Identification of permeable carbonates with well logs applying the Differential Effective Medium theory

Abstract

For carbonates, the porosity alone, as calculated with the combination of the Neutron and Density logs, is not enough to predict whether an interval will be permeable or not. A rock is permeable if the voids in it (matrix porosity, fractures, vugs) are connected. The well known Differential Effective Medium theory (DEM) allows the modeling of rocks perceived to be permeable or impermeable. Spherical pores in relatively low porosity rocks are assumed to be isolated and therefore resulting in very impervious rocks. Very flat ellipsoidal pores (penny cracks) with a random orientation are postulated to form an interconnected network of pores, resulting in a very pervious rock. These two end points can be identified in a Velocity (from the sonic log) vs. porosity (from the radioactive logs) diagram corresponding to the interval of interest, where the curves modeled with the DEM and the Wyllie curve have also been plotted. Impervious points should fall high above the Wyllie curve in such a diagram, whilst the points representing permeable rocks should fall well below the Wyllie curve. Production tests have been used to check the theory.

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Introduction

The porosity and mineralogical composition of carbonates (proportions of calcite, dolomite and shale) can be calculated with density, neutron and gamma ray logs. However, the porosity alone is not enough to determine if a carbonate will produce. It is quite often to encounter carbonates with porosities of 10% or more, which prove to be impermeable when tested. On the other hand, there are low porosity carbonates, which prove to be permeable and have a very good production of hydrocarbons. In order to be permeable, the pores have to be interconnected. In carbonates with a relatively high porosity, there may be isolated cavities or vugs, which account for the porosity, but the rock is impermeable because the vugs do not form a network. In a rock of low porosity, there may be cracks or fractures which determine an interconnection of most of the voids in the rock, resulting in a high permeability. The identification of a zone of permeable carbonates in a well is very important from the economic point of view.

The aim of this work is to identify permeable zones in a well by means of the porosity (as calculated from the radioactive logs) and the sonic log. The basic idea is to model the p velocity of rocks as a function of total porosity and compare the modeled results with the actual data. In order to model rocks perceived as permeable or impermeable, we will use the Differential Effective Medium Model (DEM). Mavko et al (1998) provide an excellent explanation of the model.

The use of the DEM to predict certain physical properties in carbonates has been carried out, for instance, by Kumar et al. (2005), and Baechle et al.(2007). The approach taken by Kumar is quite similar to the one taken in the present paper. However, in our paper we solve the system of differential equations analytically, either for dry or saturated rocks. The fact that we end up in possession of a set of equations, provides us an insight into the characteristics and limitations of the DEM. Furthermore, we compare the predictions of the DEM with a few production tests in carbonates, in an attempt to corroborate the theory. Another paper of interest is the one by Anselmetti and Eberle (1999) which, although not dealing with the DEM model, differentiates the pore type of carbonates as a function of the position of the points in a velocity vs. porosity plot using the Wyllie curve as a reference.

It should be pointed out that the answers provided by the present paper are qualitative rather than quantitative. We should be able to identify in a crossplot Vp vs porosity (as derived from the neutron and density logs), points which represent vugs interconnected by fractures (supposed to be permeable rocks) or isolated spherical vugs (supposed to be impermeable). However, whilst the end points are easily identifiable, there are intermediate points in the vicinity of the Wyllie line whose permeability cannot be diagnosed in the light of the DEM theory. One of the limitations of the DEM model consists in the fact that it is unable to model a granular medium, that is, when the originally continuous phase is a fluid with a shear modulus equal to zero, and the model is constructed adding inclusions of a mineral.

In this paper, fractures are modeled as ellipsoids with a very small aspect ratio (of the order of 0.01 or less). It is suggested in this work that, for very small aspect ratios, the ellipsoids tend to be interconnected and hence generate a network resulting in a permeable rock. It is postulated in the paper that there is an inverse relationship between the connectivity of the pores and their aspect ratio. However, for an aspect ratio of about 0.1 (the maximum value is 1, corresponding to spheres) we can reproduce the Wyllie equation quite closely. Hence, points along the Wyllie curve should not be very permeable according to the DEM and our postulates. However, it has been suggested from empirical observations that the points falling close to the Wyllie line represent intergranular or intercrystalline porosity (Anselmetti and Eberle, 1999). These rocks may be permeable or not. Hence, there is a fundamental ambiguity attached to the points falling close to the curve given by the Wyllie equation. Still, with all these limitations, it seems to be worthwhile to model carbonates using the DEM, because in many instances it allows accurate predictions regarding the productivity or otherwise of certain intervals.
Differential Effective Model theory

The coupled system of ordinary differential equations which characterize the DEM are:

\[ -\phi \frac{dK^*}{d\phi} = K_f - K^* \frac{\bar{P}}{P} \ldots \ldots [1] \]

\[ -\phi \frac{d\mu^*}{d\phi} = -\mu^* Q \ldots \ldots [2] \]

In these equations, \( K^* \) and \( \mu^* \) are the bulk and shear moduli, respectively, \( K_f \) is the fluid bulk modulus and \( \phi \) is the porosity. As written, these equations apply when the host material is the solid and the inclusions represent pores full of a fluid having a bulk modulus equal to \( K_f \). The parameters \( P \) and \( Q \) depend, among other factors, on the aspect ratio of the pores (for spheres, the aspect ratio is equal to 1, which is the maximum value possible).

In this work, the system of differential equations given by [1] and [2] has been solved analytically and the \( p \) velocity has been calculated as a function of porosity for both spherical pores and pores with low aspect ratios.

According to the DEM, if we depart from a solid block of a mineral (or composite of minerals) and begin to add spherical pores filled with a fluid, the pores will tend not to be connected and hence the resulting rock will not be permeable, particularly if the porosity is relatively low (no more than 20-25%). On the other hand, if the pores are very flat (have a very low aspect ratio), and they have a random orientation, it is quite likely that there will be intersections between the pores and hence a network of pores may exist, resulting in a permeable rock. Modelling shows that, in a velocity/porosity diagram, the theoretical curve for spherical pores lies much higher than the Wyllie curve (for a given porosity, the theoretical DEM velocity is much higher than the Wyllie velocity). If well log derived data (the velocity from the sonic vs. the porosity from the neutron and density logs) is plotted in such a diagram, the points falling in the vicinity of the theoretical curve for spheres will – according to theory – represent impervious rocks. As the aspect ratio of the model is decreased the resulting curves tend to go ‘downwards’ and, for aspect ratios less than 0.01, the curves will be well below the Wyllie curve. The assumption is that, as the pores get flatter, the likelihood that they are interconnected will increase, resulting in permeable rocks. So the points falling well below the Wyllie curve in a velocity vs. porosity diagram will tend to be permeable. It should be pointed out that the DEM allows for the modelling of pores of different shapes, simultaneously. That is, in the same rock we may model spherical vugs interconnected by very flat ellipsoidal pores, resulting in a permeable rock.

The standard DEM does not allow us to make predictions regarding those points which fall in the vicinity of the Wyllie curve, which would represent an interpaticle porosity according to Anselmetti and Eberle (op.cit.). These rocks may be permeable or not. The standard DEM does not allow us to simulate a granular medium (where we begin with an empty volume and proceed to fill it with solid particles). To do so, modifications to the original theory have to be introduced, which are beyond the scope of this paper.

Examples

Figure 1 shows a velocity vs. porosity crossplot for an interval about 20 m thick in a carbonate sequence (the mineralogy of the interval is almost pure dolomite). The relatively high porosities (a lot of points in the range 0.15-0.25) made the interval interesting. However, the interval proved to be absolutely impermeable. It should be noted that the points having the maximum porosity tend to fall...
above the Wyllie line (in blue), relatively close to the “spheres” line in purple. These points are interpreted to be unconnected vugs, and hence impervious.

Figure 2 shows a velocity vs. neutron porosity crossplot for a 40 metre interval of a carbonate composed mainly of calcite, free of shale. This interval was tested and produced about 5100 BOPD, with a 3/8” choke. Note that most of the points fall well below the Wyllie curve (in black), whilst the porosity is quite low (the average neutron porosity is 0.022). It is apparent that despite the low porosity, the permeability is quite good, so the assumption that this interval is somewhat fractured, is quite reasonable. In this figure, the line corresponding to penny cracks with an aspect ratio of 0.01 has been traced in blue. As a reference, the lower Hashin-Shtrickman limit, representing the minimum possible velocity that a calcite-water system may have, has been traced in red.

**Figure 1:** Velocity/porosity crossplot, showing the Wyllie curve in blue and the theoretical curve derived from the DEM for spheres, in purple.
Figure 2: Velocity/porosity xplot, showing the Wyllie curve in black, the theoretical curve corresponding to pores with an aspect ratio of 0.01 in blue and the curve corresponding to the Hashin-Shtrikman lower limit in red.

Conclusions

The identification of permeable zones in carbonates has been carried out in the light of the DEM model. The DEM theory allows for the identification of the most impermeable points (modeled as spherical cavities filled with a fluid in an otherwise continuous solid phase and interpreted as vuggy or moldic porosity) and the most permeable points (modeled as penny cracks or ellipsoids with a very low aspect ratio and interpreted as fractures). The theory yields an ambiguous answer regarding the points which fall, in a velocity vs. porosity diagram, close to the Wyllie curve.

References


