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A systematic method for permeability prediction, a Petro-Facies approach

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ABSTRACT

In this study, using a relatively large and complete data set of a complex carbonate reservoir, it is proven that among the numerous methods proposed for the prediction of permeability, the porosity-facies based models are the best choice from a theoretical and practical point of view. Based on petrographic examinations and petrophysical interpretations, a systematic approach is proposed for permeability prediction.

Porosity and pore type have been identified as the main influential attributes and Petro-Facies is the preferred way of permeability estimation in the un-cored wells. The Fuzzy C-Means (FCM) clustering method has been applied for the subdivision of the data space into 12 representative Petro-Facies and the corresponding relationships between porosity and permeability for each facies has been determined. After identification of the main responsive well log suite, based on the rank correlation, a classification tree approach was used for the population of Petro-Facies in the un-cored wells. Then, the relevant porosity–permeability relation was applied for permeability calculation.

This study shows that by using a systematic approach for the identification of the controlling parameters of permeability and determining the proper permeability model, it is possible to achieve a reliable permeability prediction.

1. Introduction

Permeability, the single-phase fluid conductivity of a porous material, is a key parameter in determining the economic value of hydrocarbon accumulation. It is a complex interplay of porosity, pore connectivity, grain packing, grain size and rock diagenesis. Our ability to predict the magnitude and range of permeability in undrilled areas, because of the limited access to actual measurements and its dynamic nature which must be predicted from static data, is always poor. Geostatistical reservoir modeling is an approach for getting an idea of the permeability distribution within a reservoir using a combination of the geophysical, geological, petrophysical and conceptual models. However, to have a realistic model, the magnitude of permeability must be available at least at the well locations.

Permeability is an elusive parameter in hydrocarbon reservoirs as it is very difficult to determine directly using current sub-surface logging technology. Among the various logging techniques, NMR (Nuclear Magnetic Resonance) relaxation logging, an approach which the industry was left waiting for nearly 30 years on a reliable down-hole measurement tool, shows the most promise (Coates et al., 1999). Brownstein and Tarr (1979) showed that NMR relaxation rate is proportional to the surface area-to-volume ratio of pores in tissue. The early works of Brown and Gamson (1960), Seevers (1966), and Timur (1969) revealed the potential of NMR as both a core analysis and wireline methodology. An extensive review of principles and applications of NMR logging can be found in Coates et al. (1999). The ability of NMR to distinguish between bound and free fluids increases the capability of NMR to better estimate the formation permeability. Several examples of the application of NMR as a tool for the prediction of permeability have been reported in the literature (Chang et al., 1994; Coates et al., 1994; Kleinberg and Vinegar, 1996; Howard et al., 1997; Tariq et al., 1997; Flaum et al., 1998; Logan et al., 1998; Castelijns et al., 1999; Epping et al., 1999; Quintero et al., 1999; Sezginer et al., 1999; Glover et al., 2006; Daigle and Dugan, 2009).

In addition to NMR logging, one of the most promising methods for the calculation of continuous permeability information is the use of Stoneley wave data acquired using an acoustic tool (Tang et al., 1991; Tang and Cheng, 1996; Tang et al., 1998; Qobi et al., 2001). The prediction of permeability based on dip-meter and image logs has also been reported (Doyen, 1988; Ehrlich et al., 1991; Rezaee and Griffiths, 1996; Rezaee and Lemon, 1997; Russell et al., 2002). Pore throat characteristics derived from image analysis has also been used (Doyen, 1988; Ehrlich et al., 1991; Rezaee and Griffiths, 1996; Rezaee and Lemon, 1997).

Wireline formation testing, well testing and flow meter logging are other methods for obtaining permeability information; however the scale of measurement in terms of support volume is much larger than with the logging methods.

Currently NMR is the industry-leading technique for permeability determination in boreholes. Unfortunately this log, as is the case with

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the Dorood Field, is missing in many of the older wells. Because of these limitations, the prediction of permeability from other commonly acquired logs, calibrated with core data is still a common practice in many mature oil fields.

Generally the magnitude of permeability in siliciclastic rocks is controlled by the processes active in depositional environment. In siliciclastics, texture may yield some information about permeability and porosity. Usually in terrigenous rocks, diagenesis has small effect on petrophysical properties of the rocks and it is possible to predict the reservoir quality based on the sedimentary environment. Carbonate reservoirs on the other hand because of the limited group of minerals which are highly susceptible to diagenesis, present a picture of extremes. Matrix permeability can be immeasurably low, while fluids flow like rivers through the fractures. The evaluation techniques that succeed in the sandstone reservoirs sometimes fail with the carbonate reservoirs. Ehrenberg and Nadeau (2005) noted the key similarities and differences between sandstones and carbonates and the implications are discussed regarding the dominant factors controlling reservoir quality in each lithology. For permeability prediction in the case of complex carbonate reservoirs it is first necessary to identify the main controlling parameters of permeability and select a proper approach.

In addition to the importance of recognizing the main controlling factors of permeability variation, the selection and application of the appropriate permeability model sometimes has similar effects on the final permeability estimation. Several models have been proposed for the prediction of permeability in un-cored wells; these models have been classified by different authors based on different criteria. The selection of the proper model will of course not only affect the success of the task of permeability estimation, but also determines the usefulness of the estimated permeability. The methods for permeability prediction have been divided into three categories by Mohaghegh et al. (1995): empirical, statistical, and neural modeling. Nelson (1994) categorized the permeability prediction methods into two basic groups, methods which have a theoretical basis and use parameters like porosity and other measurable rock properties, and models that directly incorporate well log measurements but have no particular theoretical underpinnings.

In this paper a new scheme of classification has been defined which encompasses all of the popular methods referred to in petroleum literature and the oil industry:

(1) *Models based on empirical or theoretical equations*: models to predict permeability from porosity and other measurable rock parameters have been classified by Nelson (1994) into three classes based on grain, surface area, or pore dimension considerations. Among the numerous models in this category, the models of Krumbein and Monk (1943), Purcell (1949), Thomeer (1960), Timur (1968), Berg (1970), Granberry and Keelan (1977), Van Baaren (1979), Swanson (1981), Katz and Thompson (1986), Heron (1987), Ahmed et al. (1989), Sen et al. (1990) and Borgia et al. (1992) have been frequently referenced in the literature. The main advantages of these models are their simplicity and their theoretical foundation while their main limitations are the lack of generalization and their dependency on the certain parameters which must be derived from the core data.

(2) *Models based on soft computing techniques*: among the various soft computing techniques, the Artificial Neural Networks (ANN), the Fuzzy Logic (FL) and the Neuro-Fuzzy were frequently used for permeability prediction. Several authors have used the soft computing techniques for estimation of permeability. Huang et al. (1996) used a back-propagation artificial neural network to model the interrelationships between spatial position, six different well logs, and permeability. Cuddy (1997) applied fuzzy logic to solve a number of petrophysical problems in several North Sea fields. In Huang et al. (1999), the authors presented a simple but practical fuzzy interpolator for predicting the permeability from well logs. Rezaee et al. (2006) used a fully-connected multi-layer perceptron network to predict permeability from porosity and pore throat radii and Kadkhodaie Ilkhchi et al. (2006) modeled and predicted the permeability using a Takagi-Sugeno fuzzy inference system. The main advantages of ANN are: the ability to solve complex non-linear problems, working in parallel, fault and noise tolerance (to certain level) and adaptive learning. The advantages of FL are: ease of understanding, flexibility with any system, being rule based system and that they are a convenient way to express expert and common sense knowledge. The Neuro-Fuzzy systems aim at combining the advantages of the two methods.
The main limitation of the soft computing techniques is that there is always a danger of over-fitting the data and the requirement for a convincing, satisfactory representative data set. When calibration is coupled with validation a useful predictive generalization can be achieved.

(3) *Models based on porosity and facies*: models based on porosity and facies are further subdivided into: (1) Reservoir layering; (2) Electro-Facies; (3) Litho-Facies; (4) Flow Zone Indicator (FZI); (5) Rock fabric approach and (6) Petro-Facies are based on the concept that there is a direct relationship between porosity and permeability for clearly defined layers, lithologies, facies or reservoir zones. Several authors have partitioned well logs into distinct classes known as electro-facies (Serra and Abbott, 1982; Davis, 1986; Serra, 1986; Doveton, 1994; Tabachnick and Fidell, 1996; Lee et al., 2002). Wolff and Pelissier-Combescure (1982) used the principal component analysis to cluster the log values into separate facies that can be regarded as indicative of lithology. Busch et al. (1985) and Delfiner et al. (1987) used discriminant factor analysis to correlate the log values to lithological facies. The methods relying on self-organizing maps (Baldwin et al., 1990) and back-propagation feed forward neural networks (Rogers et al., 1992) were also used for the estimation of lithology from logs. Toumani et al. (1994) used fuzzy clustering to determine lithology from well logs and Cuddy (1997) used fuzzy logic to predict permeability and lithofacies in un-cored wells. Saggaf and Nebrija (2000) used neural networks for identifying both lithological and depositional facies from well logs and Saggaf and Nebrija (2003) used a method based on fuzzy logic inference to identify the lithological and depositional facies from wire-line logs.

Amaefule et al. (1993) proposed a methodology for identification and characterization of hydraulic units within mappable geological units (facies). The technique, based on a modified Kozeny–Carmen equation and the concept of mean hydraulic radius is known as the Flow Zone Indicator approach.

The basic idea of the Rock Fabric method developed by Lucia (1983; 1995b; 1999) is that porosity, permeability, and fluid saturations are linked through pore size distribution, and pore-size distribution can be linked to rock fabrics.

The main limitations of the models of porosity and facies are that facies definition is a subjective task and there is not always a clearly well-defined relationship between facies and permeability in the cored sections. Another important shortcoming of these models is that for the purpose of permeability estimation in un-cored sections it is required to predict the facies, something that is not much simpler to predict than permeability itself. Table 1 summarizes the various permeability prediction approaches with their advantages and disadvantages.