CAPILLARY CONTINUITY IN FRACTURED CHALK SYSTEMS: AN EXPERIMENTAL STUDY

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Abstract

Experimental flow studies were performed on artificially and naturally fractured chalk cores to determine the degree, if any, of capillary continuity across the fractures. The displacement procedures included both gas-displacing-oil and water-displacing-oil experiments from oil saturated chalk cores initially at residual water saturation. Bulk displacement of oil was used to determine average saturations and rates of displacement while magnetic resonance imaging, MRI, was used to measure saturation distributions and possible end effects at the fracture(s).

Artificially fractured outcrop chalk cores, with a diagonally sawn fracture, were constructed with 100, 10 and 3 percent contact area between the two matrix blocks to simulate decreasing amounts of capillary continuity. The ultimate oil recovery in the water/oil displacement experiments was very similar for all three levels of contact. The MRI images indicated equal saturations in the matrix on both sides adjacent to the fracture. This appeared to indicate that as long as a minimal level of contact between the matrix blocks existed, viscous and/or imbibition forces were able to drive the oil from the inlet matrix block, across the fracture and through the outlet matrix block. In the gas/oil displacement experiments, MRI images indicated by-passed oil in the inlet block for the lower contact areas. The ultimate recovery was found to be dependent upon the contact area.

The naturally fractured reservoir chalk cores exhibited a very high degree of capillary continuity across the fractures for both the water/oil and gas/oil displacing experiments. This was indicated by both high oil recovery and uniform MRI images of the inlet and outlet portions of the displaced cores. This suggests that these natural fractures contained conductive paths across the fracture which were equivalent to or greater than 3% contact in the sawn fractures of the artificially fractured cores, and that these natural fractures had negligible effect on the flow of fluids.

Introduction

Previous research of capillary continuity in fractured systems has primarily concentrated on gravity drainage rather than viscous flow (Ref. 1-7). Viscous flow will exist, at least near the well bore, where a massive water flood or gas flood has been implemented in a naturally fractured reservoir or where the capillary continuity between matrix blocks across the fractures is high. The degree of capillary continuity across the fractures separating the individual matrix blocks within the reservoir should influence the production profile and the ultimate recovery from the reservoir.

There has been discussion regarding how fluids flow in fractured reservoirs. The proponents of one extreme argue that once a fluid has left the matrix it flows only in the fracture, never to enter the matrix again. Others argue that where asperities of one matrix block touches another across the fracture, fluids can flow from matrix block to matrix block without going through the fracture. Perhaps a more moderate approach would predict that the relative movement of fluids through the matrix and fractures would be inversely proportional to their resistance, permeability, and directly proportional to their cross sectional area. The ability of magnetic resonance imaging, MRI, to image fluid saturations inside porous media makes it possible to measure how fluids move across a fracture from one matrix block to another (Ref. 8, 9).

This research was performed to experimentally investigate the flow of fluids across fractures. The fracture systems investigated included two outcrop chalk cores with artificial fractures at several different magnitudes of fractional contact area across the fracture, to simulate reduced capillary continuity, and two naturally fractured North Sea chalk cores. The experiments included both gas-displacing-oil and water-displacing-oil systems with residual water present.

Data collected from the displacement experiments include the production profiles as a function of time, the observed ultimate recovery, and MRI images of saturation distribution. MRI imaging was conducted at the initial condition, oil saturated with residual water, and upon termination of the displacement experiment. This permitted a qualitative determination of the distribution of the residual oil as well as the identification of any end effects that may have developed along fracture systems due to a reduction or lack of capillary continuity across the fracture(s). MRI images were obtained, for one core, at different stages of the desaturation, to follow the process in more detail.

Core Description and Methodology

Niobrara Outcrop Chalk

Niobrara outcrop chalk, from central Kansas, was selected as the matrix material for the artificially fractured cores due to its similarity to North Sea chalk. Core characterization included x-ray diffraction, scanning electron microscope (SEM) photomicrographs, and thin section analyses as well as standard bulk property tests. Permeability, porosity, and residual water are presented in **Table 1**. X-ray diffraction indicated 99 percent calcite and 1 percent quartz, a mineral content closely resembling that of a "clean" North Sea chalk. The matrix, described as a foram wackestone, resembled that of most North Sea chalks and was composed mainly of whole and fragmentary skeletons of the planktonic algae coccolithophorid. The building blocks of these skeletons were found to be calcite platelets generally 1 micron (0.001 mm) or less across, and were arranged in rings typically less than 10 microns in diameter. Pore types in the Niobrara chalk samples were also very similar to those measured in North Sea chalks. Matrix porosity consisted of primary microinterparticle pores between whole and fragmentary skeletons of coccolithophorids and primary microintraparticle pores within the centers of coccolith rings. Fracturing, significant in some North Sea chalks, was not detected in these Niobrara outcrop samples.

A schematic drawing illustrating the artificially fractured Niobrara chalk is shown in **Figure 1(b)**. The fracture configuration was chosen to duplicate the general physical characteristics of the North Sea core fractures. The simulated fracture in each of the artificially fractured core was created by sawing the core in half and gently brushing away the residual matrix material. For the gas-displacing-oil experiments a 0.32 cm (1/8-inch) diameter hole was drilled down to the primary fracture in order to transfer the gas pressure to the fracture, and minimize viscous displacement in the upper matrix block.

For the artificially fractured cores, the 100 percent contact baseline cases were conducted with unscented, white facial tissue in the fracture between the matrix blocks to insure capillary continuity. The amount of contact between the inlet and outlet matrix blocks was controlled by the insertion of a thin plastic diaphragm between the matrix blocks after the core had been driven to a residual water saturation. The diaphragm was randomly filled with 0.16 cm (1/16-inch) diameter holes with a total area equal to the fractional area of contact desired for the particular experiment, 10% or 3%. Contact between the matrix blocks was maintained by placing a tissue on both sides of the diaphragm and allowing it to fill the holes. The individual matrix blocks were held together by heat shrink tubing, allowing the blocks to be easily separated for insertion or changing the diaphragm.

North Sea Reservoir Chalk
Two whole North Sea cores, each 6.6 cm in diameter and measuring 15.8 and 23.5 cm in length, were used to maximize the volume of core material investigated. Permeability, porosity, and residual water are presented in **Table 1**. A schematic drawing illustrating the general orientation of the natural fractures is presented in **Figure 1(a)**.

Description of Fluids
The fluids utilized for the flow experiments were as follows: decane as the hydrocarbon phase, nitrogen as the gas phase, and deionized water or heavy water (deuterium oxide or D_2O) as the water phase. The use of pure fluids eliminated extraction, and it's potential damage, and expedited the experiment schedule by allowing simple drying to return the cores to their initial dry state. The use of heavy water simplified the interpretation process when using the MRI, since only the decane signal was evident. Residual water was attained by flowing multiple pore volumes of decane through a 100 percent water saturated core. Residual water saturations, Swi in **Tables 2 and 3**, were very reproducible. During all displacement experiments, the core sample was subjected to a confining pressure of 10300 kPa (1500 psi).

Laboratory Flow Methodology
Similar laboratory flow apparatuses were used for the gas-displacing-oil and the water-displacing-oil experiments. These were simple Hassler-type assemblies traditionally used for unsteady-state relative permeability measurements. Confining pressure of 10300 kPa (1500 psi) was maintained by a nitrogen cap exerted on water surrounding the core assembly within the test cell. A constant pressure differential, 147 kPa (20 psi) for the Niobrara chalk and 103 kPa (15 psi) for the North Sea chalk, was maintained across the core for the gas/oil displacements. The water/oil displacements were subjected to a constant water injection rate of 5.4 cc/hr for Niobrara and 7.2 cc/hr for North Sea. The water/oil system was designed so that the produced water (D_2O) was filtered and re-injected into the core to minimize cost.

Upon completion of a displacement experiment, the artificially fractured cores were oven dried. The two halves of the dried core were then assembled, without a diaphragm, re-saturated with heavy water and driven to residual water by oil flooding the core. The two halves were then refitted with the next diaphragm containing a lower contact area and the desaturation experiment repeated.

Magnetic Resonance Imager Description
Magnetic resonance imaging, MRI, was performed with a SISCO 85/310 CSI imager. It has a 31 cm bore 2 Tesla magnet and operates at 85.55 MHz for hydrogen protons. A 9 cm internal diameter saddle coil was used as both transmitting and receiving coil. Signals from hydrogen protons were obtained with a spin-echo Hahn sequence at an echo time of 6.2 ms and a recovery time of 2500 ms. Five slices, each 2.3 mm thick, were obtained parallel to the cylindrical axis of the core. This orientation produced rectangular images. The field of view was 16 cm by 8 cm with each pixel 0.556 mm by 0.625 mm.

The stainless steel end pieces used in the Hassler pressure cell had to be removed prior to imaging to prevent image distortion mass. Nylon end pieces were used in the last tests to minimize potential damage to the core caused by removing and replacing the standard metallic end pieces. The nylon end pieces permitted imaging of the intact core assembly at various levels of desaturation, as opposed to imaging only the initial and final saturation distributions.

Experimental Results

Gas Displacing Hydrocarbon - Niobrara Outcrop Chalk
Desaturation was driven by a constant nitrogen pressure of 147 kPa (20 psi). The hydrocarbon production data, summarized in **Table 2**, showed that restricting the contact area reduced the total hydrocarbon production. The cumulative production curves in **Figure 2** show that the early rate of production increased with decreasing contact area. However, the rate of production fell off sooner for the lower contact areas than did the 100% contact area. MRI images at the end of the experiment, **Figure 3**, showed that at 100% contact the residual hydrocarbon was fairly uniformly distributed through the core. At 10% and 3% the hydrocarbon was selectively bypassed in the inlet block, while the outlet block showed a saturation similar to that observed in the 100% contact experiment. No banking of the hydrocarbon, equivalent to an end effect, was observed on the upstream side of the fracture in any of the experiments.

Gas Displacing Hydrocarbon - North Sea Reservoir Chalk
The final hydrocarbon production is given in **Table 2**. The displacement gas pressure was 103 kPa (15 psi), and was later increased to 207 kPa (30 psi) to approach the true residual oil saturation. However, no significant quantities of oil were produced at the increased pressure. This phenomena appeared to indicate that residual hydrocarbon saturation had been reached at the lower pressure. The cumulative hydrocarbon production shown in **Figure 2**, overlays the cumulative production of the artificially fractured Niobrara core at 100% contact.

MRI images after gas displacement, in **Figure 4**, indicated a fairly uniform saturation within the matrix above and below the fracture. However, a bright streak, indicative of higher hydrocarbon saturation, was located adjacent to the primary fracture. It appears that this feature was not as readily desaturated as the surrounding bulk matrix.

Water Displacing Hydrocarbon - Niobrara Outcrop Chalk
Desaturation was produced by water injected at a constant rate of 5.4 cc/hr. The hydrocarbon production data, summarized in **Table 3**, demonstrated no detectable effect of contact area on hydrocarbon production. The variation in produced hydrocarbon is probably indicative of experimental error. The cumulative production curves in **Figure 5** are very similar. MRI images at the end of the experiment, **Figure 6**, showed uniform distribution of residual oil for all three contact areas. No banking of the hydrocarbon, i.e. end effect, was observed on the upstream side of the fracture in any of the experiments.

Water Displacing Hydrocarbon - North Sea Reservoir Chalk
The ultimate hydrocarbon production is given in **Table 3**. The water injection rate was later increased to determine if residual oil saturation had been achieved. The lack of any additional hydrocarbon production indicated true residual oil saturation was reached. The cumulative hydrocarbon production, shown in **Figure 5**, is within the range of the cumulative production data observed with the artificially fractured core experiments.

MRI images of the core after testing, **Figure 7**, indicated a relatively uniform distribution of the residual oil above and below the primary fracture, with no distinct indications of an end effect adjacent to the fracture. A slightly lower decane saturation along the length of the natural fracture appeared to be evident. This observation may be attributable to the injected water channeling along the fracture due to the increased flow conductivity resulting from the presence of the fracture.

Discussion of Results

Gas-Displacing-Hydrocarbon Experiments

The effect of contact area, or capillary continuity, on the production profiles obtained from the Niobrara outcrop chalk experiments are shown in **Figure 2**. At the termination of each experiment, oil was still being produced, however, at very low rates of approximately 0.2 cc/day (0.0042 %PV/hr). A summary of the production data in **Table 2**, demonstrates the consistent reproducibility of initial conditions, as well as the effect of contact area. The brighter appearance observed in the inlet matrix block upon gas desaturation, illustrated in the MRI images in **Figure 3**, indicates that reduced physical contact between the blocks restricted the movement of hydrocarbon from the inlet matrix block. The outlet matrix block in this experiment had the appearance similar to the 100% contact area experiment. The early time production data for the reduced contact experiments actually exceeded the production rate of the 100 percent contact baseline, inset in **Figure 2**. A similar observation was observed by Labastie (Ref. 5) during a capillary continuity study. A comparison of the production data from the naturally fractured North Sea core sample, with the results from the Niobrara chalk experiments, is shown in **Figure 2** and the end point data is summarized in **Table 2**. The behavior observed between the naturally fractured North Sea core experiment and the 100 percent contact Niobrara chalk core experiment were very similar, and match for all but the earliest data. The MRI images, which show a uniform hydrocarbon saturation in the matrix adjacent to the fracture, corroborate this conclusion.

The North Sea chalk was observed to be more compressive than the Niobrara outcrop chalk when the cores were subjected to the 10300 kPa (1500 psi) confining pressure. After applying the confining pressure, the core samples were equilibrated for at least 24 hours. Typically the North Sea cores expelled up to 12 cc of fluid (approximately 4 % PV) during the 24 hour time period from the compression of pore volume by the confining pressure. The volume expelled was dependent upon the bulk volume and pore volume of the sample investigated. However, the Niobrara outcrop chalk yielded only about 3 cc of fluid (approximately 2% PV) under the same circumstances. The higher compressibility of the North Sea chalk may have effectively sealed the natural fractures in the sample. This is one potential explanation for the naturally fractured North Sea sample consistently behaving as a non-fractured sample or 100 percent capillary continuity.

The strong saturation gradient that was observed adjacent to the primary fracture in the North Sea chalk, was again apparent during a second experiment utilizing stepped pressures. Analysis suggested that this feature was most likely a gouge-filled fracture composed of finely ground chalk that was produced by slip along the fracture plane. Cementation in this fracture would explain why the matrix blocks remained intact and did not break apart everywhere along the fracture. The finer pore geometry resulting from the ground and reprecipitated chalk material may have yielded higher capillary characteristics along this feature. This is one potential explanation as to why the higher fluid saturation remained along this feature, while the bulk matrix adjacent to the feature was produced to a lower residual saturation. MRI proved to be a valuable tool in identifying these internal structures that were not readily visible from the surface examination of a core.

Water-Displacing-Hydrocarbon Experiments

The Niobrara outcrop sample utilized in the water displacing hydrocarbon chalk experiments produced from 63 to 66 percent of the OOIP for the three fractional contact areas investigated. There did not appear to be a systematic ordering of the final recoveries that could be attributable to the altered contact area between the individual matrix blocks. Even the lowest amount of contact, 3 percent, appeared to be adequate for viscous forces to drive the oil across the natural fracture(s) contained within the core. The variance in the observed recoveries appears to be within the realm of experimental error associated with repeating the displacement experiments on the same sample.

The lack of a detectable effect of contact area on the hydrocarbon production implies that the sweep efficiency, especially through the inlet matrix block, is much greater with water as the driving force than with gas. The similar intensity distribution of the inlet and outlet matrix blocks, evidenced in the MRI images in **Figure 6**, corroborates the production data. The more uniform recovery is attributable to the viscosity ratios for water/hydrocarbon being more similar compared to the gas/hydrocarbon viscosity ratios.

A comparison between the water desaturated Niobrara outcrop chalk experiment results and the naturally fractured North Sea experiment results is illustrated in **Figure 7.** This figure demonstrates oil recovery as a function of pore volumes injected, to normalize the data since a slightly different injection rate was utilized in the North Sea experiment. The Niobrara outcrop cores were subjected to increased injection rates and pressures but none of these procedures produced any additional oil. The final oil recovery from the displacement experiment conducted on the naturally fractured North Sea core was approximately 69 percent of the OOIP. This recovery value was consistent with the values observed in the Niobrara outcrop water/oil experiments. A summary of the production data for both the Niobrara outcrop experiments and the North Sea experiment are shown in **Table 3.** Since the ultimate recovery from the Niobrara experiments did not appear to be affected by the fractional area of contact in the systems investigated, it is not possible to imply which system the naturally fractured North Sea core was most similar to. The data appears to indicate that as long as even a minimal level of contact exists between matrix blocks, 3 percent for this investigation, viscous and/or imbibition forces will be able to drive the movable oil across the fracture(s).

Conclusions

Based upon observations resulting from this research, the following conclusions were drawn.

1. In gas-displacing-hydrocarbon outcrop chalk systems, the degree of capillary continuity (fractional contact area) between individual matrix blocks significantly affected the oil production profile and the ultimate oil recovery. The highest degree of capillary continuity yielded the greatest ultimate oil recovery of the systems investigated.

2. For the gas-displacing-hydrocarbon experiment, the naturally fractured North Sea sample exhibited fluid flow characteristics similar to the outcrop core sample with 100 percent capillary continuity.

3. In water-displacing-hydrocarbon outcrop chalk systems, the degree of capillary continuity (fractional contact area) between individual matrix blocks did not detectably affect the oil production profile, nor the ultimate oil recovery. The ultimate oil recovery appeared to be relatively independent of the degree of capillary continuity for the systems investigated.

4. For the water-displacing-hydrocarbon experiment, the naturally fractured North Sea sample exhibited fluid flow characteristics similar to all the outcrop chalk systems investigated.

5. Magnetic Resonance Imaging, MRI, is a valuable tool for determining local fluid distributions within core samples.

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Table 1 - General Properties of Chalk Core Samples

Core Material	Flow Test	Ko (md)	Porosity (% PV)	Swi (% PV)
Niobrara	Gas / Oil	1.0	32.4	17.2
Niobrara	Water / Oil	0.8	32.2	18.9
North Sea	Gas / Oil	2.26	45.5	20.2
North Sea	Water / Oil	1.04	34.9	19.3

Test Case	Soi (% PV)	Swi (% PV)	Sor (% PV)	Recovery (% OOIP)
Niobrara - 100% Contact	82.9	17.1	26.9	67.6
Niobrara - 10% Contact	82.5	17.5	37.6	54.2
Niobrara - 3% Contact	82.5	17.5	38.9	52.3
North Sea Chalk	80.1	19.8	25.3	67.8

Table 2 - Production Data from Gas / Oil Displacement Experiments

Test Case	Soi (% PV)	Swi (% PV)	Sor (% PV)	Recovery (% OOIP)
Niobrara - 100% Contact	81.3	18.7	28.7	64.7
Niobrara - 10% Contact	80.4	19.6	34.1	62.9
Niobrara - 3% Contact	83.4	16.6	29.1	65.1
North Sea Chalk	80.8	18.9	25.1	68.9

Table 3 - Production Data from Water / Oil Displacement Experiments

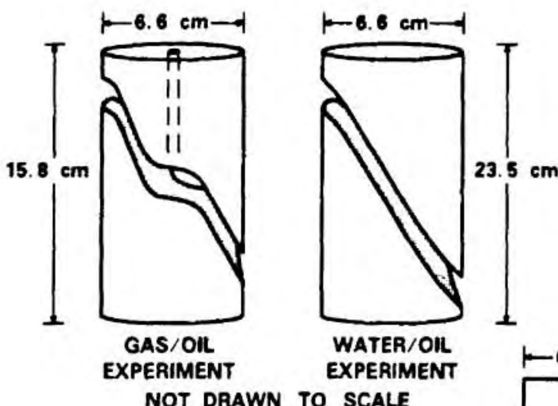

Figure 1a
Illustration of primary fracture orientation in North Sea chalk samples.

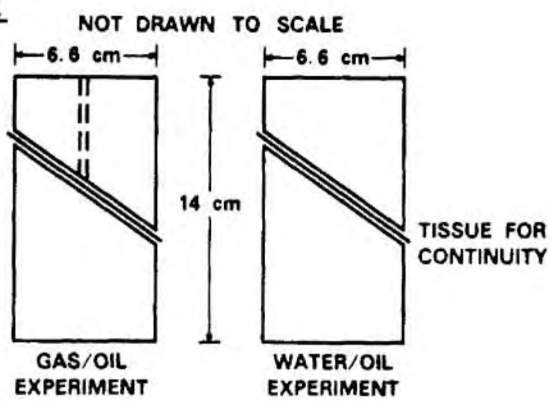

Figure 1b
Cross-sectional view of the configuration for Niobrara chalk samples.

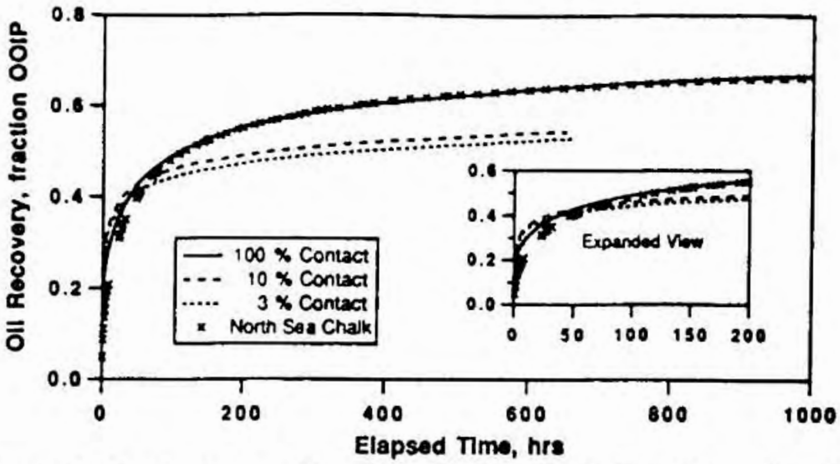

Figure 2 - Production profiles from the gas-displacing-oil experiments.

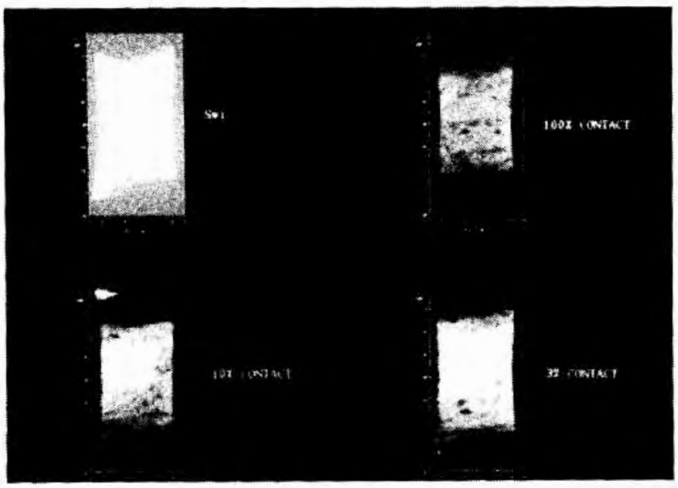

Figure 3 - MRI from gas-displacing-oil experiment in Niobrara Chalk as a function of contact area.

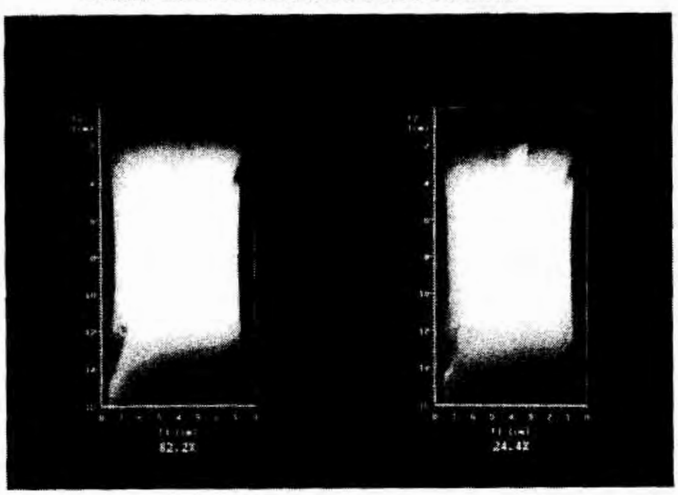

Figure 4 - MRI from gas-displacing-oil experiment in North Sea Chalk.

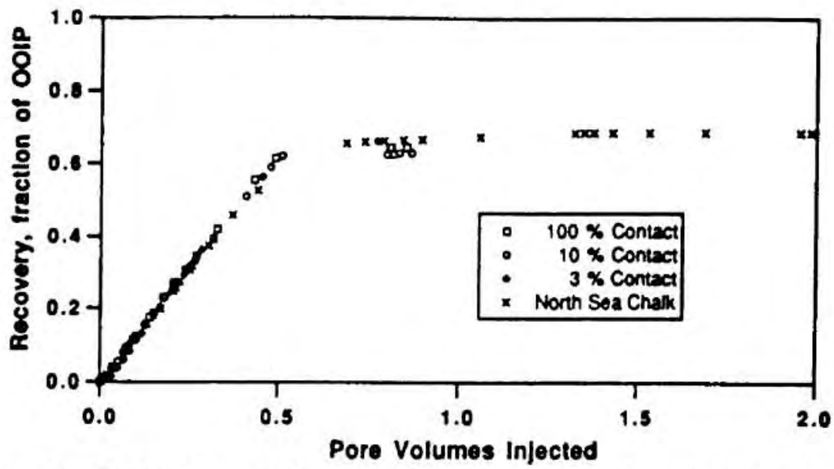

Figure 5 - Production profiles from the water-displacing-oil experiments

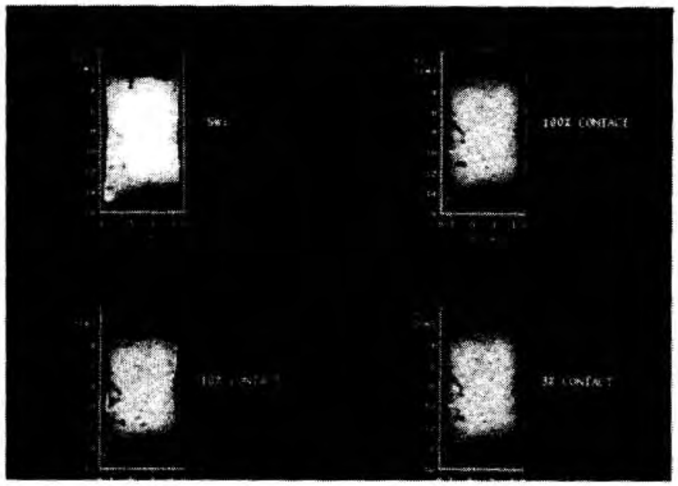

Figure 6 - MRI from water-displacing-oil experiment in Niobrara Chalk as a function of contact area.

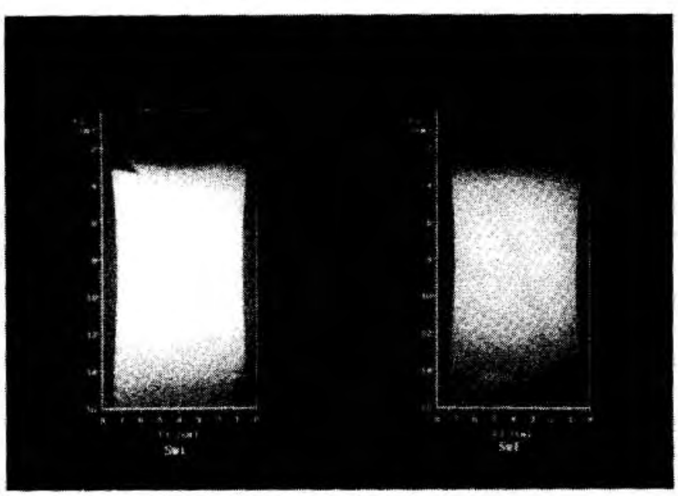

Figure 7 - MRI from water-displacing-oil experiment in North Sea Chalk.