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Correlation of Porosity Types Derived From NMR Data and Petrographic Image Analysis

Summary

Petrographic Image Analysis (PIA) is used to derive porosity types from thin section. These pore types are then used to construct petrophysical models. Pore type information can also be derived from Nuclear Magnetic Resonance (NMR) relaxation data (T_1 and T_2). Pore types were derived from PIA and NMR for four sets of rocks (three sandstones and one carbonate). The pore types derived from PIA correlate with pore types derived from NMR. The correlation was identified for NMR pore types derived from T_1 and T_2 relaxation measurements. The correlation can be used to determine the surface relaxivity which is used to transform relaxation time to a characteristic length.

Introduction

The porous microstructure of a rock consists of pores and their associated throats. These pores and throats make up a three dimensional network that controls petrophysical properties such as permeability, formation factor and resistivity index. Attempts to use traditional petrographic methods, which are very subjective, to link petrographic and petrophysical properties, often produce very ambiguous results. To establish links between petrographic characteristics and petrophysics, an objective and quantitative method for characterizing and classifying porosity is needed.

Recently, a number of papers have appeared that described a set of procedures to derive pore types from images acquired from thin section. Each pore type is a subpopulation of the macroporosity with a characteristic size and shape. Later work, established that these pore types, in a particular rock, are associated with a distinct set of throat sizes. Knowledge of the pore type proportions and their associated throat sizes was used for the prediction and understanding of petrophysical properties.

NMR measurements, of longitudinal (T_1) and transverse relaxation (T_2), respond to differences in size, shape and abundance of the pores. These T_1 and T_2 relaxation curves can be transformed into pore size distributions that can be decomposed into subpopulations of pores or pore types.

The purpose of the following discussion is to illustrate that pore types derived from image analysis are correlative with pore types derived from NMR pore size distributions.

Theory and Procedures

The procedures used to derive pore types from image analysis and NMR are very similar. PIA is accomplished by acquiring digital images of porosity as viewed in thin section. These porosity elements or "porels" are subjected to an erosion and dilation process to characterize the size and geometry of the porels. A set of "self training" algorithms (SAWVEC) are than used to classify each porel as a particular pore type. These pore types differ with respect to size, shape and abundance. The result, is a characterization of each sample in terms of the pore types present and their abundance. These pore types are related to capillary pressure data through regression to determine the average throat size associated with each pore type. Because the pores and the pore throats are quantitatively characterized, petrophysical models can be constructed.

NMR is used to gain information about the pores by quantifying the interaction of protons and the pore walls. The relaxation rate is proportional to the pore size and the amount of surface roughness. As the pores get larger, the amount of time for relaxation to occur takes longer. Because rocks are composed of pores of differing sizes, the NMR relaxation curve is a sum of exponential relaxations and the relaxation curve can be decomposed into a pore size distribution.

The following equations describe the significant relationships between NMR and rock properties. Equation 1 describes the relaxation m a rock:

$$M_{(t)} = \sum_{i=1}^{n} A e^{(-t/T_{1i})}$$

where $M_{(t)}$ = proton magnetization at recovery time t; A_i = the volume fraction of pores of size i; T_{1i} = longitudinal relaxation time constant of pores of size i. Eq. 1 can be decomposed into a pore size distribution using a number of techniques. Relaxation in a single pore is described by:

$$\frac{1}{T_1} = \frac{1}{T_{1B}} + \frac{S}{V\alpha} \Big/ T_{1sm}$$

where T_{1B} = the relaxation time constant of bulk water; S/V = the surface area-to-volume ratio of the pore; α = the thickness of the surface monolayer which has a relaxation time constant of T_{1sm}.

Equation 2 can be simplified to:

$$\frac{1}{T_1} = \rho\left(\frac{S}{V}\right)$$

where ρ = the surface relaxivity or α/T_{1sm}. The reciprocal of S/V has units of length, so Equation 3 can be simplified to:

$$T_1\rho = L$$

where L is some length characteristic of the pore which is believed to be half of the pore diameter derived from PIA. The same equations and relationships can be derived for T_2.

The NMR T_1 data was collected on an IBM/Bruker Minispec PC 10 at 10 MHz. The T_1 data relaxation data was decomposed into pore size distributions represented by histograms with thirty-five bins. The T_2 data was collected using a NUMAR Corespec 1000 operating at 1 MHz. These distributions were represented by histograms with thirty-four bins. The T_1 and T_2 pore size distributions were analyzed with the SAWVEC algorithms to determine the number of pore types.

Four data sets will be considered. T_1 data and PIA data were collected on the Belly River Sandstone, Cut Bank Sandstone and dolomite samples from the Boyle Formation. T_2 and PIA data were collected from the Perry Sandstone.

Results

T_1 and PIA Results. PIA analysis on the Belly River Sandstone yielded four pore types. The mean diameter associated with these pore types

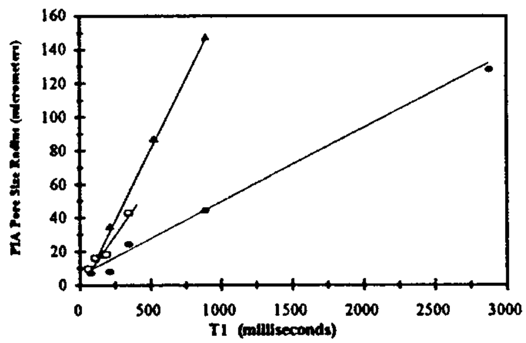

Figure 1. Cross plot of PIA pore diameter and NMR T_1 for correlative porosity types.

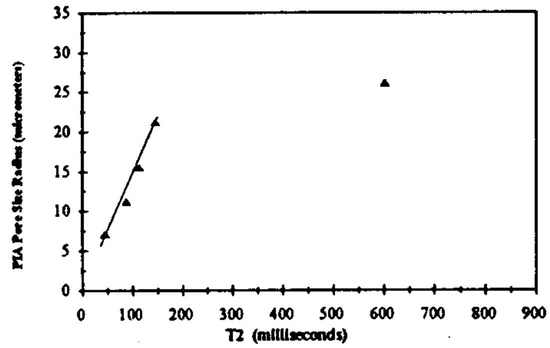

Figure 2. Cross plot of PIA pore diameter and NMR T_2 for correlative porosity types.

ranged from 19 to 86 micrometers. The number of pore types derived from NMR was five. The mean T_1 relaxation time associated with these pore type ranged from 4.5 to 347.4 milliseconds. The NMR and PIA pore types were correlated by size. For example, the PIA pore type with the largest diameter was correlated with NMR pore types with the largest relaxation time.

Figure 1 is a cross plot of PIA pore type radii and T_1 relaxation times for correlative pore types. A best fit line through the points yields a slope of 0.01 cm/sec and represents the surface relaxivity. As noted above, there are more NMR pore types than PIA pore types. That discrepancy is the result of the magnification used for digitization in the PIA process. The smallest resolved porel was only 2.50 micrometers in diameter. From the relationship illustrated in Figure 1, the smallest NMR derived pore type is 1 micrometer in diameter. That pore type is below the resolution of the PIA procedures used for the Belly River Sandstone.

Five PIA pore types were derived for the Cut Bank Sandstone. The average diameter for these pore types ranged from 14 to 256 micrometers in diameter. Seven NMR endmembers were derived. The mean T_1 relaxation time for these pore types ranged from 5.8 to 2880 milliseconds. The PIA pore types and NMR pore types were calibrated in the same manner as the Belly River data set. Figure 1 is an illustration of the relationship between PIA pore type radii and T_1 relaxation time for correlative pore types.

The relationship between the PIA pore types and NMR pore types for the Cut Bank Sandstone is more difficult to interpret. The slope (0.006 cm/sec) of the best fit line represents the average surface relaxivity. The point representing the biggest PIA pore type and biggest NMR pore type falls somewhat of the line. The most probable reason for the larger residual is that this pore type is very large and has a relaxation time at or beyond the fast diffusion limit of bulk water.

The two smallest NMR pore types do not correlate with any PIA pore types. These pore types are smaller than the smallest porel imaged using the PIA methodology for the Cut Bank Sandstone. These two NMR pore types would have diameters of 0.35 and 4.5 micrometers. The smallest resolvable porel was only 5 micrometers in diameter. These two pore types are associated with porosity found with clay and the microporous chert grains found in the Cut Bank samples.

Similar comparisons were made with the dolomite samples from the Boyle Formation. Four pore types were derived using the PIA techniques. These pore types have a mean diameter of 20 to 148 micrometers. Five pore types were derived from the NMR T_1 relaxation data. These pore types have a mean relaxation time that ranged from 49.6 to 4772 milliseconds. The pore types were correlated using the same techniques developed for the sandstones (Figure 1).

Again, the number of PIA pore types differ from the number of NMR pore types. The largest pore type had a relaxation time greater than the relaxation time of bulk water and probably does not represent a pore that could not be viewed in thin section. NMR Pore type four is believed to represent the vug sized pores that were to large to be imaged (they were larger than the field of view used during the digitization process). The remaining pore types correlated very well with the slope of the line representing the surface relaxivity. The surface relaxivity was calculated at 0.0165cm/sec.

T_2 and PIA Results. A similar set of procedures, as described above, was applied to the PIA and NMR T_2 data derived from the Perry Sandstone. A PIA analysis of the Perry yielded five pore types. These pore types ranged in size from 14.3 to 52.3 micrometers. Five NMR pore types were derived from the T_2 pore size distributions. The range of relaxation tunes for these pore types was 44.1 to 601 milliseconds.

Figure 2 is a cross plot of the PIA radius versus the NMR relaxation time for the correlated porosity types. The linear relationship between these pore types represents the T_2 surface relaxivity. The surface relaxivity was 0.0145 cm/sec The relationship between T_2 and PIA derived pore size is not as strong as that observed between T_1 and PIA derived pore size. We speculate that the perhaps the weaker relationship is the result of internal gradient fields. Perhaps the relationship between the T_2 and PIA derived pore size is best represented by a nonlinear relationship.

Discussion and Conclusions

The correlation between the PIA derived porosity types and NMR derived porosity types is significant. Porosity types from PIA are derived from a complex cross section derived from thin section; a two-dimensional measurement. NMR pore types are derived from the surface area-to-volume ratio; a three-dimensional measurement. Because of the correlation we conclude that two independent measurement techniques produce the same characterization of the pore space. Both sets of measurements characterize the pore space with respect to size and geometry. The only difference between the two measurement techniques is resolution. NMR is capable of resolving smaller porosity types.

There is one significant problem associated with the use of NMR for the derivation of porosity types. The construction of petrophysical models is more difficult. T_1 and T_2 must be scaled to pore size using some additional measurement. The literature contains many references about different techniques to obtain the surface relaxivity. Because of the correlation between NMR and PIA derived pore types, surface relaxivity can be derived. The advantage of using PIA is that the scaling of time to length is made relative to observable pore features. Other techniques do not provide a scaling that can be validated with observation of actual rock material.

The correlation between NMR pore types and PIA pore types is also significant as the correlations can be used to gain a better understanding of the relationship between NMR relaxation and pore geometry. Because pore types are also related to diagenesis, we can potentially relate the NMR relaxation process to the pore wall chemistry.

Future work should focus on using NMR derived pore types for petrophysical modeling. Success was achieved for modeling capillary pressure curves and permeability models. The ultimate goal would be to derive porosity types from NMR open-hole logging tools, however, significant improvements in those tools are needed.