Invited Lecture

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PETROGRAPHIC IMAGE ANALYSIS FOR PREDICTION OF PETROPHYSICAL PROPERTIES AND WATERFLOOD DISPLACEMENT EFFICIENCY: SOME MISSING LINKS

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Abstract

PIA is a method used to quantify the two dimensional aspects of pore geometry comprehensively and rapidly and, using statistical techniques, to identify those pore types or attributes which are the best predictors of petrophysical properties of interest. Pore types, once identified, are used to predict petrophysical properties where core test data are not available.

PIA provides the most effective method available for understanding how specific rock-pore attributes affect fluid flow and displacement processes. PIA also has applications in predicting petrophysical properties of interest in samples too small for conventional core testing, for example drill cuttings or core rubble.

This presentation is restricted to a review of the applications of PIA to prediction of porosity, permeability, drainage capillary pressure, initial water saturation (Swi) and waterflood residual oil saturation (Sor).

Throat sizes cannot be identified or measured on 2-d surfaces through porous rocks and, since permeability and drainage capillary pressure are primarily affected by throat size, it is surprising that these properties can be successfully estimated by PIA. Part of the explanation rests with the pervasive correlation between pore sizes and connecting throat sizes in porous rocks. The reasons for these relationships are not yet understood.

PIA results indicate that specific size and shape characteristics of pore types have strong effects on permeability, drainage capillary pressure, Swi and Sor and that the necessary information to predict these properties is contained on 2-d sections of reservoir rock.

Introduction

The objective of this review is to illustrate how Petrographic Image Analysis (PIA) can be used to identify the link between rock-pore properties and petrophysical properties and to show how this information contributes to reservoir evaluation and production strategies.

PIA is a method used to quantify the two dimensional (2-d) aspects of pore geometry comprehensively and rapidly and, using statistical techniques, to identify those pore attributes which are the best predictors of petrophysical properties of interest (Ehrlich et al., 1984). Critical pore attributes once identified are then used to predict petrophysical properties where core test data are not available. Properties include porosity, permeability (Yuan, 1990; Ehrlich et al., 1991; Coskun and Wardlaw, 1993; Ioannidis et al, 1996), drainage capillary pressure (McCreesh et al., 1991), electrical conductivity (formation factor) (Ehrlich, 1991), relative permeability (Giess and McGovern, 1993) and the critical end points Swi and Sor (Coskun et al. 1993; Coskun and Wardlaw, 1995 and 1996).

The method requires a "training set" of samples with known petrophysical properties and supplements but does not replace core testing.

The main applications of PIA are in estimating petrophysical properties in samples too small for conventional core testing, for example drill cuttings or core rubble, and in providing the most effective method available for understanding how specific rock-pore properties affect core test results. This reduces the "cookbook" aspects of core testing and optimizes the application of core tests to improve understanding and prediction of reservoir properties and performance.

This presentation is restricted to the applications of PIA to prediction of porosity (Φ), permeability (k), drainage capillary pressure (Pc), initial water saturation (Swi) and waterflood residual oil saturation (Sor). Porosity and Swi are required to predict oil in place, permeability is required to estimate fluid flow rates and residual oil saturation is required to estimate oil displacement efficiency and to make judgements concerning the benefits of tertiary recovery and/or infill drilling to recover residual or remaining (bypassed) oil.

Total recovery efficiecy following waterflooding (Re) is the product of microscopic displacement efficiency for water-contacted rock (De) and volumetric sweep efficiency (Vs):

$$Re = De * Vs$$

Since there is no independent method to determine Vs, it is calculated using Re, commonly estimated by decline curve extrapolation, and by knowing De from core tests or by other methods (Wyman, 1977).

Limitations of Core Tests

Applying the results of core tests to reservoir property and performance prediction commonly is restricted because:

1) replicate tests were not performed on the same sample and the precision of the measurement is not known

2) different test methods give different results which usually are unexplained and the most reliable method is not identified (Fig. 1). [1]

3) different rock samples tested using a single method have widely different test results which are not explained in terms of sample differences (Fig. 1)

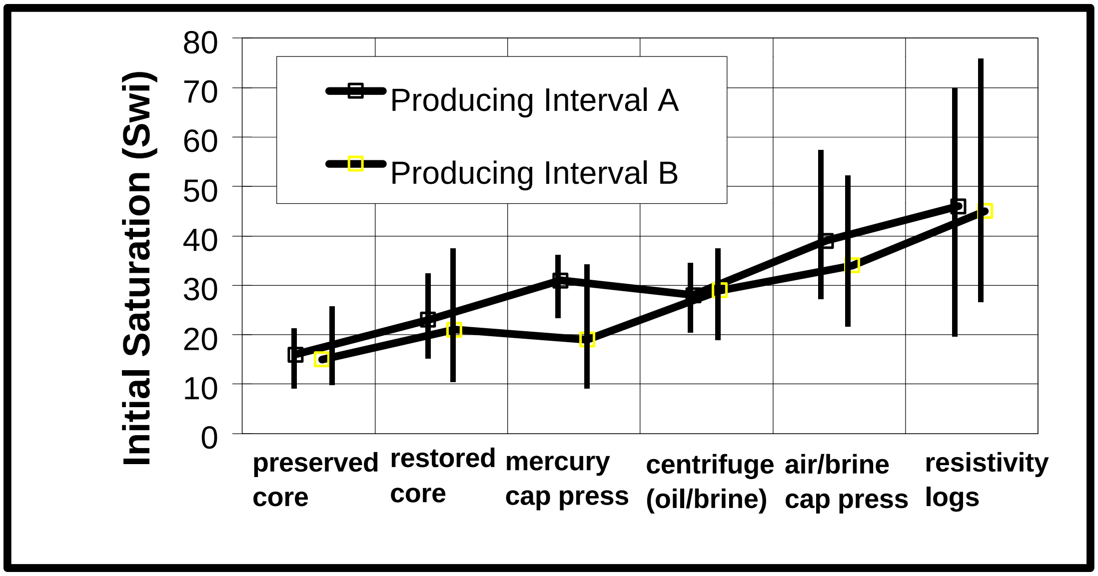

Figure 1. Initial water saturation determined by several methods on suites of samples from the same reservoir but from two different producing intervals. Samples from both intervals had approximately the same porosity and, in the case of the mercury capillary pressure, centrifuge and air-brine capillary pressure, were tested to similar maximum capillary pressures.

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[1] Melrose (1988) made a careful comparison of three of the methods represented in Fig. 1 (mercury capillary pressure, centrifuge and air/brine Pc (porous plate)) and found good agreement at the relatively low capillary pressures used here. The higher Swi for the air/brine method (Fig. 1) may be due to inadequate time for equilibrium in routine commercial tests of low permeability samples.

PIA, in providing a link between rock properties and test results, helps in understanding differences amongst samples (3 above) and allows extrapolation of core test results to untested regions of a reservoir.

Method of PIA Analysis

In 2-d slices of rock impregnated with colored epoxy, pore systems appear as discrete areas. These have been referred to as porosity elements or "porels" by Ehrlich et al. (1991). Although the porels are not connected in the plane of the section they must be connected in 3-d space in order to have been impregnated. The term porel has no implication that an area is either a pore (bulge) or throat (constriction) in the pore network although the chance that the section would pass through the plane of minimum cross section between two pores (ie. a throat) is negligible.

Using either an optical microscope or a scanning electron microscope (SEM) a digital image is obtained of all porels on a section. The porels are then subjected to iterative erosion-dilation cycles that probe their sizes and geometric complexities (Ehrlich et al, 1984). Frequency distributions for the components obtained during erosion-dilation (E-D) differencing can be used to deduce the number, shape, size and volumetric proportions of porels.

Classification of "pore types" is achieved using a pattern recognition algorithm of PIA (Ehrlich et al, 1991). In PIA, pore types are defined in terms of characteristic distributions of sizes and shapes of porels present. The classification procedure is based on Q-mode factor analysis using smooth and rough porel size distributions. The number of pore types represents compositionally the most distinct pores, in terms of size and shape, within the analysed samples and the pore structure of each sample is explained in terms of the proportions of these pore types. A detailed explanation of the porosity classification procedure and its theoretical basis can be found in Klovan and Miesch, (1976), Ehrlich et al. (1984, 1991) and Full et al (1981, 1982, 1984).

It is assumed that the number of pore types varies between samples and that the number of samples is larger than the number of pore types. Regression analysis is used to determine the importance of specific pore types as predictors of the petrophysical properties of interest McCreesh et al. (1991).

PIA Measurement of Porosity

Optical porosity is measured by dividing the total number of porel pixels (total porel area) by the total number of pixels in the scene and is termed the optical porosity. Porosity is a volume-fractional parameter, whereas porosity in a 2-d slice is an area-fractional parameter. Optical porosity can be used as an estimator of 3-d porosity assuming that the digitized area is representative of the sample, that the porosity is distributed isotropically (Underwood, 1970) and that the magnification allows resolution of the smallest pores of interest.

Pore-Throat Size Relationships and Estimation of Permeability by Mercury Porosimetry and PIA

Permeability is probably the single most important property of a reservoir rock and is best measured from core plugs or full diameter cores but, where only core fragments or drill cuttings are available, permeability can be estimated using mercury drainage capillary pressure curves or by using PIA methods.

PIA provides a means to identify the sub-set of porels which carry most of the flow. In unconsolidated sediments, these circuits have been referred to as loose packed domains and they are thought to be preferentially preserved during compaction and chemical diagenesis (Ehrlich et al., 1997).

Mercury porosimetry

The entry pressures on a mercury drainage capillary pressure curve are inversely proportional to throat diameters and, since permeability is proportional to the square of throat diameters, it is not surprising that mercury curves could be used to estimate permeability. This was demonstrated by Swanson (1981) and by Thomeer (1983). Swanson used porosity in combination with the coordinates of a unique point on a hyperbolic plot of the mercury curve to derive permeability.

PIA

Permeability-porosity correlation is strong for some rock suites and, in these cases, it is easy to understand how permeability might be predicted by PIA from porosity. Also, by using measurements of porosity in combination with surface area, which is related to porel perimeter, permeability can be calculated using the Kozeny-Carman equation (Ruzyla, 1986). This model assumes the porous medium to be equivalent to a conduit and does not consider the network properties of the medium or the presence of pores and throats.

However, permeability can be predicted by PIA without use of the Kozeny-Carmen equation with its assumptions and without requiring a strong correlation of permeability to porosity.

Since throat sizes cannot be identified or measured on 2-d surfaces through porous rocks and, since permeability is primarily a function of throat size, it is surprising that permeability can be successfully estimated by PIA in the absence of correlation with porosity. Part of the explanation rests with the pervasive correlation between pore sizes and connecting throat sizes in porous rocks. That is, larger pores are connected to larger throats and smaller pores to smaller throats. The reasons for these relationships are not yet understood but their occurrence makes possible the use of porel properties for estimation of throat sizes and properties such as permeability, drainage capillary pressure and electrical conductivity which are primarily affected by throat size.

Demonstration of this pore-throat size relationship was implicit in a pioneering study by Ehrlich and coworkers (McCreesh et al. 1991) who successfully used PIA to generate synthetic capillary pressure curves for different rock types.

Concurrently with this work, Li et al (1986) used computer simulations to generate drainage and imbibition capillary pressure curves for a variety of specified pore structures. The intent was to demonstrate the sensitivity of curve shapes to elements of the pore structure. This investigation revealed several differences in the form of capillary pressure curves for uncorrelated and correlated pore-throat structures (Wardlaw, 1990). Subsequently, similar features were identified on capillary pressure curves obtained from rock samples and were interpreted in terms of degree of pore-throat correlation. These interpretations were then confirmed by direct measurement of pore and connecting throat sizes in the same samples (Wardlaw et al, 1987). These studies provided proof that the sizes of pores and of connecting throats commonly are correlated in rock samples and provide a rationale for generating synthetic capillary pressure curves using PIA methods on 2-d surfaces.

Works by Brumfield (1988), Etris (1991), McCreesh et al. (1991) and Ehrlich et al. (1991) have combined two dimensional pore geometrical data with mercury injection curves in order to relate throat size and pore size distributions. These workers then estimated permeability by using pore and throat size distributions in a modified version of the Hagen-Poiseuille equation. Although these models allow useful prediction of permeability, they require experimental measurement by mercury intrusion porosimetry, which is expensive and time consuming.

Coskun and Wardlaw (1993) proposed a simple model to predict permeability from 2-d image analysis data only. The model is empirical and based on porosity and the diameter distribution of the largest inscribed circles within porels. The regression analysis between a newly derived correlative parameter and measured permeability shows an excellent agreement, with a coefficient of determination of 0.90 and a standard error of estimate of 1.68. It is thought that the success of the method depends on the strong relationship between porel size and throat size distributions. This relationship is demonstrated in this study by comparing synthetic drainage capillary pressure curves, constructed using porel size-distribution data, with experimental mercury capillary pressure curves for the same samples.

Significant implications of the results reported, for the sample group, are that porosity and porel size are of first order importance in their effects on permeability, and that tortuosity, pore shape, and pore connectivity have only small effects on permeability, unless these properties are themselves correlated with porosity or pore size (Coskun and Wardlaw, 1993).

Ioannidis et al. (1996) used porosity and autocorrelation function to predict permeability from 2-d sections of a wide variety of rock samples including those investigated by Coskun and Wardlaw. Their results provide further evidence that statistical parameters measured on binary pore images can be used to estimate permeability. They used porosity and an integral correlation scale, corresponding to a characteristic pore dimension.

Discussion of the problems of PIA, sample scale and permeability measurement have been discussed recently by Anguy et al. (1995).

Pore-throat correlation and permeability estimation from NMR data

Pore size distributions can be derived from NMR data and sub-populations of pores of differing sizes and types can be recognized. Bowers et al. (1995) and Carr et al. (1996) have discussed the cross validation of NMR T1 relaxation distributions of porosity and how they are related to distributions obtained from image analysis of porosity in thin section. Both sets of distributions can be decomposed into pore types. Apparently, the relationships between pore types and throat sizes using NMR generated pore types are the same as those using image analysis generated pore types. Thus, there is the possibility that pore size spectra from NMR data could be used to predict permeability. Kenyon et al. (1995) found that NMR relaxation measurements could provide estimates of permeability that were significantly better than could be obtained from porosity alone.

PIA and estimation of Initial Water Saturation (Swi) and Residual Oil Saturation (Sor)

PIA was used to characterize the pore systems of two reservoir sandstones (a North American (NA) and a North Sea (NS) oil reservoir) using 2-d images of epoxy impregnated thin sections. Pore systems of each reservoir were defined by pore types which have characteristic sizes and shapes which are the product of conditions in the depositional environment as well as during subsequent diagenesis. Seven pore types for the NA reservoir and five pore types for the NS reservoir are necessary to capture the pore characteristics (Coskun and Wardlaw, 1995 and 1996; Wardlaw and Coskun 1994).

Initial water saturation and residual oil saturation are controlled by similar pore geometrical factors in both reservoirs although these reservoirs have sandstones which were deposited in different environments (fluvial braided river and off-shore marine) and with differing diagenesis, pore geometry and wettability. Swi, which is defined as water saturation at a constant high capillary pressure, increases with increasing relative volumes of small pores for samples from both reservoirs (Coskun and Wardlaw, 1995). These small pores commonly occur as domains of microporosity as illustrated by Morrow (1971) and identified by him as the major cause of high Swi.

Residual oil saturation obtained from waterflooding experiments are strongly related to the connectivity (estimated from the roughness spectra) and the degree of uniformity of the pore system in both sets of reservoir rocks. Sor increases with increasing non-uniformity and decreasing pore connectivity (Coskun and Wardlaw, 1996). These properties probably affect Sor in similar ways for a wide range of wettability conditions.

Stochastic models have been developed to relate Swi and Sor to pore geometric variables. The two models, specific to each reservoir, explain 72% and 73% of variations in initial water saturation for the NA and NS reservoirs, respectively. The average amount that actual Swi values differ from the estimated average Swi is 3% and 3.5% for the NA and NS reservoirs respectively. The models for the Sor prediction indicate that 64% and 79% of the variations in Sor can be explained by pore geometric variables and that the average amount that actual Sor values differ from the estimated average Sor is 4.8% and 2.9% for the NA and NS reservoirs, respectively.

These results indicate that size and shape characteristics of pore structures have strong effects on Swi and Sor and that most of this information can be obtained from 2-d thin sections of reservoir rock. PIA provides an efficient quantitative method to obtain information about pore geometry and to identify the pore properties which have large effects on Swi and Sor. The technique provides a large improvement over estimating Swi and Sor from porosity which does not provide information about the size of pores or the uniformity of the pore system.

Conclusion

PIA provides the most effective method available for understanding how specific rock-pore attributes affect fluid flow and displacement processes. PIA also has applications in predicting petrophysical properties of interest in samples too small for conventional core testing, for example drill cuttings or core rubble.

The method requires a “training set” of samples with known petrophysical properties and supplements but does not replace core testing. PIA optimizes the application of core tests to improve understanding and prediction of reservoir properties and performance.

Although PIA uses information from 2-d surfaces, it is possible to predict 3-d attributes such as permeability and drainage capillary pressure which are primarily controlled by throat sizes which are not identifiable on 2-d sections. Part of the explanation for this is thought to be pervasive correlation between pore sizes and connecting throat sizes in porous rocks.

PIA results indicate that specific size and shape characteristics of pore types have strong effects on permeability, drainage capillary pressure, Swi and Sor and that the necessary properties for prediction are contained on 2-d sections of reservoir rock.

Permeability can be predicted with an empirical equation based on porosity and the diameter distribution of the largest inscribed circles within porels.

The initial water saturation (Swi), which is defined as water saturation at a constant high capillary pressure, is found to be closely related to the relative volumes of small pores.

Residual oil saturation (Sor), obtained from waterflooding experiments, is strongly related to the connectivity and the degree of uniformity of the pore system . Sor increases with increasing pore non-uniformity and decreasing pore connectivity.

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