TWO-DIMENSIONAL FLUID SATURATION IMAGING IMPROVES ESTIMATES OF OIL RECOVERY IN HETEROGENEOUS CARBONATES

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ABSTRACT

Until recently, interpretation of coreflood displacement tests relied upon the assumption that the process can be mathematically treated as essentially one-dimensional. However, this boundary condition is frequently violated due to the natural heterogeneity exhibited by many real reservoir rocks. Recent developments in the medical field in imaging technology adapted for use in the core laboratory have ameliorated the situation. Unfortunately, CT or MRI scanning technology is very expensive to acquire and maintain and thus remains out of reach for most researchers. Indeed, CT scanners have chiefly been used in core analysis purely to eliminate heterogeneous material from study.

A new system, based on two-dimensional imaging of slabbed core samples, has been developed which enables analysis of the spatial distribution of fluids at the whole core scale. This new apparatus determines fluid saturation non-invasively by exploiting the contrast in gamma attenuation coefficient between the fluids present in the pore space. The system features a special core holder made of advanced alloy materials, semi-transparent to gamma rays, capable of applying representative confining stresses. Robotic arms are used to scan the source/detector assembly around the vessel to provide a two-dimensional image during flooding.

The equipment has been developed at significantly lower cost than CT scanners and also has markedly lower maintenance costs. In addition, the instrument is compact and does not require specialised, costly housing arrangements. It thus renders feasible the acquisition of two-dimensional fluid saturation data during coreflood displacement testing at comparable cost to more traditional technology.

Initial research findings indicate substantial spatial variations in post-waterflood residual oil in heterogeneous material at the core scale. A number of Middle East carbonate core samples have been evaluated. The rock material studied features heterogeneity resulting from a variety of syn-depositional factors as well as subsequent diagenetic overprint: data for samples containing cemented natural fracture systems, a variety of fossiliferous material and rock fabric featuring both bioclastic and dissolution porosity are presented.

INTRODUCTION

Both gamma and X-ray attenuation are nowadays in widespread use to assist interpretation of coreflood experiments. However, with the exception of CT scanners, these systems assume rock homogeneity in at least two dimensions and are used chiefly to study end-effects in otherwise homogenous material.

Much of the natural heterogeneity in reservoirs may be reasonably approximated by two-dimensional models at the core scale: for example, material containing thin beds or cemented fractures. With this in mind, the authors sought to build a system based on existing nucleonic technology which could produce two-dimensional information about fluid saturation and porosity. It was decided to construct a system which could scan a slab of core material contained in a special flat "box" coreholder using a computer-controlled source / detector assembly moving in a planar locus. In this way two-dimensional maps of porosity or saturation may be produced.

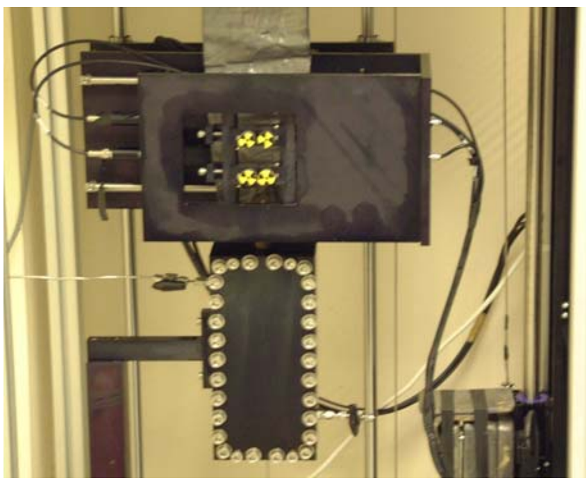

Figure1: Coreholder and Scanning Assembly

Figure 1 shows the specialised coreholder assembly which can house slabs up to 100 x 200 mm in size. The vessel is manufactured from advanced alloy material semi-transparent to gamma rays to maximise transmission. The source / detector assembly is an array of four 200 mCi gamma ray sources each with dedicated scintillation detector sandwiching the coreholder.

The basic equation relating gamma ray transmission to material thickness is as follows:

$$I / I_o = e^{-\mu x} \qquad (1)$$

where:

I_o = incident gamma ray countrate

I = transmitted gamma countrate

μ = attenuation co-efficient
X = material thickness

In the context of transmission through a flat slab of constant thickness, the logarithm of countrate at any point along the slab then forms a linear relationship with saturation and also porosity if the sample is saturated with a single fluid. Calibration of the linear relationships requires a minimum of two known points. For saturation this may be readily accomplished by forcing the saturation to the 100% extremes of oil and water. To measure porosity requires more subtlety since porosity cannot be altered as such, however two calibration points would usually be feasible to estimate as follows:

1. End-plattens may be fashioned which give a good approximation of the attenuation of zero porosity rock. The zero porosity point may also be measurable inside the slab directly if any part of the slab under examination is completely cemented.

2. The average porosity of a slab is trivial to independently determine. In conjunction with the other calibration point, linear co-efficients may be derived which match the independently derived average porosity with the average porosity from the attenuation data.

EXPERIMENTAL PROCEDURES

All of the samples tested were approximately the same size: 100 mm long by 50 mm and 10mm thick. The samples were loaded into the flat coreholder at some initial water saturation. A hydrostatic confining stress of 3000 psi was used for all samples. The samples were then flooded with kerosene at back-pressure to remove any remaining trapped air. A waterflood was performed at a flood rate of 1.5 ml/hr using brine doped with potassium bromide to improve the attenuation contrast. The samples were scanned throughout flooding to a pixel resolution of 4 mm square. The system can acquire a scan comprising approximately 300 pixels in about an hour. Flooding proceeded for a total throughput of around 25 ml. Upon completion of the waterflood, all of the samples were miscible solvent cleaned and calibration scans performed at the 100% saturation extremes. The 100% oil calibration was used in the calculation of the porosity maps.

RESULTS AND DISCUSSION

A total of four data sets are presented: three carbonate samples and a single clastic sample. Two of the three carbonate samples feature a single large heterogeneity of bioclastic origin. The third carbonate was tested in the preserved state and was expected to show a greater oil-wetting tendency than the other two. The single clastic sample contains a cemented fracture which runs across the slab and was thus expected to form a barrier to flow. Both a porosity contour map together with a photograph and saturation maps throughout flooding are presented for each sample in this section.

Sample 1 – Limestone (Peloidal Bioturbated Wackestone).

Description:- Several partially dissolved / replaced fossilised molluscan shell fragments are visible in various areas of the slab. Matrix is primarily partially recrystallised pelloidal material (microcrystalline, microporous micrite) together with variably dissolved (to form pores) or replaced (cemented) calcareous algal debris. The intensity and distribution of the microporosity is patchy, and broadly in line with the porosity distribution map, Figure 2.

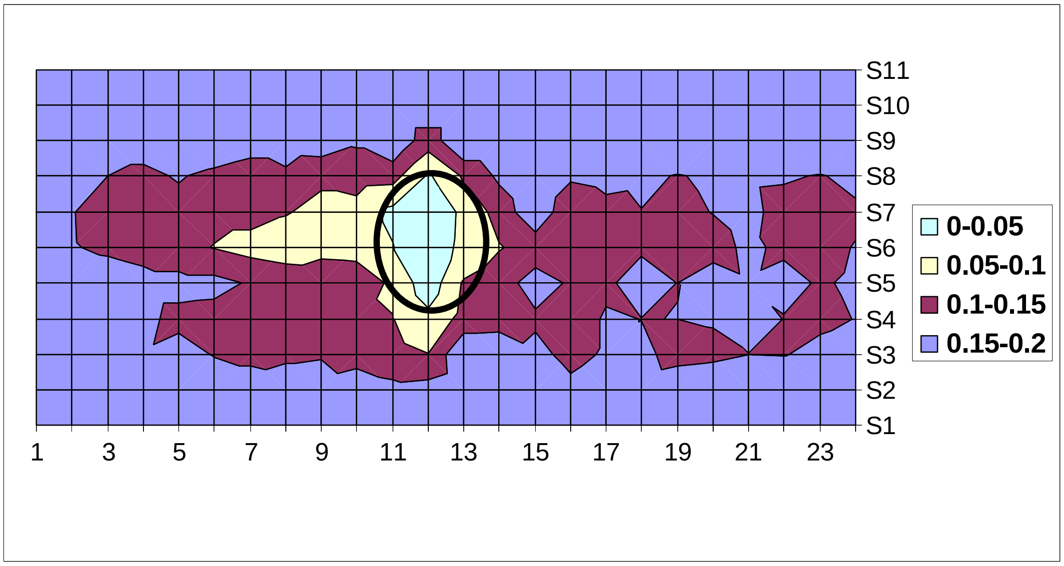

Figure 2 – Sample 1 Porosity Contour Map

Figure 3 – Sample 1 Core Photograph

The main feature of this sample is the cemented bioclastic fossil in the centre of the slab. The greatly reduced porosity in this region is clear in the porosity map of Figure 2, in which the fossil is also circled. It may also be noted that the porosity running along the centre of the long axis of the slab is significantly lower than toward the top and bottom, which had implications for the waterflood performance. For the purposes of porosity calibration, the pixel with the lowest gamma transmission was assumed to equate to zero porosity.

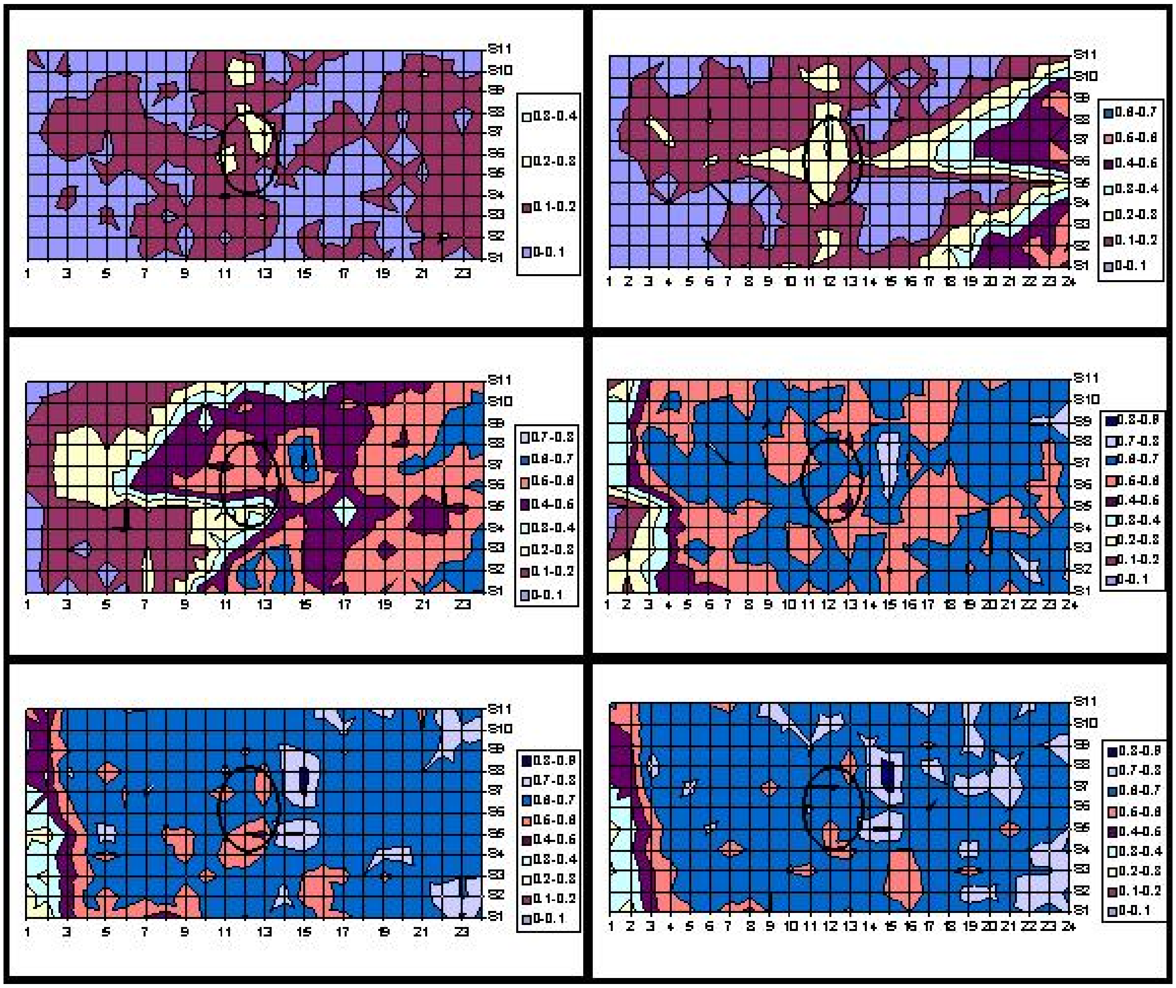

Figure 4 – Water Saturation Contour Maps – Sample 1.

The waterflood sequence for sample 1 is shown in Figure 4, running from top left to bottom right. This slab had been prepared by miscible solvent cleaning prior to acquisition of initial water saturation by porous plate. Connate water saturation was typically low but somewhat increased in the region of the cemented fossil. The seemingly strong bifurcation of the flood front appears to relate to the lower porosity in this region of the slab. There appeared to be an area of relatively poor recovery just in front the central bioclast shortly after the passage of the flood, but towards the end of the flood a region in front of the fossil clearly exhibited the lowest remaining oil saturation. This could relate to the injected water having to flow round the obstruction causing a locally increased flowrate. An oil-wetting drainage end-effect is also clearly present at the outlet end of the sample, despite the cleaning procedure used.

Sample 2 – Limestone (Peloidal Bioturbated Wackestone).
Description:- Partially cemented fossilised molluscan shell fragment, top right, with remainder of slab variably porous and permeable, linked to the degree and distribution of matrix recrystallisation, dissolution / replacement of calcareous algae, and also probable bedded fabric (notably parallel to long axis of the sample).

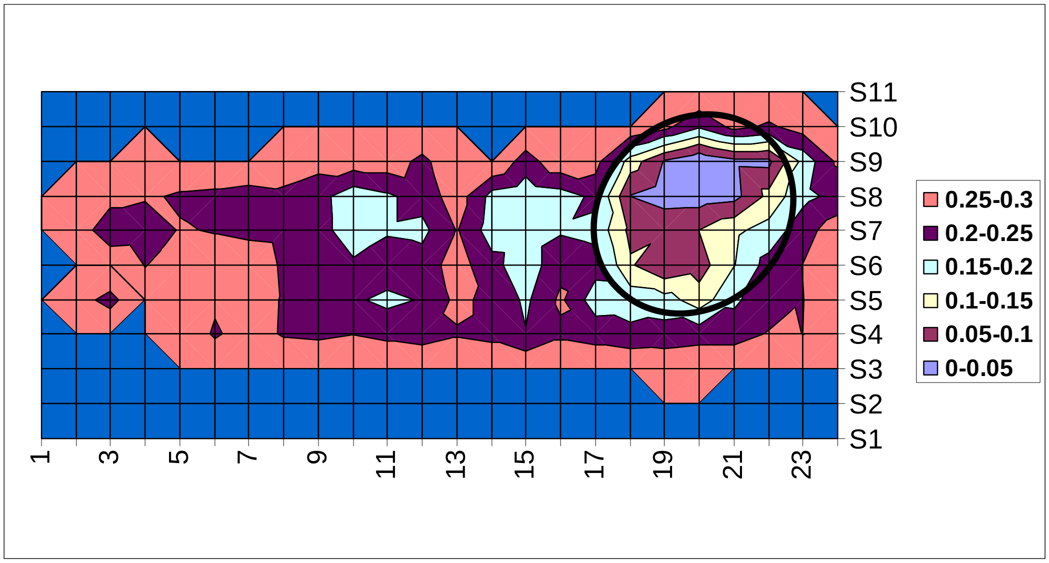

Figure 5 – Sample 2 Porosity Contour Map

Figure 6 – Sample 2 Core Photograph

The cemented fossil in the corner of the slab is clearly visible in the porosity contour map. However, this sample has been chamfered quite excessively (to protect the sleeve) which has resulted in a significantly artefacted calculated porosity at the top and bottom edges. Nonetheless, significant porosity heterogeneity is clearly present within the sample. As with sample 1, the lowest transmission seen was used as a zero porosity calibration point.

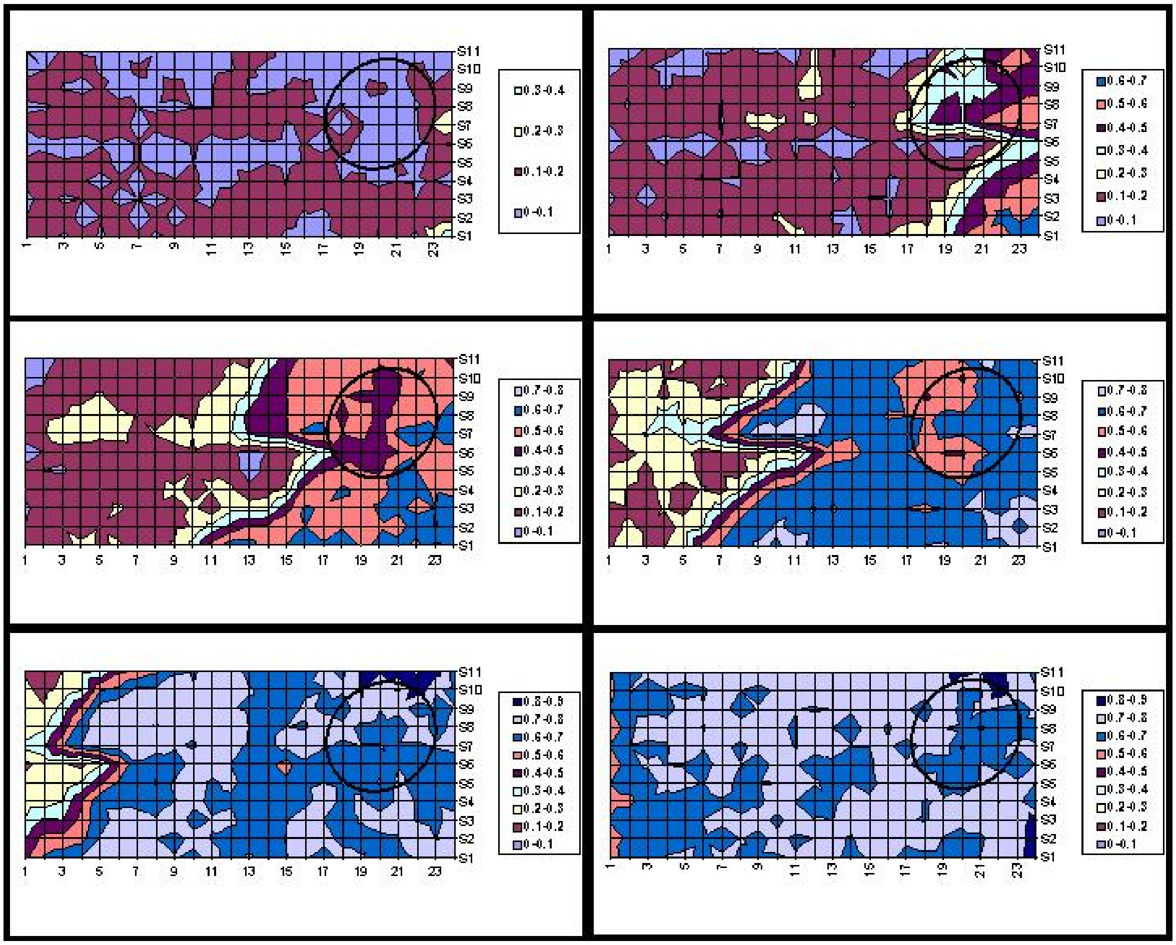

Figure 7 – Water Saturation Contour Maps – Sample 2.

The waterflood sequence for sample 2 is shown in Figure 7, running from top left to bottom right as previously. This slab had also been prepared by miscible solvent cleaning prior to acquisition of initial water saturation by porous plate. Connate water saturation might reasonably be expected to be high in the region of the fossil, however water saturation calculation in very low porosity material is difficult due to both the very low contrast between phases compounded by the difficulty in flushing these areas to the saturation extremes. However this problem is confined to the lowest porosity areas. The third and fourth image show that the fossil disrupted oil production and initially created a zone of high remaining oil just behind the bioclast. However towards the end of the flood a region of very high water saturation appeared above the fossil, whilst the high residual oil patch vanished. This again suggests that water was being diverted by this obstacle. A more modest but still significant end-effect was present in this sample upon cessation of flooding.

Sample 3 – Limestone (**Bedded, Pelloidal Wackestone / Mudstone)**.
Description:- Sample exhibits distinct bedding, top right to bottom left, inclined at an angle of approximately 45 degrees. The right portion of the slab is a wackestone, with porosity linked to recrystallisation and dissolution / replacement of various fabrics, while the central, inclined bed is a significantly less porous and permeable calcareous mudstone, with stylolitic features and clay seams.

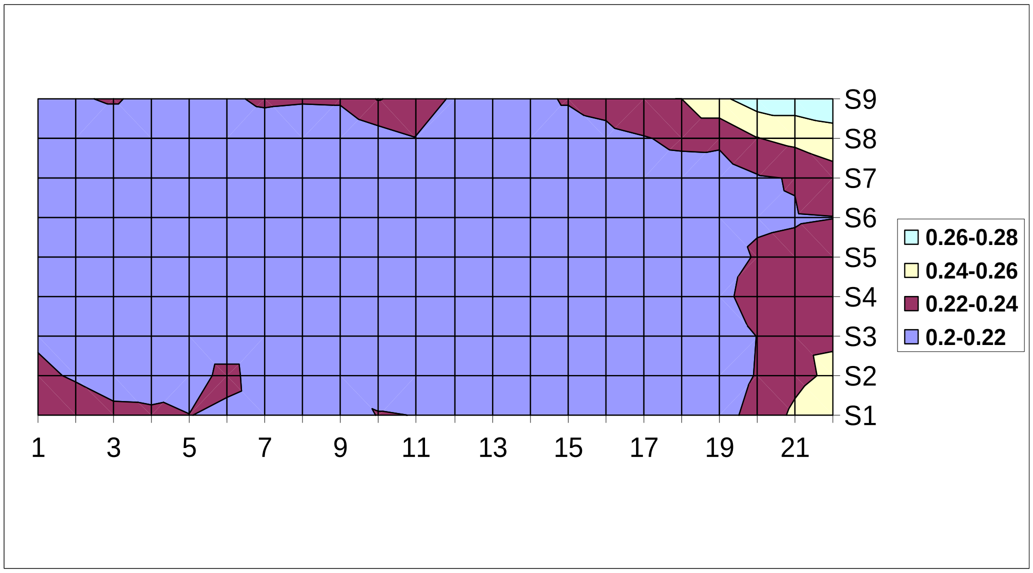

Figure 8 – Sample 3 Porosity Contour Map

Figure 9 – Sample 3 Core Photograph

This sample is a little more homogenous than the other two limestones featured in this paper. It nonetheless contains bedding running at approximately 45° to the long axis of the sample. Its other outstanding feature is that it was tested in the preserved state without cleaning, so more oil-wet behaviour during flooding was expected. The porosity map in this sample is also more approximate since no zero porosity calibration point was available. The map was nonetheless included since it suffices to show the relative homogeneity of the sample.

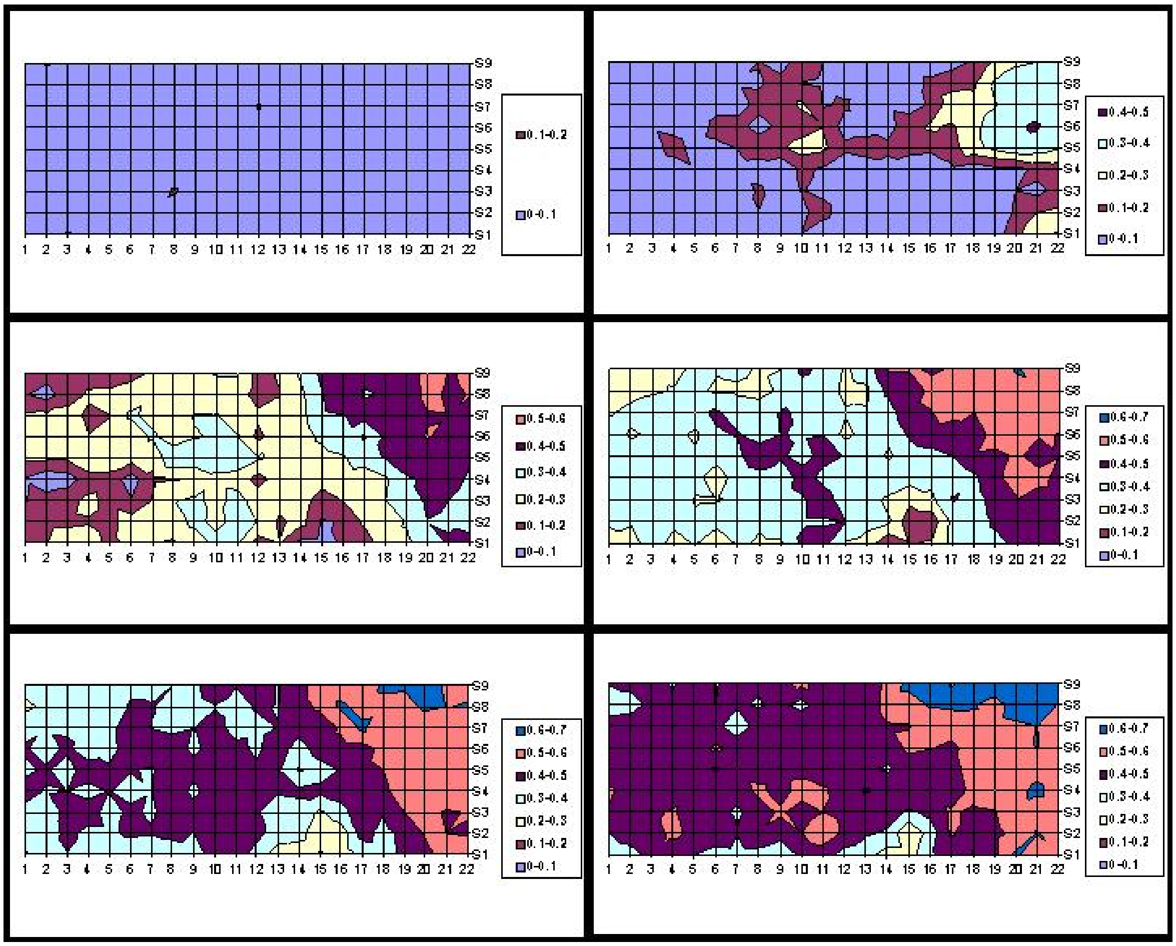

Figure 10 – Water Saturation Contour Maps – Sample 3.

This sample was tested in the preserved state. Remaining crude in the sample was displaced with refined oil prior to flooding. The waterflood sequence for sample 3 is presented in Figure 10. The front appeared to initially follow the better porosity material above the centreline of the long axis. However, a notable feature of the flood is the very strange fingering which is clearly evident in the second image and also the third at around the breakthrough time at the outlet end of the sample. The diagonal bed boundary visible in the core photograph is also evident throughout the life of the flood in terms of its impact on fluid saturation. These phenomena may relate to the strong oil wetting which was expected of this sample. Substantial stripping of oil along the length of the sample continued long after breakthrough together with a sizeable drainage end-effect, which are also characteristic of an oil wet system.

Sample 4 – Sandstone (Quartz Arenite).

Description:- Medium to coarse grained, moderately sorted, moderately rounded. Grains composed almost entirely of quartz, with minor clay matrix. The sample is crossed by a bifurcated fracture, which is completely filled with rock flour and clay materials. This filled fracture forms a lower permeability barrier to fluids flow. Additionally, slippage along the fracture has caused slightly more porous, coarser grained sandstones (left of slab) to be positioned at the same horizon as slightly finer, less porous sandstone unit (right of slab).

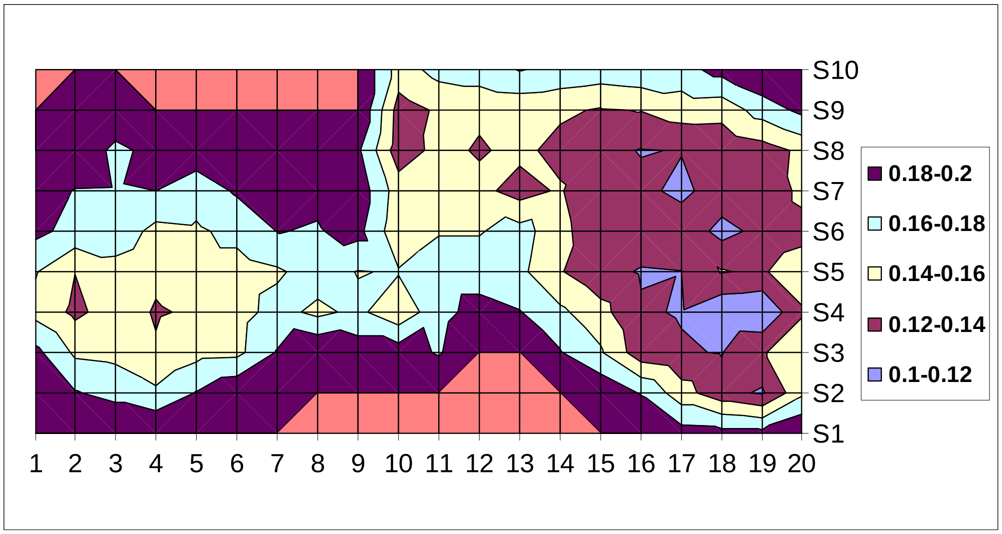

Figure 11 – Sample 4 Porosity Contour Map

Figure 12 – Sample 4 Core Photograph

In addition to the obvious cemented band running through the sample, this slab possesses very significant porosity heterogeneity either side of this feature which will translate into a large contrast in absolute permeability. At various points along the sample, a variability in the region of a factor of two in porosity clearly exists.

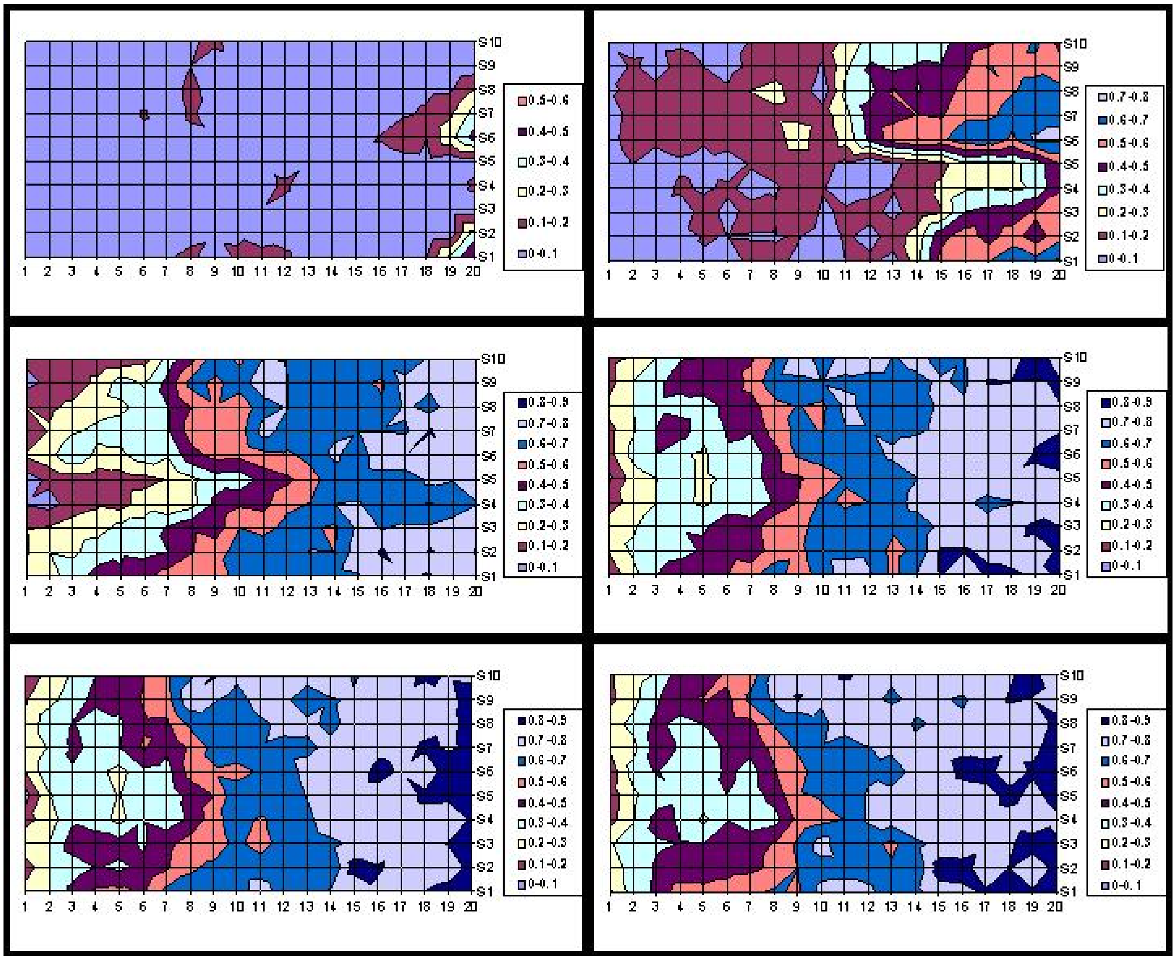

Figure 13 – Water Saturation Contour Maps – Sample 4.

The waterflood sequence for sample 4 is presented in Figure 13. This sample had been aged using dead crude oil after acquisition of initial water saturation in the cleaned state. The crude was displaced with refined oil prior to flooding. It seems that the cemented band in this sample was not the dominant factor controlling the flooding behaviour. Rather, the porosity heterogeneity in the upstream region disrupted the initial flood front, and forced the flood to circumnavigate this low porosity region. As the flood progressed, the lower porosity area downstream also came into play and created an island of higher residual oil than in the immediate locality. A strong gradient in residual oil also existed upon completion of flooding apparently due to the induced oil wetness from the ageing process.

CONCLUSIONS

1. The feasibility of producing a system with relatively low construction and maintenance cost for generating two-dimensional image data has been demonstrated.

2. Heterogeneities in core samples disrupt water flood fronts and can generate localised extremes in remaining oil saturation during displacement processes.

3. Two-dimensional monitoring of coreflood displacement test yields greater insight into the affect of heterogeneity than one-dimensional saturation profiling.

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