IMPACT OF STRESS ON FLUID FLOW: A DETAILED STUDY ON LOW PERMEABILITY ROCKS

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ABSTRACT

Tight gas reservoirs have recently become very important as they contain valuable undeveloped reserves. However, their petrophysical properties are very difficult to determine and in general poorly understood, due to their special characteristics mainly very small pore size. In addition, it is often argued that the permeability of reservoir rocks can be very stress-sensitive (Thomas and Ward, 1972). This effect is particularly important for low permeability rocks such as tight gas sandstones and unconsolidated sands. Petroleum production often results in an increase in effective stress within the reservoir. To accurately model fluid flow in stress sensitive reservoirs it is important to have quantitative data on the relationship between permeability and the effective stress that a reservoir is likely to experience during production. Some studies have been devoted to understand the stress dependence of the petrophysical properties of core samples.

The main aim of this paper is to investigate the stress sensitivity of the permeability and relative permeability for a wide range of low permeability sandstones. Our results show that the stress-sensitivity of the gas permeability of the samples studied varies significantly. For example, the permeability of the very low permeability tight gas sandstones is strongly stress dependent; particularly at low effective stresses. On the other hand, very quartz cemented low permeability rocks are only slightly stressed dependent. The reduction in permeability that each sample experienced is probably due the variation on the pore sizes, pore shapes and grain packing and sorting. It has also been observed that the permeability is more stress dependent when partially water saturated than when dry.

INTRODUCTION

It is often argued that the permeability of reservoir rocks can be very sensitive to the stress conditions to which they become exposed (Thomas and Ward, 1972). This effect is particularly severe within some reservoirs such as some tight gas sandstones and unconsolidated sands. Petroleum production often results in an increase in effective stress within the reservoir. To accurately model fluid flow in stress sensitive reservoirs it is important to have quantitative data on the relationship between permeability and the effective stresses that a reservoir is likely to experience during production. Many studies have been devoted to understanding the stress dependence of the petrophysical properties (e.g. porosity, permeability and electrical properties) of core samples (Jing et al., 1992; Al-Harthy, 1999). Particular attention has been given to determine the impact of stress variations on the permeability of tight gas reservoirs. For example, Thomas and Ward (1972) suggested that the porosity of tight gas sands is far less stress sensitive than the permeability. They have also argued that the effect of stress on the effective permeability of partially saturated samples was not significant. Walls (1982) found that the stress-sensitivity of the permeability of tight gas samples was highly non-linear. In particular, the permeability was found to be highly stress sensitive at low effective stresses but not so stress sensitive at high effective stresses. Furthermore, Walls (1982) pointed out that the effective permeability sandstones was particularly stress sensitive; this was explained in terms of changes in the pore structure and flow path of the samples. Increasing the effective stress applied to dry samples resulted in the closure of flat cracks and the creation of dead-end pores. In the case of partially saturated rocks, increasing the effective stress causes the movement of water from thin cracks and high aspect ratio pores into the larger rounder pores resulting in a reduction in the gas relative permeability. Some of these observations were confirmed by Sampath and Keighin (1982) which were based on photographic studies, suggested that small intergranular pores that were present in samples brought to the surface would close at higher confining pressures. Brower and Morrow (1985) argued that increasing the confining pressure did not always result in a significant decrease in permeability. Instead, it was argued that the stress sensitivity of permeability depends upon the pore structure. Davies and Holditch (1998) found that the main controls on the stress-sensitivity of permeability are the size and shape of pore throats. Davies and Davies (1999) also suggested that pore geometry controls the stress dependence of permeability in both consolidated and unconsolidated sandstones. For unconsolidated reservoirs, they found that the permeability of sands with large pores was far more stress sensitive than sands with a smaller pore size distribution. On the other hand, for consolidated type reservoirs, rocks with high aspect ratio pores (long and narrow) are more stress sensitive than low aspect ratio pores, which can be described as a bundle of tubes. More recently, Rushing et al (2003) found that the combined effects of effective stress and water saturation on Klinkenberg corrected permeabilitties are more significant in lower-quality reservoir rocks.

The literature review indicates that both single phase and two phase relative permeabilities can be significantly stress-sensitive. To further investigate the stress sensitivity, and clarify the role of stress, both gas absolute and gas relative permeability of various low permeability rocks were carried out.

MATERIALS AND EXPERIMENTAL TECHNIQUE

Experiments were conducted to investigate the stress dependence of the permeability of the following three types of rock samples:

1. Tight gas sandstones.

2. Cataclastic fault rocks.
    - a) Cataclastic faults within the Hopeman sandstone, Clashash Quarry, Invernesshire.
    - b) Cataclastic faults from Vale of Eden, Brough site, Cumbria.
    - c) The 90 Fathom Fault, Cullercoats, Northhumberland.
3. Siltstone samples, Mam Tor, Derbyshire.

A full characterisation of the microstructural and petrophysical properties of these samples was carried out (**Figure 1**). The permeability measurements were performed on a uniaxial, Hassler type coreholder. For low permeability samples, the pulse decay technique has been used to perform the gas permeability measurements at high pore pressure. For samples with permeability higher than 0.5 mD, the measurements were performed using gas steady-state method and corrected for the Klinkenberg effect. Full details of the equipment and the methodologies can be found in Al-Hinai et al (2006) and Al-Hinai (2007). The absolute gas permeability of all samples described above was measured at a range of confining pressures. The water saturation of various samples was then altered using the vapour chambers (Al-Hinai, 2007). The gas effective permeability was then measured over a range of pore and confining pressures in order to establish the stress sensitivity of gas relative permeability.

RESULTS

Tight gas sandstones

Several experiments were undertaken to investigate the stress dependence of the single phase permeability of these tight gas sandstones. The sandstone has a grey-brown well cemented quartz grains, of predominantly aeolian origin. The main diagenetic reaction responsible for reduction in porosity is quartz cementation and pressure solution. Some K-feldspar is still present but illitisation limited probably by the lack of detrital clays. The moderately permeable, Group A, samples experienced a 20% reduction in permeability as the confining pressure was increased from 1000 to 2500 psi (**Figure 2**). The dependence of the permeability on confining pressure for four of the low permeability samples (Group B) was investigated using the pulse-decay technique. The results (**Figure 3**) show that the permeability of these sandstones is significantly stress dependent over the range used. For example, the permeability of sample O3−1 falls to about 30% as confining pressure is increased from 1000 to 2200 psi. The stress dependence of the permeability of these samples appears to decrease as confining pressure is increased. These results are significant for tight gas sandstones, and show that the normal method of measuring the permeability at low confining stress usually overestimates the permeability at reservoir conditions. It is also important to note that the sample permeability experienced hysteresis during loading and unloading cycles (**Figure 4**). In particular, the permeability of O3 − 5 decreased by 50% as the effective stress was increased from around 600 to 1700 psi. However, the permeability only returned to 70% of its original value when the effective stress was returned to 600 psi.

Cataclastic faults- Hopeman

The Hopeman fault rock has experienced a large grain-size reduction as a result of the faulting-induced grain-fracturing. The faulting process has reduced the porosity and pore-throat sizes. The fault rock has a porosity of 5% and a single-phase permeability of 0.002-0.006 mD, which is over five orders of magnitude lower than for the undeformed reservoir. Hg-injection results show that the fault rock has a peak pore aperture diameter of around 0.0145 µm.

The stress dependence of absolute gas permeability of four cores of the Hopeman Fault was measured using the pulse-decay permeameter. The results plotted as a function of the mean effective stress (**Figure 5**) show that the permeability of the Hopeman fault rock is only slightly stress dependent over the range used. For example, the permeability of sample HP2Z falls from 0.0035 mD at an effective stress of 300 psi to 0.0032 mD at 1500 psi.

Cataclastic faults- Vale of Eden

The Vale of Eden fault rock studied has a porosity of 6% and a single-phase permeability of 0.012 mD, which is over four orders of magnitude lower than for the undeformed reservoir. Hg-injection results shows that the fault rock has a peak pore diameter of around 0.2 µm.

The stress dependence of permeability was measured on one core of fault rock (Chedan B) from the Brough Site using the steady-state permeameter - all permeability values are Klinkenberg corrected. The results (**Figure 6**) show that permeability is reduced from 0.0161 mD to 0.0089 mD as the effective stress is increased from 500 to 3000 psi. This reduction in permeability can be classified as a moderate reduction (> 50%) in comparison with the reduction that is experienced in some of the tight gas sandstones. The effect of effective stress on gas relative permeability has also been determined for the Cheden C sample. In particular, as the humidity chamber was used to give the sample a Sw of 17% and then the gas relative permeability was measured at a range of effective stresses. The results (**Figure 7**) show that increasing the effective stress from 500 to 1500 psi results in a reduction in gas relative permeability of 50%, which is a larger reduction than was observed in the unsaturated samples.

Cataclastic faults- 90 Fathom

The 90 Fathom Fault has a porosity of around 10 % and a permeability of around 0.11 mD. The microstructural examination reveals that the fault rocks do not contain deformed kaolin, suggesting that deformation occurred before its precipitation. The excessive cataclasis does, however, suggest that the sediment was covered by appreciable overburden at the time of deformation.

The stress dependence of absolute permeability was measured on one sample of fault rock (Fathom B) from Cullercoats using steady-state permeametery - all permeability values are Klinkenberg corrected. The results (**Figure 8**) show that permeability is reduced from 0.12 mD to 0.064 mD as the effective stress is increased from 500 to 4000 psi. The reduction in permeability is similar to that experienced by the Vale of Eden fault samples.

Siltstone- Mam Tor

Microstructural examination reveals the sample is a siltstone composed of quartz, albite, calcite, dolomite, mica and clay. Quantitative XRD shows that the sample has a modal composition of 56.5% quartz, 13.5% albite, 10.8% kaolin, 5.2% calcite, 4.3% illite-smectite, 4.0% chlorite, 3.2% mica, and 1.6% dolomite. Overall, the sample appears to have undergone extensive mesodiagenetic alteration (grain-contact quartz dissolution, albitisation, quartz cementation etc). The samples have a permeability values averaging 0.001mD.

The stress dependence on the gas permeability of three samples of Mam Tor siltstone was determined. The measurements were made at a pore pressure of 350 psi and confining pressure was varied between 750 and 2500 psi. The results (**Figure 9**) shows that absolute gas permeability experienced a reduction in the range of 60 to 80 % of the original permeability as the effective stress was increased from around 500 to 2000 psi. The reduction in permeability is in the same order to that experienced by the tight gas sandstone samples.

The stress dependence of the gas relative permeability of three samples whose saturation had been varied using vapour chambers was also obtained (**Figure 10**). The effective gas permeability of samples with Sw of 40 to 44 % was reduced by over an order of magnitude as the confining pressure increased from 1000 to 2500 psi. In other words, the stress dependence of relative permeability is far higher than the stress dependence of absolute permeability for these samples.

The effect of stress cycling on gas relative permeability was also investigated. It was found that the permeability lost during loading was not recoverable during the unloading cycle. However, when the stress around the sample is released, the effective gas permeability is similar to the initial value (see **Figure 10b**). On the other hand, as the water saturation increases (for instance see **Figure 10c**, sample D1 with a water saturation of 66.0%) the effect of the stress on effective gas permeability becomes far more significant and the effective permeability was reduced from about 0.0006 mD to 0.00005 mD by increasing the confining pressure from 1000 to 2000 psi. As the effective stress was increased more, the effective gas permeability reduction increased, until most of the pores become so blocked by water that the effective gas permeability becomes difficult to be determined.

DISCUSION

1.1. Stress dependence of single phase permeability

The stress-sensitivity of the gas permeability of the samples studied varies significantly. For example, the permeability of the very low permeability tight gas sandstones is strong stress dependent; particularly at low effective stresses. The reason for this is that the open pores that allow considerable amount of flow are rapidly closed as effective stress is increased. Furthermore, most of the samples experience some hysteresis effect during the initial loading and unloading cycles, but this effect is diminished during subsequent cycles. The permeability of most of the Hopeman Fault rock samples is only slightly stress dependent probably because they are very quartz cemented. Fault rock from

90 Fathom Fault and Vale of Eden Fault experienced some permeability reduction at very high effective stresses. For example, the permeability of the 90 Fathom Fault (with a permeability of 0.025 mD) was found to fall by 50% as stress was increased from 300 to 1500 psi. This 90 Fathom Fault is far less lithified and more compressible than the Hopeman fault rock samples. The Mam Tor samples experienced a large reduction of permeability with increasing effective stress in a similar trend to the low permeability tight gas sandstones. The permeability reduction of Mam Tor samples was in the range of 60 to 80 % of the original permeability when the effective stress increased from 500 to 2000 psi. The results clearly show that to estimate the in situ permeability, a correct confining pressure needs to be applied when measuring the permeability of such tight rocks. Measurements made with low confining pressure can overestimate the permeability by several orders to the actual permeability under in situ conditions.

The reduction in permeability that each sample experienced is probably due the variation on pore sizes, pore shapes and grain packing and sorting. For example, Yale (1984) has studied the impact of different pore shapes to explain the impact of stress on permeability, conductivity, and formation factor. He identified that the aspect ratio of pores (the ratio between the average grain radius and the radius of curvature) is a fundamental control of the permeability reduction experienced by the samples. For low aspect ratio pore shape, the permeability reduction with stress is quite high in comparison to high aspect ratio pores. Furthermore, the author also argued that grain boundary pore shape can be used to explain the reduction in permeability for both high and low permeability samples by varying the aspect ratio, whereas the tapered type pore shape cannot explain the reduction in permeability for high permeability samples. It is envisaged that the packing of the grains and the deposition environment and later diagenesis will influence the shape of the pores.

1.2. Stress sensitivity of partially saturated rocks

It is also observed that the permeability of samples is far more stress dependent when water saturated than when dry. For example, the effective permeability of the Vale of Eden fault rock is reduced by 50% by increasing the effective stress from 500 to 1500 psi. Similarly, the gas relative permeability measurements from the Mam Tor samples proved far more stress sensitive than the single phase permeability value (**Figure 11**). The results show that single phase gas permeabilities decrease on by a factor of 3 when the confining stress is increased from 300 to 2000, while the gas relative permeability values, decreases by up to a factor of 14 under these conditions. These results are consistent with those of Ali et al. (1987) who for high permeability rocks found that the oil relative permeability of was more stress sensitive than the water relative permeability. It was argued that this was due the pore occupancy of the fluids. As the sand grains are forced closer together, due to the increase in effective stress, a general shift in the pore throat size distribution towards smaller values occurs. Therefore, at constant water content, such an increase in effective stress caused a redistribution of the wetting phase. On the other hand, this will lead to a smaller blockage of the oil, and hence less reduction of the oil relative permeability.

The impact of stress on the gas effective permeability depends on the amount of water within the pore space. For example, it has been observed for one of the Mam Tor sample (D1 with Sw=67%) that the gas flow stopped when the effective stress was increased, and the permeability could not be measured. This can be explained by the illustration in **Figure 12** which shows that as the effective stress is increased two possible processes may occur to the porous medium. Firstly, the grains arrange itself to the current stress apply to the sample, which can lead to grain-grain contact. Secondly, due to the stress applied to the sample, the water film inside the porous medium can also get affected by the amount of the stress which can result in snap-off and blockage of the gas pathway.

CONCLUSIONS

The stress dependence tests on the single phase permeability show different trends. The Hopeman Fault samples are the least stress sensitive, followed by the other cataclastic fault samples (90 Fathom and Vale of Eden). On the other hand, Mam Tor siltstones and the tight gas samples are the most stress sensitive. Although there may not be enough data points to make any generalisations, it may be noteworthy that:-

- The most stress sensitive samples (Mam Tor and tight gas samples) are the ones that have experienced a large uplift following maximum burial.
- The least stress sensitive samples (Hopeman) are the most extensively cemented by quartz.
- The samples with intermediate stress sensitivity are not as quartz cemented as the Hopeman Fault and have not been as uplifted as the Mam Tor samples.

The gas relative permeability measurements proved far more stress sensitive than the single phase permeability values. Therefore, if fault rocks also show such a large stress sensitivity to relative permeability it would be expected that their petroleum relative permeability could decrease (become more sealing) as the reservoir is drawn down. Ultimately, the results indicate that it may be necessary to understand both the relative permeability and the stress sensitivity of relative permeability when assessing the impact of stress on the performance of the production from tight gas reservoirs and when studying the impact of faults on fluid flow within petroleum reservoirs.

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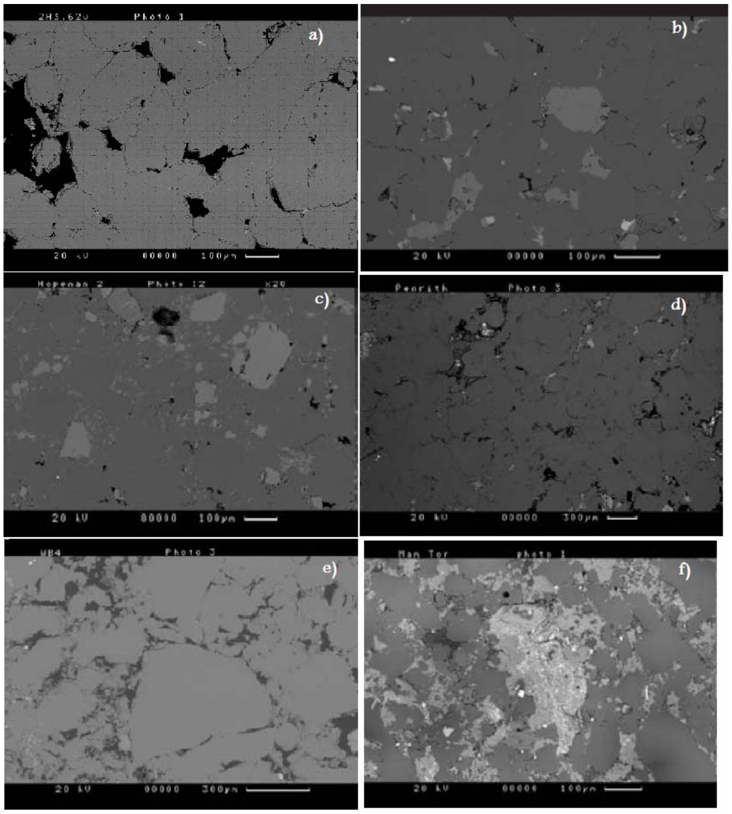

Figure 1 BSE micrograph showing : a) high permeability tight gas sample; b) low permeability tight gas sample; c) Hopeman fault rock sample; d) Vale of Eden fault; e) 90 Fathom fault; f) Mam Tor rock sample.

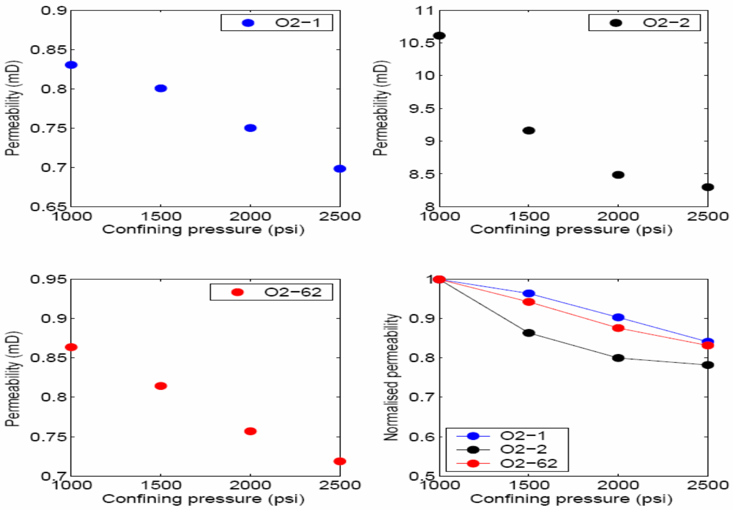

Figure 2 Diagram showing the stress dependence permeability results for group A of the tight gas samples. The gas permeability was measured using steady state method and Klinkenberg corrected.

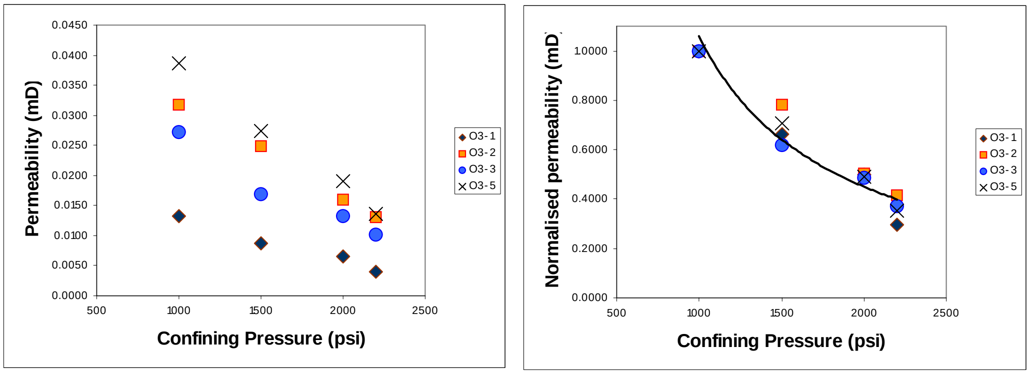

Figure 3 Diagram showing stress dependence of the gas permeability (measured using gas pulse-decay) for group B of tight gas samples.

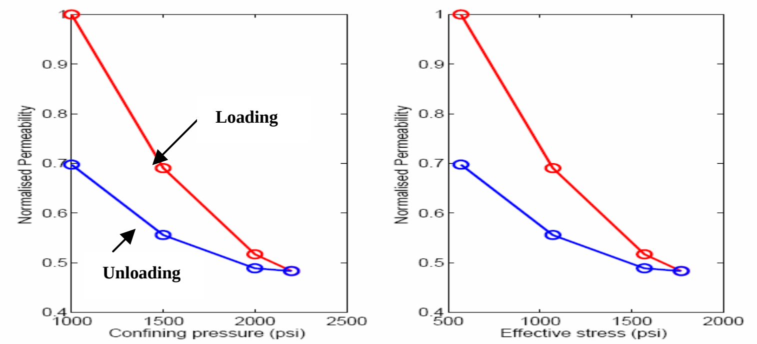

Figure 4 Diagram showing the hysteresis experienced by the tight gas sample, $O3-5$, during loading and unloading cycle.

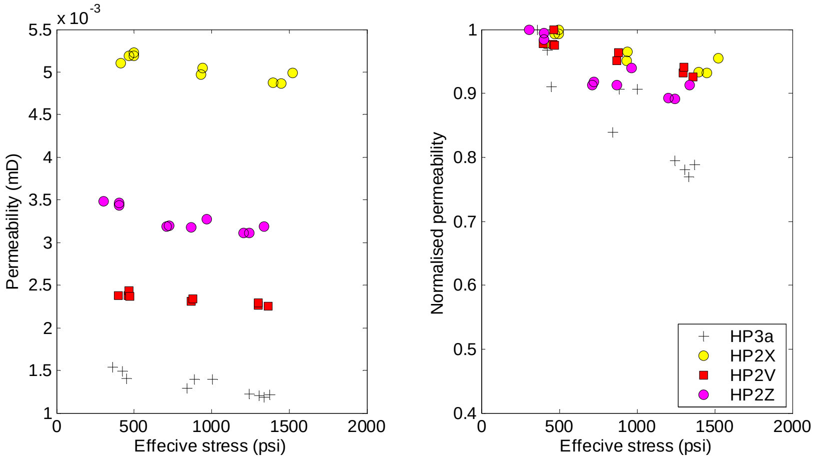

Figure 5 Diagram showing the stress dependence of permeability for five samples of the Hopeman Fault, measured using gas pulse-decay.

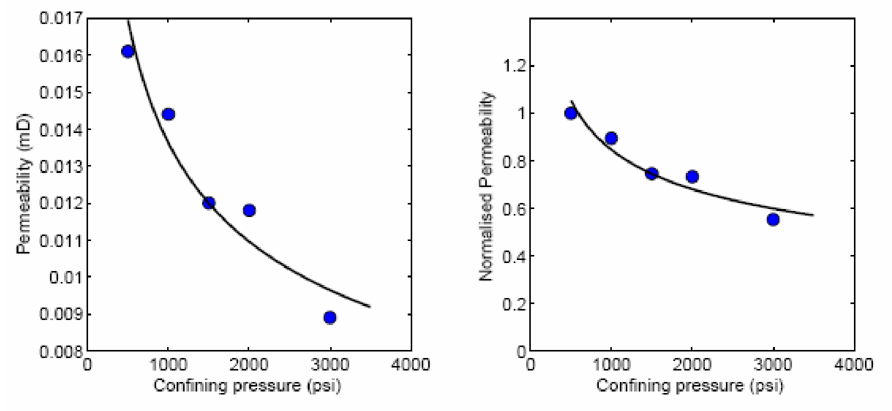

Figure 6 Diagram showing stress dependence of permeability of a core from the Vale of Eden (Cheden B). The gas permeability was measured using steady state method and Klinkenberg corrected.

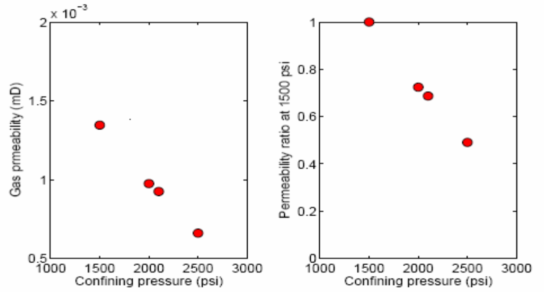

Figure 7 Gas effective permeability at different confining pressure and a pore pressure of 1003 psi for sample Cheden C (Vale of Eden). The water saturation was 17%.

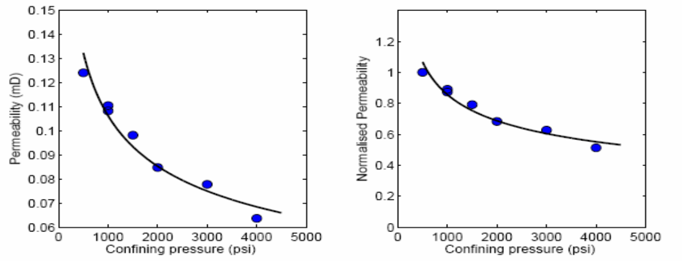

Figure 8 Diagram showing the results from the experiments to determine the stress dependence of permeability of the sample Fathom-B, from the 90 Fathom Fault, Cullercoats. The gas permeability was measured using steady state method and Klinkenberg corrected.

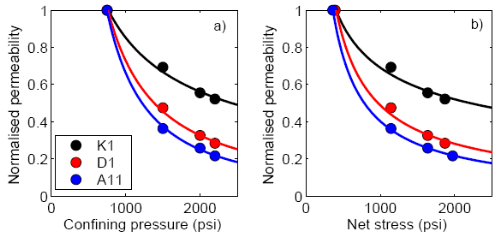

Figure 9 Diagram showing gas permeability as a function of effective stress (assuming Biot effective stress coefficient = 1) for Mam Tor samples, measured using gas pulse-decay.

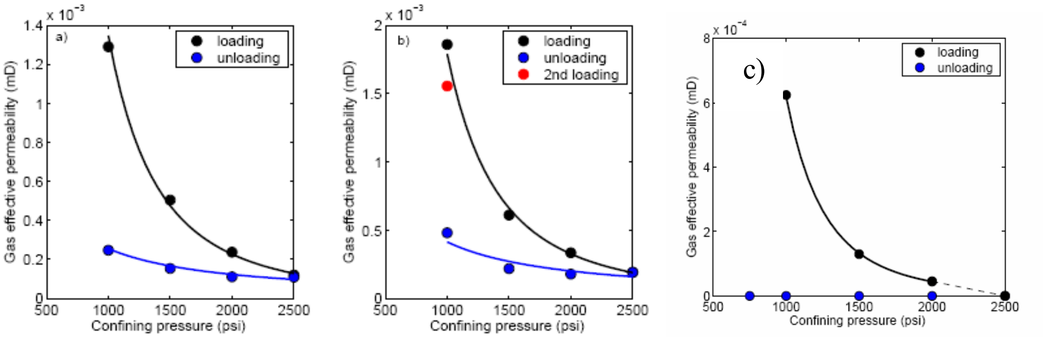

Figure 10 Diagram showing some results of the impact of stress on the gas effective permeability for two samples. a) D2 at *Sw* = 44.4%, b) E2 at *Sw* = 40.5%, c) D1 at *Sw* = 66.0%. The measurements were performed with a pore pressure of 450 psi.

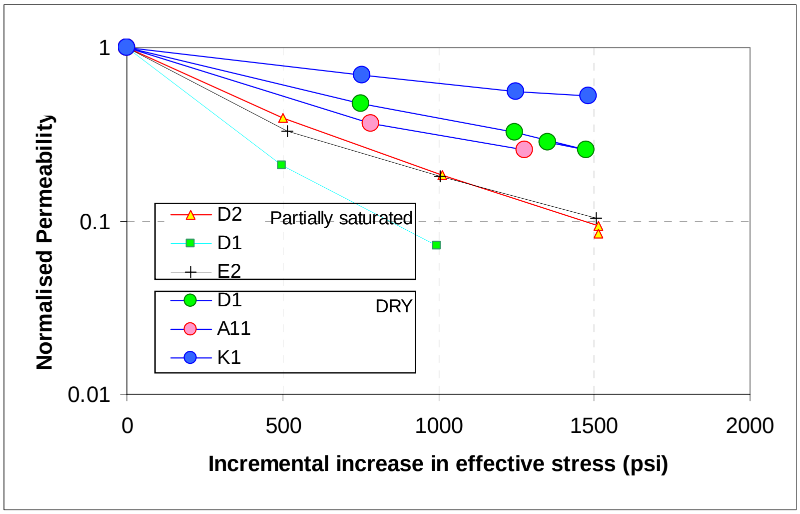

Figure 11 Diagram showing a plot of permeability ratio as a function of effective stress (assuming Biot effective stress coefficient = 1) for dry and partially saturated samples of Mam Tor siltstone. It is clear that the presence of brine in the samples extenuates the stress dependence of permeability.

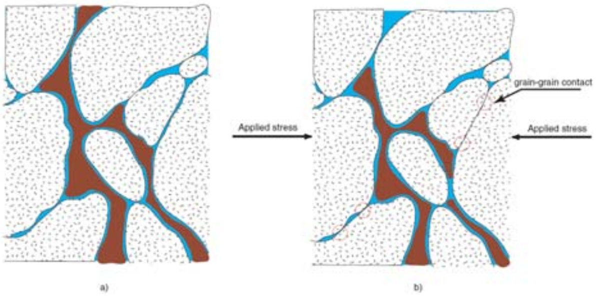

Figure 12 Diagram showing a schematic of the effect of effective stress on a partially saturated sample. a) Before applying the stress, b) after applying the stress. The applied stress can have two effects. Firstly grain-grain contact could occur. Secondly, a snap off phenomena could occur to the water film due to the applied stress, which can result in the blocking the movement of the gas phase.