fluid. The samples were thoroughly cleaned using toluene prior to permeability measurements. The sample minerology was obtained using QXRD techniques. The quantification of rock minerals were performed by spray drying technique as explained in Hillier (1999, 2000), this could be done on samples with random orientations.

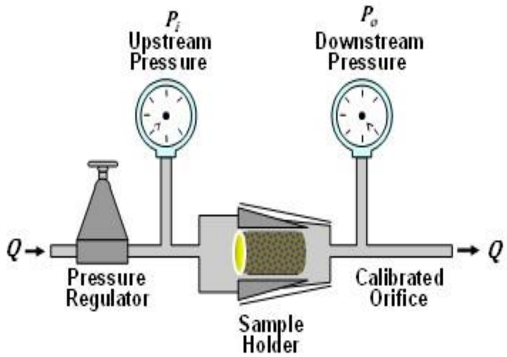

Fig. 2. Diagram is the outline of experimental setup for steady-state flow tests.

3. EXPERIMENTAL RESULTS

Samples mineralogy properties

Information on the mineralogical compositions is listed in **(Table-2)**. In this study, the mineral composition of samples was obtained by QXRD analysis. From quantitative XRD analysis the rock is composed of quartz (~30% to 73%), K-feldspar (1.2% to 11%), calcite (1.7% to 20%), with detrital clay of ~25%, the dolomite found in range of about 0.5% to 18.5%, siderite was 0.1% to 5.5% with pyrite of 1.8% to 12.5%. The sandstone has a modest diagenetic history comprising the precipitation of calcite, anhydrite and little dissolution of potassium-feldspar. The potassium-feldspar displays different dissolution textures; the kaolin was present in clusters and is composed of 10µm.

Table-2 Average range of mineralogical composition of the samples collected from Kirthar fold belt region. These results are based on QXRD analysis of 25samples collected for this study.

	Quartz	Clay minerals	Potassium feldspar	Calcite	Dolomite	Siderite	Kaolinite	Pyrite	other minerals
Min	**44**	**14**	**1.2**	**1.7**	**0.5**	**0.1**	**0.5**	**1.8**	**0.25**
Max	**75.8**	**25**	**12.5**	**20**	**18.5**	**5.5**	**5.5**	**12.5**	**10.8**
Mean	**59.5**	**19.5**	**6.8**	**10.8**	**9.5**	**2.8**	**5.2**	**7.15**	**5.52**

Permeability:

The results obtained from steady state permeability measurements are shown in Table 4. The permeability determined with gas gave almost identical values to brine (NaCl)however, we found discrepancy when permeability was measured using distilled as a pore fluid. The difference in between two methods of measurements was only by factor 3 not more than this as observed from comparison of the results.

Table-4 Intrinsic permeability results summarized and were measured by different techniques

Sample ID	Confining stress (Psi)	K_{gas}(mDarcy)	K_b (mDarcy)	K_{di} (mDarcy)	Ratios (K_g/K_b)	Ratios (K_g/K_{di})
KT1A	500	0.012	0.0078	0.0052	2	23
KT2B	500	0.002	0.0045	0.00077	4.4	12
KT3C	500	0.019	0.002	0.0012	10	16
KT4D	450	25	0.028	0.0084	9	30
KT5D	500	0.082	0.0082	0.0019	10	43
KT6E	500	0.011	0.0023	0.0017	5	6

4. DISCUSSION

Impact of fluid chemistry

The absolute permeability of tight rocks was measured with three different pore fluids i.e. gas, brine and distilled water to assess the sensitivity of the absolute permeability. Generally the slippage effects-corrected gas permeability should be similar to the liquid permeability measured on same samples (Rushing *et al.*, 2004; Chowdiah, 1987). Although, the present study of tight gas sand samples in Kirthar fold belt sand have shown that gas permeability values are greater than permeability measured using liquid as a pore fluid **(Fig. 4)**. The distilled water permeability results showed the lowest for all samples **(Fig.4)**. On average the reduction brine permeability notices was around 30% and the distilled permeability was an order of magnitude less than gas permeability values. The similar variances in gas and liquid permeability also been reported by other authors (Sampath and Keighin, 1982; Faulkner *et al.*, 2000; Baraka-Lokmane, 2002).

Referring to research papers published (e.g. Jones and Owens, 1980; Sampath and Keigin, 1982). Dong *et al*. (2012) showed that the permeability corrected for Klinkenberg effects and the liquid permeability are virtually identical for samples which are having higher permeabilities values greater than 1 m Darcy. However, the Klinkenberg-corrected permeability is larger than the permeability measured with liquid suing a pore fluid to samples with permeability less than 0.1 mD. This observation was also supported by other authors (Faulkner and Rutter, 2000; Cui and Brezovski, 2013, and Ghanizadeh *et al*. 2014).

It is essential to find the reasons for such difference in permeability values as these provide relative control of fluid flows within tight sand reservoirs. The dissimilarity observed in permeability of sandstones using different pore fluids could be the physiochemical reactions between water and clay mineralogy (Lever and Dawe, 1987). The clay minerals found in these sands were present in different arrangements; such as coated on the surfaces of sand grains and pore lining clays (Neasham, 1977). The kaolin was found in form of 'booklets' lose platy minerals (Wilson and Pittman, 1977). Thin section results showed occurrence of kaolin clay mineral and was the main clay mineral (Khilar and Fogler, 1987). The Kaolin mineral could easily break on flooding of water and has tendency to move and most likely block the fine pore throats of the samples (Lever and Dawe, 1987; Khilar *et al*., 1990; Revil and cathels, 1999; Rosenbrand *et al*., 2013). In general, the Kaolin clay mineral has been observed that the particles size ranges in between 0.5μm to 20μm with thickness of 0.1μm to 1μm (Wilson and Pittman, 1977; Gupta *et al*., 2011). Hence, it has a significant impact on permeability alteration during laboratory measurement or field injection of improved recovery. The mechanism of fine particles mobilization and entrapment is explained by Candela *et al*. (2014). They performed experiments on two types of samples fractured and intact from which they observed that as pore pressure oscillation starts particles mobilization and permeability of the samples resulted in increase. However, the intact samples which were associated with very small pore/ confined pore throats, the fine particles moved and blocked pores that resulted in reduced permeability within these samples (e.g. Candela *et al*. 2014). We also observed that in our low permeability tight sands the fine particles clogged the pore throats resulted in decreased permeability. we used filter paper at ends of core plug to see the fine particle production but we did not observe any accumulation on filter paper.

Numerous studies have also reported about the fine particles migration during permeability experiments (Khilar, *et al*., 2006; Yuan and Shapiro, 2011). The clay minerology affects samples permeability in two different ways (i) particle mobilization with pore fluid to block the pore constrictions in case of pores throats have very small size equal to particle size hence resulting pore blockages. (ii) If size of the pore throat is larger than fine particles transport occurs resulting in enhancement of permeability (Candela *et al*. 2014). Therefore in our samples reduction of permeability was observed rather than enhancement as in first case of pore blocking. Several authors provided with theoretical models how fine particles are retention occurs within the confined pores, the rate of deposition; bridging; draining of grain particles towards confined pore throats resulting in blockage of pore throats (e.g. McDowell-Boyer *et al*., 1986; Sen and Khilar, 2006). The kaolinite during the process of pore fluid injection gets disturbed and its interaction with water may alter the viscosity of pore fluids (Rosenbrand *et al*., 2014) hence the tight rocks permeability. Many authors attempted to collect the fine particles which are mobilized during permeability experiments together with injected effluents and produced at the outlet of samples (Rosenbrand *et al*., 2013). Similarly present study attempted to collect effluents and was filtered through the 0.2μm filter paper but we did not observed fine particles presence on the filter paper. Therefore, this provided an evidence of the absence of fine migration. However, clay mineral entrapment and swelling at the fine pore throats could be reason of reduction in liquid permeability within tight gas samples studied during this study. **(Fig.5)** provides the permeability versus clay mineralogy, it is obvious that as the percentage of clay increases permeability of the samples decreases. Present study samples were very tight and did not appear in increased permeability values.

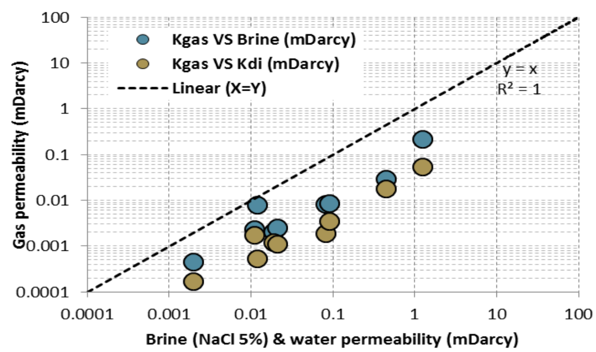

Fig. 4Plot showing the permeability changes as a function of brine and distilled water permeability of tight gas sands (log-log plot).

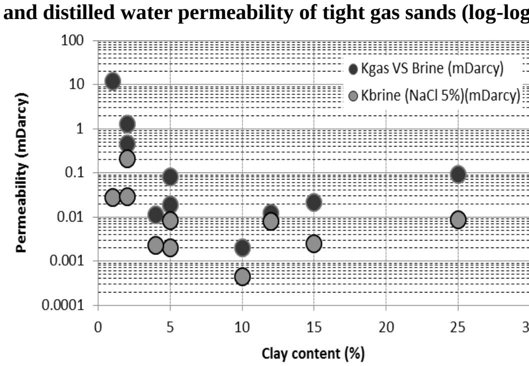

Fig. 5Plot showing the relation between gas and brine permeability versus clay content of the samples analysed.

Controls on gas and liquid permeability

The controls on gas and brine permeabilityhave proved incredibly illusive; it is difficult to convey the effort that has been expended during the present study on controls of fluid chemistry on permeability and we reach at some solid ideas regarding what controls the gas and brine permeability within tight gas sandstones. Our results have provided with some possibilities which are presented below;

- **Micro cracks effects and fine particles migration** –it is possible that the gas and brine permeability could be controlled by several factors including fines migration, the presence of micro cracks, micro fractures and that the complex interaction between these factors means that there is no simple quantitative way to predict gas and brine permeability ratios.
- **Inadequate time for samples saturation prior to permeability measurement**

Prior to permeability measurement the samples were saturated with brine, placed in a core holder and the confining pressure was increased to 1500 psi and 2 hours was given for equilibration. This has proved too fast for equilibration to occur. However, the experiments conducted in which we saturated while under a longer period of confining pressure and resulted in a 3 fold lower permeability than when they were rapidly loaded.

- **Presence of trapped gas** – If samples liquid permeability was intended to perform for this reason samples saturated if 100% saturation is not achieved with brine then there is possibility of trapping of gas and the pore throats might be blocked with gas. However, this was not the case for present study samples as the samples were compressed using 200 psi brine pressure and it is sufficient pressure to compress or to dissolve the remaining gas.

5. CONCLUSIONS

We examined the impact of clay mineralogy and brine composition on permeability of tight gas sand samples of Kirthar fold belt lower Indus Basin Sindh Pakistan. Analysis was performed by integrating permeability results with mineral composition obtained from X-ray diffraction. Following observations made;

1. The main components of the sample mineralogy displayed variable amount of clay mineralogy that dominates within the samples investigated. Moreover, it was found from experimental results that the samples with higher clay content resulted in lower permeability. In addition QXRD was performed that displayed different components of clay minerals, illite-smectitie, kaolinite and chlorite.

2. Results revealed lower permeability to distilled water and to brine than gas in all samples. Lower permeability to water was the result of presence of clay mineralogy and its reactions with water.

3. Permeability less than <0.1mDarcy was more sensitive to water and showed more reduction when measured using distilled water as a pore fluid, this was due to the formation of layer of clay bound water and resulting in reduced pore throat available for fluid to flow.

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