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New Analytical Techniques for Core Analysis of Fractured Reservoirs

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Abstract

Conventional laboratory techniques that assess reservoir permeability are constrained to using whole core samples or small diameter plugs. Cores that are recovered from structurally complex terrain often contain numerous vertical to sub-horizontal fractures throughout the recovered interval. Application of conventional laboratory tests commonly leads to permeability values that are invalidated due to the presence of the fractures. Where samples are of suitable quality for conventional tests, the resultant $\mathbf{K}_{\mathbf{max}}$ values may be skewed to reflect unfractured zones, thus excluding intervals of significant fracture development. Fractured intervals commonly contain significant volumes of hydrocarbons and form the main migration pathway for hydrocarbons to the wellbore.

New techniques using both a profile micro-permeameter (PDPK300™) and customized digital photography have been developed to allow the permeability of fractured reservoir rocks to be examined. Core samples are cut to produce a flat surface upon which the micro-permeameter tests are conducted. Using a small diameter probe, (4.7 mm), single point permeability values are measured on a regular grid spacing to produce an iso-permeability map for the core surface. Values for the rock matrix as well as the fractures and nearby boundary regions are measured. The results allow the contribution of matrix, fracture and boundary conditions to the overall sample permeability to be quantified.

Core samples are impregnated with fluorescing epoxy and examined under UV light source. A high resolution digital camera with a customized UV illumination allows detailed macro-images using emitted light to be produced for the same core surface. Variations in fluorescence across the core surface can be used to map differences in permeability. Low permeability, commonly the rock matrix, is represented by weakly fluorescing areas. In contrast, areas that are highly fractured and have high permeability values fluoresce more intensely due to the epoxy impregnation. Image analysis allows contribution of fractures, boundary conditions and matrix areas to be quantified.

Introduction

The measurement of permeability values of core samples from fractured sedimentary rocks using conventional core analytical techniques traditionally has been limited due to the physical condition of the core itself. Permeability measurements of the sample commonly reflect the rock matrix, and do not adequately express the contribution to the overall rock permeability of the fractures.

The Pressure Decay Profile Micropermeameter (PDPK300™) and UV imaging system, are two laboratory devices that have recently been used in an attempt to resolve the problem of fracture permeability recognition and to quantify the contribution of fracture porosity to overall rock and reservoir porosity and permeability.

This paper presents two new techniques to examine the relationship of fractures and permeability for several samples of fractured sandstone rocks of the Cardium Formation from the Alberta foothills. Results from the experiments indicate that a significant portion of the reservoir porosity and permeability may be attributed to the fracture system. Conventional core analytical techniques are unable to measure this component and hence tend to underestimate the overall reservoir properties.

Geological Setting and Definition of Problem

Samples were collected from the Conoco Mudge (2-6-48-19-W5M) and Conoco Banshee (13-14-46-18-W5M) wells. The cored intervals represent the highly fractured Cardium Sandstone (Ram Member), located structurally near the hinge of a" tight" plunging antiformal fold developed in the leading edge of the Canadian Foothills belt known as the "Triangle Zone". Triangle zones form at the outer limit of thrust and fold belts as the result of the emplacement of a wedge of sedimentary rocks along a delaminated horizon within unfaulted foreland basin strata (Price, 1981, 1986). This wedge was defined by Jones (1982), as being sandwiched between bounding thrust faults which are defined as the upper and lower detachments. In the foothills of Alberta, silici-clastic rocks are commonly faulted and folded leading to intense fracture development within the rocks. These rocks commonly display characteristics that suggest the reservoirs are "tight" with low permeability values, yet they can be prolific reservoirs due to the presence of a pervasive fracture system. These fractures not only contribute to the overall reservoir porosity but also provide the conduit to link what matrix porosity may be present. The problem that must be addressed is to develop laboratory techniques that can measure the contribution of the fracture system to the overall reservoir storage and producibility.

Fractured reservoirs have always presented a problem to reservoir geologists and engineers. The reservoir commonly contains significant volumes of hydrocarbons that cannot be explained by the results obtained from conventional porosity or permeability tests conducted on core samples. The main reason for this limitation is the methodology utilized in the laboratory test procedures.

Conventional core analytical techniques require intact core samples for either full diameter *Hassler Type* analyses or typical plug tests. In both cases the core must be intact to withstand the pressures used in the test procedures. Core samples that are friable or fractured are not used in the experiments as they do not withstand the pressure of the test procedures, or they provide an easy conduit for the test fluid to flow through and hence nullify the results. Data that are obtained from competent core samples commonly only reflect the unfractured component of the rock mass and the results tend to be skewed.

New analytical techniques allow broken and fractured samples to be used, particularly where full core samples are not possible. Preparing the core to produce a flat surface allows a wide variety of samples to be tested through different planes of orientation, thus reducing the possibility of skewing the sample data to reflect only non-fractured zones.

Sample Preparation

Initially each sample is laid out in a trough and embedded in a bed of quick set epoxy to eliminate any saw induced fractures during surface preparation. If the core has not been cut, the epoxy encompasses approximately one half of the core with the remaining portion lying above the level of epoxy. If the core has already been cut, the epoxy level is placed approximately 6 to 12 mm below the cut surface of the sample. This edge prevents the epoxy from wicking up the edges of the core and sealing off the surface to be analysed. Once the sample has been encased and the sample surface chosen (usually the cut surface, cut parallel to the core axis), the total area to be gridded is marked on the planar surface with the corner co-ordinates clearly defined. The sample is now ready for micro-permeability or digital imaging.

Micro-permeameter

The Pressure Decay Profile Micro-permeameter (PDPK300™) is a laboratory device developed by Core Laboratories Limited, that allows point permeability measurements to be made at selected interval, (Jones, 1992). Through the utilization of the profile micro-permeameter, the matrix contribution (K_{matrix}) can be accurately determined within the reservoir. In addition, due to the ease and speed with which the measurements can be made, it is feasible that an extremely high density permeability grid pattern be designed on a prepared, naturally fractured core segment. This procedure allows the recognition of permeability variations as the probe tip advances toward or away from the fracture.
To develop permeability profiles for slabbed core samples, a rectangular grid pattern was established over the surface area. Results from grid pattern experimentation revealed that optimum spacing of data points to reflect what is seen visually on the sample surface was a

square grid with spacing at 2.5 mm. Once the data has been collected, the values were imported into surface mapping software to produce a series of iso-permeability maps. Micro-permeability data are presented as an iso-permeability map and compared to the hand sample (Figure 1a and b). To allow quantification of the permeability values and accommodate the order of magnitude variation of measured values, (0.001mD to >1000 mD), the data were contoured using logarithmic values.

It can be seen that what appears to be a zone of permeability enhancement forming a boundary condition, is present surrounding most of the fractures present in the Mudge sample. This "halo" contributes significantly to the overall sample porosity providing enhanced hydrocarbon storage area. In addition, the halo zone produces an enhanced zone of permeability that would allow the hydrocarbons to flow to the wellbore.

Permeability values acquired through conventional core analyses as well as micro-permeameter for selected Mudge core samples are summarized in Table 1. It can be seen that the permeability values ($\mathbf{K}_{air\text{-}max}$), are widely variable, reflecting the presence of fractured and unfractured intervals. Full diameter samples commonly have permeability values that are believed to represent the interplay of a fracture during the testing procedure. In essence the test was nullified and the permeability value recorded reflects the permeability of the fracture itself and excludes that of the rock matrix. Five small plug samples were analyzed and consistently the permeability values obtained in the test were less than 1 mD for the $\boldsymbol{K}_{air\text{-}max}$. The actual physical condition of the core itself, (highly fractured and rubblized), tended to skew the sample interval from which small plugs could be drilled. These permeability results are therefore biased the other direction as they do not reflect the contribution of the fracture in conjunction with the matrix.

If the core were intact, the total permeability value obtained from conventional laboratory tests would represent contribution from three rock elements, $\mathbf{K}_{matrix}$, $\mathbf{K}_{fracture}$ and $\mathbf{K}_{halo}$. In contrast, using the PDPK300 (micro-permeameter) allows the permeability of the fracture, halo and matrix to be recorded independently. The contribution of each can then be calculated, ($\mathbf{K}_{total} = \mathbf{K}_{matrix} + \mathbf{K}_{fracture} + \mathbf{K}_{halo}$)

Using simple gridding methodology, the contributions of these components can be weighted accordingly for the sample area that more accurately reflects the contribution of the fracture and halo zone to the overall reservoir permeability.

Table 1

Kmax (mD) Measurements	Full Diameter Core	Small Plug	Micro-permeameter	Contribution % to Sample Area
high value	10240	0.99	3270	
low value	1.04	0.07	0.0574	
matrix	???	<1	0.05-0.576	76.8**
fracture	???	N.A.	728-3270	1.1**
halo	N.A.	N.A.	0.904-89	22.1**
average	Variable	0.53	32.16	

N.A. -- Not measurable
** Note: Contribution % to sample area is calculated from the image processing of the digital photography.

The average permeability value for the sample assumes that the fractures would have a permeability of 2000 mD and that the halo zone has an average permeability of 44.9 mD. These values will vary throughout the sample and so the final permeability number should be considered more as an approximation of order of magnitude rather than an accurate value for reservoir conditions. It must also be stated that the sample testing is performed at ambient conditions and that under reservoir pressures and temperatures, the actual reservoir permeability will probably be somewhat lower.

What is most significant of this comparison in not so much the actual reservoir permeability number, but rather the order of magnitude difference that occurs when the contribution of the fractures and the halo zone are included. This dramatic increase in reservoir permeability may explain the prolific production of natural gas from the Mudge well that cannot be explained through normal core analyses.

Digital Photography

After micro-permeameter work is complete, impregnation with fluorescing epoxy/dye mixture can proceed. Spurr low viscosity embedding media mixed with commonly available Rhodamine B dye is degassed in a vacuum dessicator. The samples are placed in a semi-cylindrical trough and immersed in the degassed mixture. The trough is inserted into a stainless steel vacuum bomb, kept under a vacuum of 26 inches of mercury for two hours, and placed in an oven for curing at 50° - 70° / C. The advantage of Spurr media, is that curing does not begin until the application of heat, so that during the period that the vacuum is applied, low viscosity of the epoxy is maintained to allow maximum impregnation. Once cured, the samples are trimmed to working dimensions and polished using conventional lapping techniques.

Digital images are made of the sample surface under high intensity UV light conditions. A customized stand was fabricated to allow macro-scale digital imaging of the sample surface using a UV illumination and filtration set up commonly used in fluorescence microscopy of Rhodamine impregnated preparations. A standard HBO 100 light source conventionally used in fluorescence microscopy was mounted on the stand, which also allowed a 425 nm. Excitation filter to be inserted into a filter pocket in front of the bulb. A 460 nm. Emission filter was then mounted on the camera, completing the replication of the Rhodamine illumination conditions. The resulting digital images are shown in Figure 2. Areas within the sample that are porous have been impregnated with the low viscosity epoxy and fluoresce brightly. Non porous "tight" areas have not accepted epoxy and show little fluorescence. Processing of the digital images allows fluorescent thresholds representative of matrix, fracture and boundary condition to be defined. Using image analysis, surface areas are calculated and the contribution of the fractures and boundary conditions to the overall sample area is determined. While the area does not indicate the overall reservoir permeability, some conclusions can be drawn about the overall reservoir storage and potential producibility.

For the Mudge and Banshee well bores, digital camera images were created that are believed to be representative of the degree of fracture development in the core intervals. (Figure 2a and b). In the Mudge sample, the major fractures are widespread and appear to have several subsidiary fractures bifurcating from the major fracture planes. Surrounding each fracture is a boundary condition halo that appears to have a higher degree of matrix porosity than the remaining sandstone matrix. This halo is relatively constant in width along the fracture length suggesting some form of reservoir fluid has reacted with the matrix material to enhance the fracture zone and produce a broad band of high permeability. In contrast, the fractures of the Banshee well are more open than Mudge but do not display any boundary or halo effects.

Image processing allows the areas of contribution of the matrix, fracture and halo to be quantified for the sample area. In both samples, the average contribution of the fractures is less than 2% of the entire sample area. The major difference can be seen in the contribution of the halo zone. In the Mudge sample, the halo constitutes 22.1% of the sample area, whereas in Banshee, the halo is 2.1%. The rock matrix constitutes the remainder of the sample area. This large contribution of halo zone may explain the producibility differential between the two wells. The Mudge well flows at a rate of 10 times greater than the Banshee well. Porosity measurements made on the sandstone matrix material indicate a range of 6-7%. In the productive wells such as Mudge, the halo zone provides the primary hydrocarbon storage regions as well as enhanced reservoir permeability for fluid migration.

Comparison of Techniques

A comparison of the two new analytical techniques reveals an excellent correlation between fracture distribution and both high values of permeability measured from the micro-permeameter and fluorescing zones from digital photography. Both techniques appear to map the fracture distribution accurately. The one advantage the profile micro-permeameter technique has over the digital camera image method is that actual permeability numbers are generated. Caution must be exercised when using these values however, as the core analysis is not completed under reservoir conditions. The core permeability values are measured at ambient conditions with no surrounding reservoir or overburden pressures, and the actual permeability value measured is Kair-max and does not take into account factors such as water saturation. The values and graphic maps produced from the analyses are best used for qualitative analyses to compare different styles of fracture development and the propensity of the fractures as they relate to variations in lithotype and structural setting.

The major advantage of the digital camera image technology is the relative ease and low cost to acquire the images, and the option of enhancing or focusing on specific areas of interest. Petrographic thin sections can be produced from the exact surface imaged. Using a confocal laser microscope, digital image areas can be examined in great detail at a variety of magnifications without altering or destroying the thin section. Petrographic features such as micro-fracturing associated with the halo zone, dissolution features, overgrowths and drill fluid invasion are easily recognized in the digital image, but are not available in the micro-permeameter data, (Figure 3).

CONCLUSIONS

Profile micro-permeameter and digital camera imaging analytical techniques were applied to several core samples from fractured Cretaceous age sandstone reservoirs from the foothills region of western Alberta. Results from initial tests indicate that these techniques provide the geologist with an increased ability to assess the geological and reservoir properties of the rock mass. Fractures within the rock mass and their relationship towards enhancing the hydrocarbon storage potential and reservoir characteristics can be observed. Application of these techniques will enable a more accurate assessment of the true potential and producibility of fractured reservoirs to be made. Current ongoing research studies are examining the application of these analytical techniques to fractured carbonate reservoirs.

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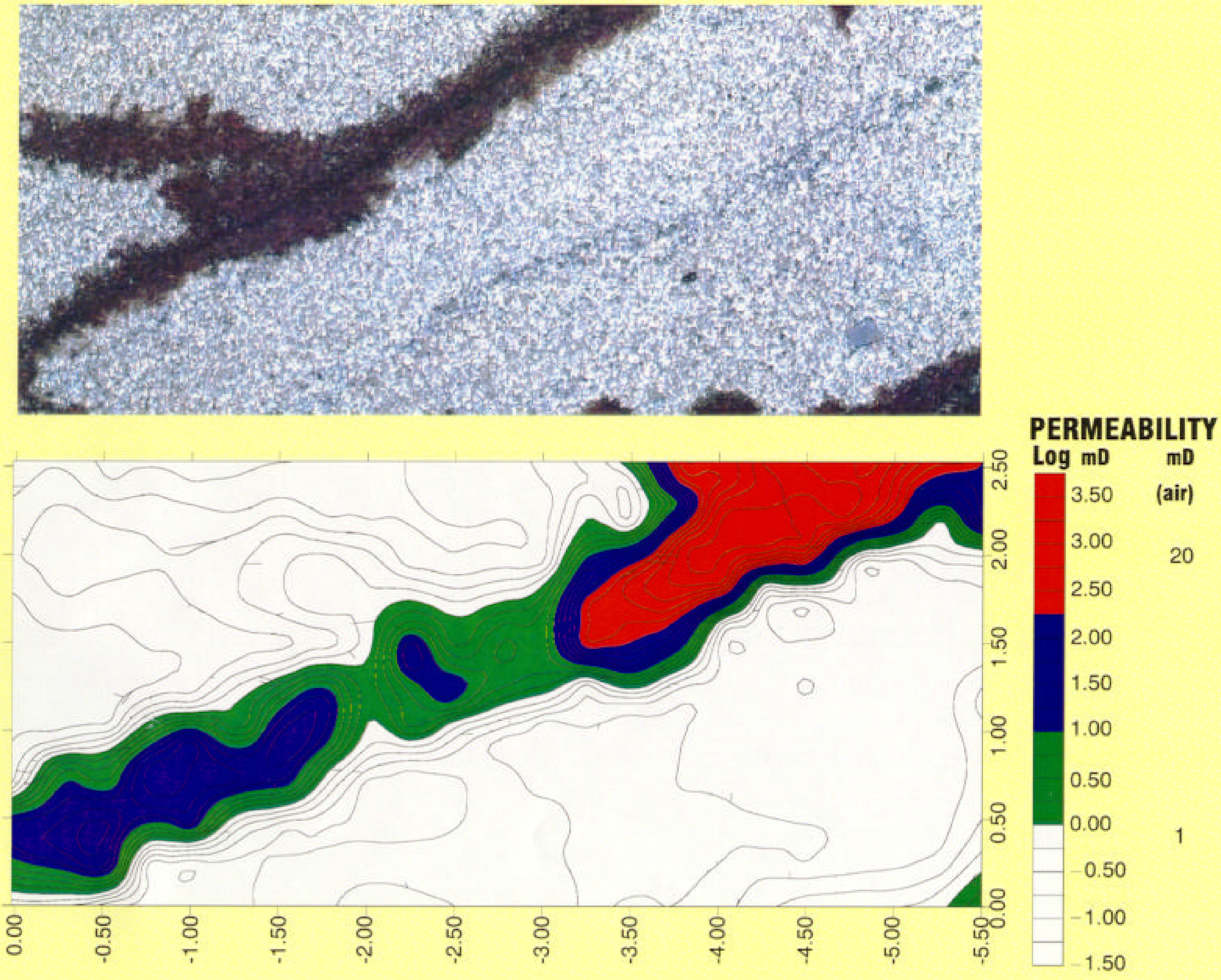

Figure 1: Comparison of iso-permeability gridded surface map to actual scanned image of hand sample.

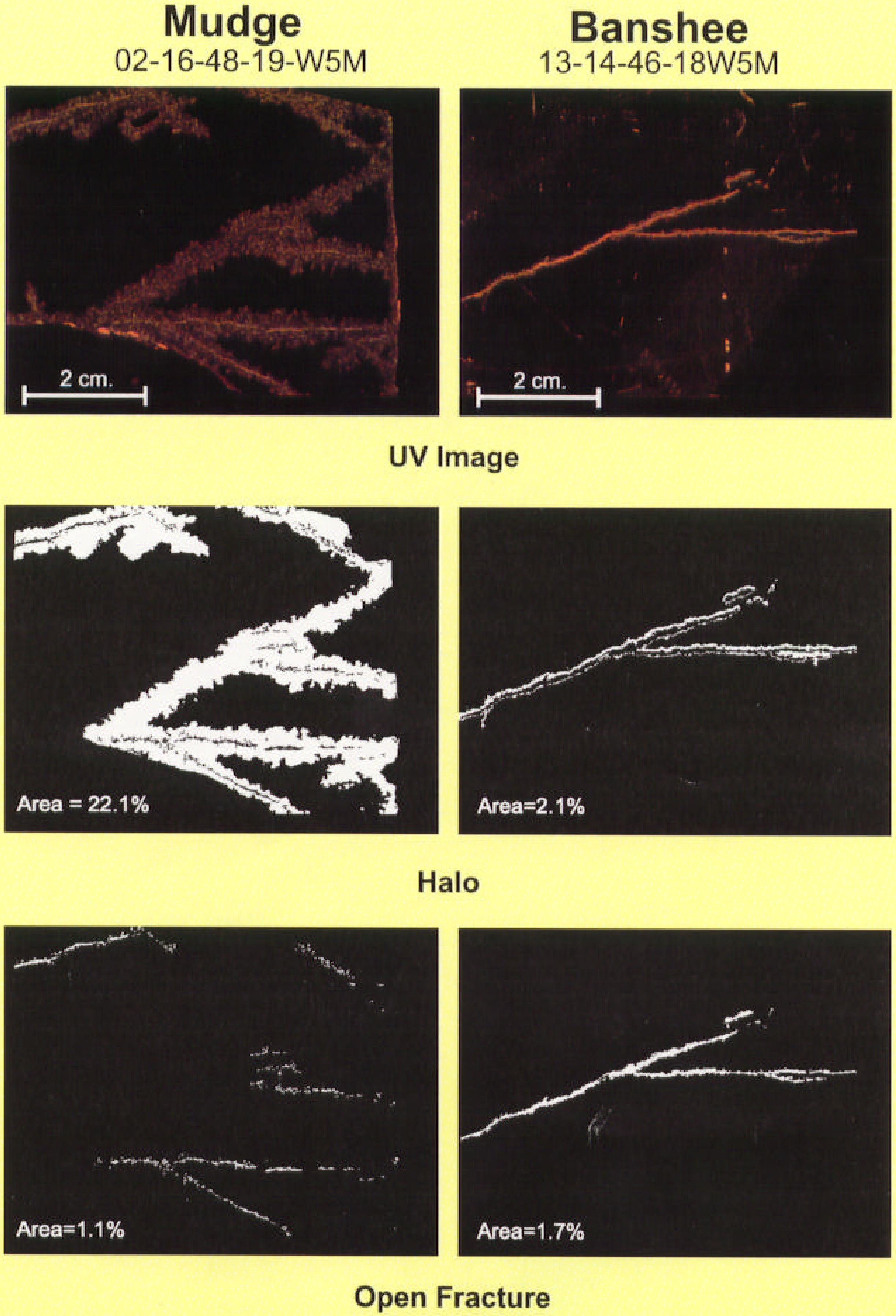

Figure 2: Comparison of digital images for the Mudge and Banshee wells, illustrating the contribution to the halo and open fractures to the overall reservoir porosity and permeability.

Figure 3: Digital camera image illustrating the invasion of drilling fluid into the micro fractures for the Mudge sample.