STRESS SENSITIVITY OF SATURATION AND END-POINT RELATIVE PERMEABILITIES

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ABSTRACT

Production induced changes in stress due to reductions in pore pressure have the potential to alter the flow properties of reservoir rocks. There are a large number of experimental results, which show that single-phase permeability is a function of applied stress. In hydrocarbon reservoirs two or even three phases may flow simultaneously through the pore network, however very little data exists on the stress sensitivity of multiphase flow.

To measure the stress sensitivity of two-phase flow, the relative permeability of a sandstone was measured as a function of applied stress. The sandstone was an aeolean sandstone from a surface deposit. The sandstone was strongly water wet with an Amott-Harvey index of 0.91. The porosity of the samples were between 25.4 and 28.0% and the Klinkenberg corrected gas permeability between 1051 and 1644mD. Samples were saturated with brine under high pressure, flooded with oil at different stresses to an equilibrium initial water saturation, then waterflooded to residual oil saturation. The average water saturation or oil saturation in the sample was calculated from the volume of brine or oil produced.

The initial water saturation was stress sensitive in all cores tested. During the dynamic desaturation of a sample at a given stress equilibrium water saturation was reached between 2 and 8 pore volumes of injected oil. The stress was then increased and a new equilibrium water saturation reached. At an injection rate of 40ml/hr water saturations of approximately 0.400 were achieved at 400psi, this dropped to 0.385 at 3000psi and 0.377 at 8000psi. The variation of water saturation with stress can be qualitatively explained in terms of the changing pore volume and the balance between capillary and viscous forces. At a given stress and injection rate there is a balance between the capillary and viscous forces in the pores. The flowing oil is excluded from pores below a certain size by capillary forces. When the stress is increased the entire pore network deforms. Brine is squeezed out of small brine filled pores into the larger pores, where it is swept out of the sample.

The effective permeability end points $k_o(S_{wi})$ and $k_w(S_{or})$ were stress sensitive, more so than the single phase permeability. A 15% drop in $k_o(S_{wi})$ was noted from 400-3000psi. This compares to an 8% drop in the single-phase permeability of this material. This shows that the end point relative permeabilities were also stress sensitive.

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INTRODUCTION

An accurate knowledge of a reservoirs porosity and permeability is crucial to accurate simulation of reservoir performance and enhanced reservoir management. Reservoir simulators tend to include a porosity that varies with stress. They also have options to include a single-phase permeability that varies with stress but this option is rarely implemented. The single-phase permeability of reservoir rocks is however dependent on the stress experienced by the rock mass. In the simplest case where the vertical (σ_v) and 2 horizontal stresses (σ_H and σ_h) the stress is isotropic and given by the overburden stress minus the pore pressure. Hydrocarbon production usually decreases the pore pressure causing an increase in stress on the rock mass. This causes coupled changes in reservoir properties: permeability and porosity will decrease, the elastic moduli and resistivity will increase (Jones et al 2001). These coupled interactions between geomechanics and fluid flow have a significantly effect on production rates (Chin et al 2000).

The reduction in pore volume and single phase permeability with stress is well documented (Fatt and Davis (1952), Dobrynin (1962). However very few hydrocarbon reservoirs contain only one liquid phase. The response of a reservoir containing more than one fluid to a change in stress is less well understood. Very little work has been done to examine the stress sensitivity of water saturation and relative permeability. The work, which has been done, comes to a variety of conclusions.

Fatt (1953) measured gas-oil relative-permeability at simulated overburden pressures of 3000psi. The conclusion of the study was that the relative permeability was not significantly affected by the application of overburden pressure. The method used was to evaporate kerosene from the core with a stream of air to achieve varying saturations, then flow gas to measure the end point permeability. The saturations were measured by weighing the core post test and using the pore volume at stress. The core appeared to be subjected to multiple stress cycles, this could reduce stress sensitivity. Small errors in saturations could shift the relative permeability curves and therefore alter the conclusions. The author also noted that if the saturation was established before the stress was applied there was a drop in effective permeability compared with a test where the saturation was established at stress. This was said to be due to the application of stress reducing porosity, the volume of oil in the sample was postulated to remain constant due to capillary forces, so the gas saturation decreased.

Wilson (1956) measured the water-oil relative-permeability at confining pressures up to 5000psi, using the steady state method. Each sample was subjected to several drainage-imbibition cycles, 2 cycles at 30psi overburden and 2 at 5000psi overburden. He noted that the changes in effective permeability of oil at S_{wi} were very nearly in proportion to the effect of stress on single-phase permeability. However, the graph data did show effects of stress on relative permeability. With the relative permeability curves for the samples stressed to 5000psi above those at 30psi, this means that the $k_{ro}(S_{wi})$ is less stress sensitive than the single phase permeability. In the discussion the author concluded there was a small but detectable effect of stress on relative permeability, which was in contrast to Fatt (1953).

In a more recent paper Ali et al (1987) reported experiments on Berea sandstone, in which they measured the reduction in porosity, single-phase permeability and oil-brine relative permeability with applied overburden up to 6000psi. They used the unsteady state method to measure the relative permeability. They noted a decrease in k_{ro} with applied stress and a very small decrease in k_{rw}. They also noted an increase in S_{wi} and S_{or} as stress increased. This study suggests that both k_{ro} and k_{rw} are more stress sensitive than the single-phase permeability.

It is impossible to come to any firm conclusion regarding the stress sensitivity of relative permeability from the evidence of the studies cited above. An experimental investigation was undertaken to increase understanding of the stress sensitivity of relative permeability.

METHODOLOGY

The strategy of the experimental investigation was to approach the problem using two different methods. Firstly individual core plugs were flooded to S_{wi} or S_{or} at low stress levels and the stress increased to directly measure the stress sensitivity of $k_{ro}(S_{wi})$ and $k_{rw}(S_{or})$. Secondly relative permeability was calculated from the results of core flooding experiments on core plugs at different stresses using the unsteady state method. Single-phase permeability and pore volume measurements were also made as a function of stress. The relative permeability was normalised using the single-phase permeability at the relevant stress level. The stresses chosen were 400psi, 3000psi and 8000psi. The lowest stress level was considered as a base case and represented the initial effective stress on a reservoir. The intermediate stress level was the effective stress on the same reservoir after significant drawdown.

SAMPLE DESCRIPTION AND PREPARATION

The material chosen for the study was Locharbriggs Sandstone, an aeolean sandstone from a quarry in south west Scotland. The mineralogy of the material was approximately 80% quartz, 13% feldspar, 5% clays and 2% other minerals, notably hematite which gives it its red colour. The core plugs were all cored from a single homogeneous block using a water flushed core barrel. The core plugs were dried in an oven at 80°C. The porosity was measured using a conventional helium porosimeter. The samples were then vacuum saturated with brine, which gave 90-95% brine saturation. The samples were then saturated in a high-pressure cell at 2000psi pore pressure for two days. The brine saturation was then confirmed to be 100% by weight. The single-phase permeability at 400psi was measured prior to the flooding experiments. The porosity and permeability of the samples used is shown in Table 1. One core (L1) had its wettability determined using the Amott technique (Amott 1959), it gave an Amott-Harvey wettability index of 0.91, which makes this material strongly water wet.

The brine used in the experiments was a 9% NaCl brine, with a density of 1.067g/cc and a viscosity at 20°C of 1.31cp. The oil used was multipar H, a refined light hydrocarbon oil, with a density and viscosity of 0.760g/cc and 1.33cp respectively.

Sample	L1	L2	L3	L4	L5	L6
Porosity	0.280	0.258	0.280	0.254	0.256	0.257
k_{sp}(400psi)mD	1644	1372	1644	1614	1486	1051

Table 1 Single-phase permeability at 400psi (k_{sp}) and porosity

EXPERIMENTAL EQUIPMENT AND TECHNIQUE

In the experiments the cores were mounted vertically in a core holder normally used in rock deformation experiments, known as a Hoek cell. This cell provided a means of applying confining pressure to the sample. It consisted of a steel body (rated to 10000psi) within which was located, a polyurethane sleeve. Confining pressure was transmitted to the radial surface of the sample via hydraulic oil in the annulus between the steel body and the sleeve. The confining pressure simulates the horizontal stresses. The vertical or greatest principal stress was applied using an external ram, via porous platens. During the course of an experiment brine or oil was pumped through the sample via the porous platens. Sample strain, axial and radial was measured through-out the experiment using strain gauges. The instantaneous sample dimensions were used for calculating permeability.

Movement of fluid though the sample and volume measurements were made using a pumping network (Figure 1). The network allows oil or brine to be pumped in either direction through the core, the direction can be reversed instantaneously. Expelled volume measurements of oil and water were used to determine average saturation.

The network can be used in a variety of modes. For single-phase permeability measurements brine was pumped in the inlet using a Pharmacia pump (1000psi, 1-499ml/hr). Fluid flows through the core and was collected in a reservoir mounted on a balance. The weight measurements were used to confirm the flow rate. The balance was also used in this configuration to measure the expelled pore fluid.

During oil flooding experiments, oil was flooded top to bottom. During the oil flood a mixture of oil and water was produced by the core, this flowed into the separator, the water sinks to the bottom of the vessel and the oil flowed up to the collector vessel. The production of water was determined by measuring the increase in height of the meniscus. A telescope mounted on an electronic vernier gauge measured the height of the meniscus. Corrections were made for dead volume and lag time in the system. During the water flooding part of the experiment brine was flowed bottom to top, the effluent is collected in the bottom of the separator, the oil floats off causing the meniscus to drop.

The accuracy of the saturation measurements depended on how accurately the height of the meniscus can be determined. Under ideal conditions the height can be determined very accurately, but the meniscus can be distorted making measurement difficult. The uncertainty in each measured parameters are shown in Table 2. Two different types of uncertainty are shown the absolute uncertainty and the relative uncertainty. The relative uncertainty was when there was a change in a parameter such as when a small amount of brine was expelled after a change in stress, the change in saturation can be determined very accurately. The absolute uncertainties are shown on Figure 5 for the end point results of experiment L2.

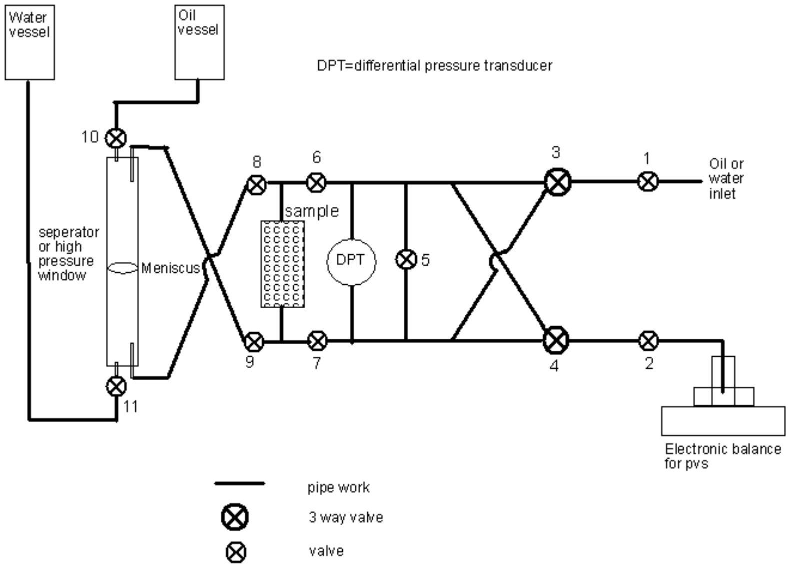

Figure 1 Schematic of pumping network used

Parameter	Absolute uncertainty	Relative uncertainty
Saturation	±0.017	±0.0015
permeability	±3.2%	±1.5%
Relative permeability	±0.022	±0.01

Table 2 Uncertainty in measured parameters

During the course of an experiment, a PC based data logger recorded the experimental parameters of stress, sample strain, mass of pore fluid expelled and differential pressure across the sample.

EXPERIMENTAL RESULTS

Three types of experiments were performed, 1) single phase measurements using brine, 2) flooding experiments where either S_{wi} or S_{or} was established at low stress and the stress increased and, 3) waterflooding experiments at each of the individual stress levels of 400, 3000, and 8000psi. In each experiments only one loading cycle was used, this was done to remove any effect of loading history.

The results of an experiment to measure the single-phase properties are shown on Figure 2. The starting point of the experiment was 400psi. The permeability was measured by flowing though the sample at a constant rate of 400ml/hr and measuring the pressure drop across the sample; brine was flowed in both directions and at a variety of rates through the sample. Once the pressure drop across the sample had stabilised the permeability was then calculated from Darcy's law, using flow rate, pressure drop, brine viscosity, and the sample dimensions. The flow was then stopped. The next increment in stress was applied when the expelled fluid mass had stabilised. The increment in stress caused a reduction in pore volume, which was measured by the expelled fluid mass, once this had attained a constant value, the next stage of flow was started. This was continued up to the highest stress. The pore fluid mass expelled was converted to a reduction in pore volume by dividing by density and making a correction for the conformance of the sleeve on to the sample.

The pore volume reduction showed approximately a 5% reduction at 8000psi, the reduction was faster at low stress and appears to be tailing off at high stress. The reduction was similar in magnitude to that reported by Fatt (1952) and Ali et al (1987).

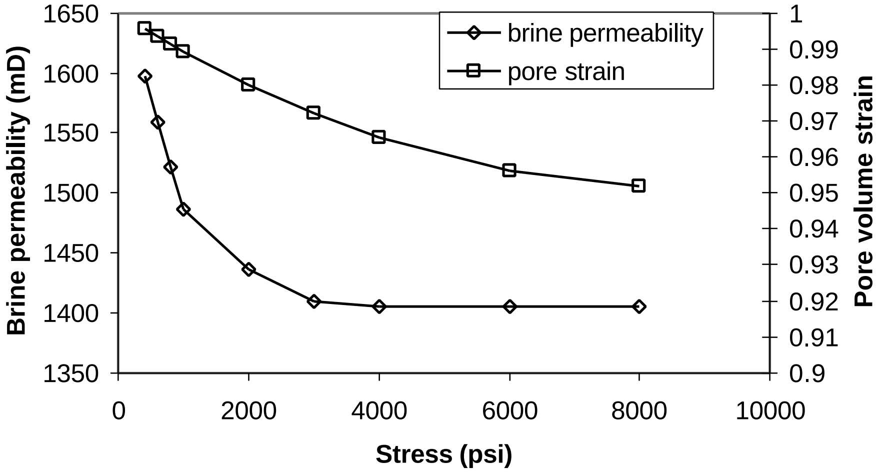

Figure 2 Variation of single phase brine permeability and pore volume reduction as a function of applied stress.

The permeability reduction with stress was initially rapid and then tailed off, above 4000psi the permeability was essentially constant. The reduction at 8000psi was 12%, this was a similar reduction to that reported for Berea sandstone in Ali et al (1987). The pore volume reduction was used in the analysis of the two-phase flow experiment, to calculate the saturation at high stress levels.

In the first set of 2 phase flow experiments, two cores were used L1 and L2. Core L1 was flooded at 400psi with oil until no more brine was produced, this was taken as the initial water S_{wi} saturation for these conditions. Core L1 was then water flooded with brine at 400psi until no more oil was produced. The stress was then increased to 3000psi while still flooding with brine. Once equilibrium in differential pressure and oil production was reached the stress was increased again to 8000psi. The raw data on differential pressure and oil production are shown on Figure 3. Brine was injected into the sample at 40ml/hr, the pressure rises rapidly to a maximum at 12minutes then declines to a steady level. The oil production increases linearly to breakthrough at 15-16 minutes. After the initial brine breakthrough there was a short period in which both oil and brine were produced. Then after approximately 18 minutes the oil production ceased for the duration of the experiment. The stress was increased to 3000psi at 30mins, then 8000psi at 50minutes. There was no additional oil production associated with the jumps in pressure. The differential pressure did however increase. The end point relative permeability was calculated at the end of each stress period. The values are shown in Table 3 along with the values for the other experiments. For L1 S_{or} increased with stress, this small effect was due to the volume of oil in the sample remaining constant but the pore volume decreasing due to the increased stress. Fatt (1953) also noted this effect. The end point relative permeability $k_{rw}(S_{or})$ was also a function of stress.

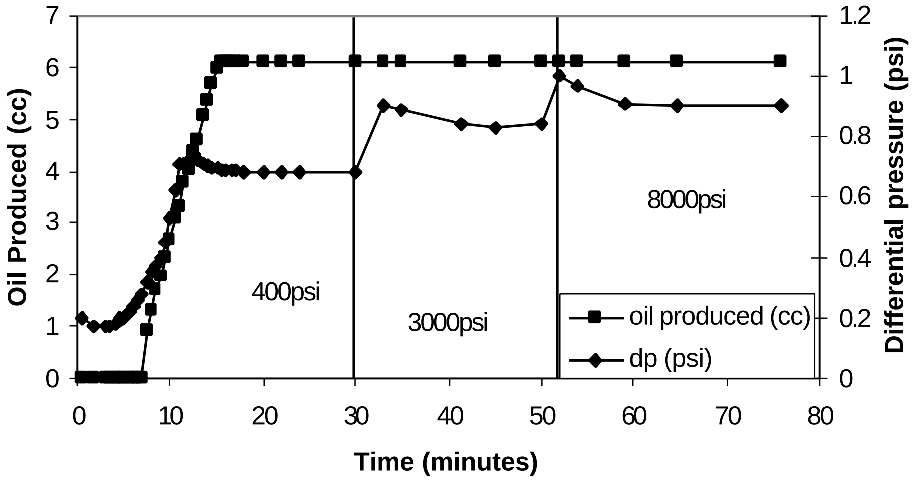

Figure 3 Differential pressure and oil production for experiment L1

For the experiment on core L2, the core was flooded firstly to S_{wi} at 400psi then the stress increased to 3000psi then to 8000psi. The differential pressure and brine production are shown on Figure 4. Core L2 was flooded at 40ml/hr until the brine production and differential pressure had stabilised at 70minutes. The pump rate was then increased to 400ml/hr until stability at 100 minutes. The stress was then increased to 3000psi and then to 8000psi. The end point saturation and relative permeability are shown in Table 3. The relative permeability decreased with stress, but the behaviour was complicated by the brine saturation, which also decreased with stress.

In the second set of two phase flow experiments, experiments were performed at 400psi, 3000psi, and 8000psi, L3, L4 and L5 respectively. In each experiment the sample was initially saturated with brine. The sample was flooded to S_{wi}, then waterflooded to S_{or}. The results of the experiments are shown on Figure 5 and the end points in Table 3. The relative permeability was derived using the method of Jones and Roszelle (1978). Unfortunately the water flood data gave very few saturation points after breakthrough, due to the extremely rapid drop in oil production after breakthrough. The relative permeability curves are Corey (Corey et al 1956) type fits (eqn 1 and 2 below) based on the end points and the few other points generated by the method of Jones and Roszelle (1978). The Corey exponents n_{oil} were fitted to the data using a non-linear least squares method, the values are shown in Table 3. Also shown in Figure 5 are the end point data from experiments L1 and L2.

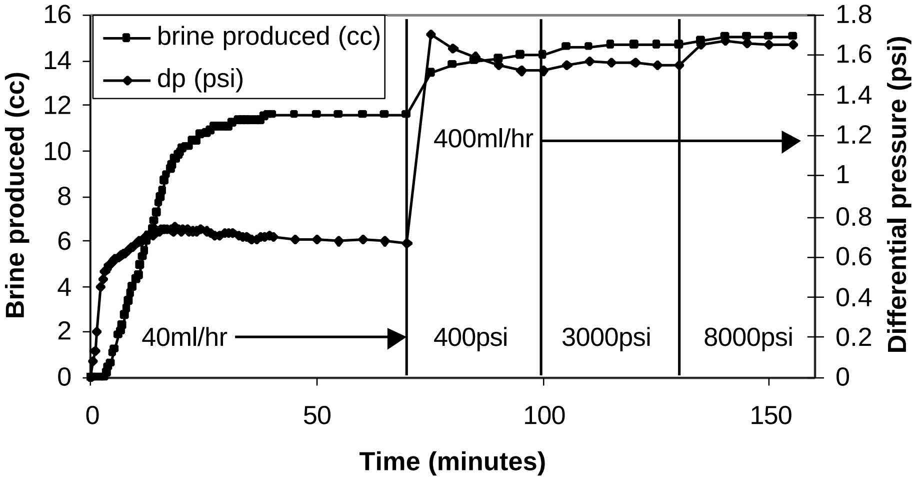

Figure 4 Differential pressure and brine production for experiment L2.

sample	Stress (psi)	S_{wi}	$k_{ro}(S_{wi})$	S_{or}	$k_{rw}(S_{or})$	Corey exponent n_{oil}
L1	400	0.438	0.509	0.289	0.116	
	3000			0.296	0.100	
	8000			0.301	0.100	
L2	400	0.399	0.614			
	3000	0.384	0.603			
	8000	0.377	0.570			
L3	400	0.438	0.509	0.289	0.116	2.79
L4	3000	0.390	0.484	0.288	0.095	2.27
L5	8000	0.392	0.469	0.309	0.105	2.08

Table 3 End point relative permeability and saturation for the 5 experiments

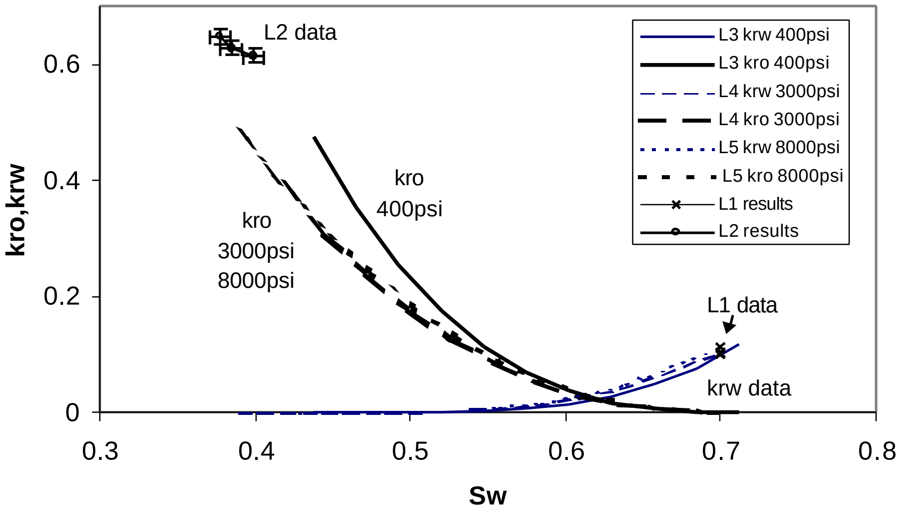

Figure 5 Relative permeability curves for experiments L3, L4 and L5, together with the end point data of experiments L1 and L2.

DISCUSSION

The results presented above show that for this material the end point relative permeabilities $k_{ro}(S_{wi})$, $k_{rw}(S_{or})$ and the S_{wi} and S_{or} were stress sensitive. The end point $k_{ro}(S_{wi})$ are rather low for a water wet rock at 0.47-0.61. This may be due to the S_{wi} being quite high at around 0.4 and not a true irreducible water saturation, or there being a build up of water at the outflow end due to capillary forces.

For experiment L2, S_{wi} decreases with increased applied stress. An explanation for this is that at a given stress and flow rate there was a balance of capillary and viscous forces. Locharbriggs sandstone was strongly water wet as shown by the Amott values of 0.91. During an oil flood the oil will sweep out the brine in the pores. The oil can only enter a pore if the viscous forces can overcome the capillary forces locally. At equilibrium there will be large pores which have been swept out and are full of oil, except for the water wet pore lining, and small pores which are full of brine. If the stress is increased, the pore network deforms and the pores get smaller. For the small pore this will result in small quantities of brine being squeezed out into the large pores where it either flows away in the pore lining films or is swept away by the flowing oil. The large pores also deform but they are with the exception of a thin brine layer, full of oil. The only effect of the squeeze on the large pore is to expel oil from the sample.

In experiment L1 S_{or} increased with increasing stress, this was due to a reduction in pore volume with stress. The same volume of oil in a smaller pore volume gave a higher S_{or}.

In experiment L1 the $k_{rw}(S_{or})$ dropped as the stress was increased, S_{or} also increased. In contrast in experiment L2 the $k_{ro}(S_{wi})$ increased as the stress was increased, Swi also changed with stress, this was an actual decrease with more brine being produced. For both experiments L1 and L2 the changes in relative permeability were complicated by simultaneous saturation changes. For a true comparison the changes in relative permeability at constant saturation must be deduced.

The variation in $k_{ro}(\sigma)$ at constant S_w can be estimated by assuming some functional dependence of k_{ro} on S_w. A commonly used dependence is the Corey Equations.

$$k_{rw}(S_w) = k_{rw}(S_{or})\left(\frac{S_w - S_{wi}}{1 - S_{wi} - S_{or}}\right)^{n_w} \text{............}\mathbf{(1)}$$

$$k_{ro}(S_w) = k_{ro}(S_{wi})\left(\frac{1 - S_w - S_{or}}{1 - S_{wi} - S_{or}}\right)^{n_o} \text{.............}\mathbf{(2)}$$

Equations 1 and 2 gave a power law dependence of the relative permeability on the water saturation S_w, scaled by the end point permeability. These equations were evaluated using the end points obtained in experiments L1 and L2, and using typical values for the exponents of $n_W=4$ and $n_o=2$. This gave rise to a family of three oil and three water relative permeability curves. The variation of relative permeability with stress at constant saturation was evaluated from the graphs. The value of k_{ro} at Sw=0.4 and k_{rw} at Sw=0.7 are shown in Table 4. The $k_{ro}(0.4)$ decreases with applied stress, this implies that the two-phase permeability were more stress sensitive than single phase permeability. The effect was small but larger than the experimental uncertainty, the relative uncertainty of ±0.01. The $k_{rw}(0.7)$ initially decreased then increased, these changes were small and comparable to the uncertainty of the measurements.

The experiments L3, L4 and L5 confirm the general trend to lower relative permeabiliy at high stress. There was a large difference between the $k_{ro}(S_w)$ at 400psi to that at 3000psi and 8000psi, the effect was larger than the absolute experimental uncertainty. The $k_{ro}(S_w)$ values for 3000psi and 8000psi were almost identical. The $k_{rw}(S_w)$ values appear to increase slightly but were identical within the experimental uncertainty.

The experiments L3, L4 and L5 may be affected by sample heterogeneity. Even through all the samples used in this study were cored from the same small block, sample L3 had higher porosity and permeability. It may be that the differences in porosity and permeability are causing the differences in the irreducible saturation at relative permeability. However the results of the three experiments L3, L4 and L5 at individual stress levels agree at least qualitatively with the experiments L1 and L2 where the stresses were changed. The best fit Corey exponent n_o for these experiments appears to decrease with applied stress, more work is needed to determine if this was a real effect.

The results of this study partially agreed with the work of Ali et al (1978), although there were important differences. The most important difference was that Ali et al (1978) reported an increase in S_{wi} with overburden pressure. The reason they gave for this increase was that the stress caused an increase in capillary forces due to decreased pore sizes.

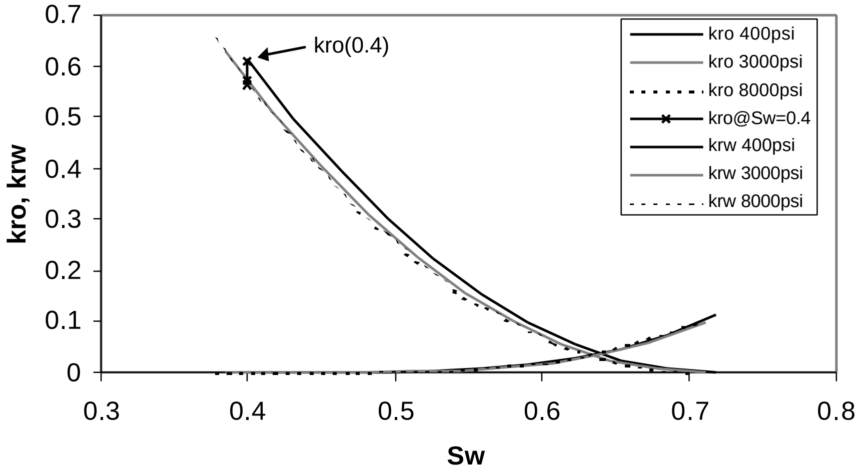

Figure 6 Method for evaluating the relative permeability at constant S_w

Stress (psi)	$k_{ro}(S_W=0.4)$	$k_{rw}(Sw=0.7)$
400	0.611	0.091
3000	0.570	0.085
8000	0.562	0.092

Table 4 Values of relative permeabilities at constant saturation.

CONCLUSIONS

The conclusions for two-phase flow under increasing stress in this material are:

- S_{wi} decreased with applied stress due to water squeezing out small water filled pores into to larger pores filled with oil.
- S_{or} increased with applied stress due to a reduction in pore volume with a constant oil volume in the core.
- $k_{ro}(S_w)$ decreased with applied stress, the effect was small but larger than the experimental uncertainty.
- There were no significant changes in $k_{rw}(S_w)$ with applied stress.

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NOMENCLATURE

σ_v = vertical stress or overburden (psi)
σ_H = maximum horizontal stress (psi)
σ_h = minimum horizontal stress (psi)
S_w = brine saturation
S_{wi} = initial brine saturation.
S_{or} = residual oil saturation.
$k_o(S_{wi})$ = effective oil permeability at S_{wi}
$k_w(S_{or})$ = effective brine permeability at S_{or}.
$k_{ro}(S_w)$ = oil relative permeability
$k_{rw}(S_w)$ = brine relative permeability.
n_w n_o = Corey exponents for brine and oil

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