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Carbonate microstructure determination by inversion of acoustic and electrical data: Application to a south Florida aquifer

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Abstract

We demonstrate the feasibility of a petrophysical inversion technique to reconstruct the secondary pore-space microstructure in carbonate double-porosity aquifers. This technique consists of the joint inversion of acoustic (P- and S-wave velocities) and electrical resistivity well logs using a unified pore-space model and a self-consistent effective media approximation for theoretically calculating the elastic moduli and electrical conductivity. We invert experimental well log data from a South Florida aquifer in the western Hillsboro Basin of Palm Beach County, Florida. The inversion results allow us to find the detailed vertical distribution of primary and secondary porosities in the carbonate aquifer formation associated with high total porosity. The secondary-porosity system of this formation has a complex microstructure and corresponds to a model with two types of pore shapes: cracks approximated by flattered ellipsoids, and spheroid-shaped vugs. The quantitative pore-structure characteristics agreed with the qualitative description of computed tomography core images and optical microscope thin sections. The relationship between primary and secondary porosities is an important and informative characteristic of carbonate formations that demonstrates a good correlation with nuclear magnetic resonance-derived permeability. This suggests that knowledge of a formation's different porosities can be used to infer relative formation permeability, based on a joint inversion of acoustic and resistivity well logs.

Keywords: Double porosity; Joint inversion; Electrical conductivity; Acoustic velocities

1. Introduction

Characterizing pore spaces in carbonate formations is critical to an evaluation of hydrological and environmental problems in aquifer exploration and exploitation, as well as water and soil contamination. Carbonate formations have a complex pore microstructure characterized by broad pore size and shape

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distributions. The pore structure consists of the primary pore system, composed of small-scale microcrystalline and intergranular pores with close-to-sphere shapes, and large-scale secondary pore systems such as microfractures and connected and isolated vugs (Choquette and Pray, 1970; Lucia, 1999). Determining secondary porosity type and estimating the values of primary and secondary porosity are basic problems in hydraulic permeability prediction, reservoir evaluation, and adequate exploitation of carbonate aquifers.

Anselmetti et al. (1998) described a method to quantitatively predict pore size distribution in carbonate samples from thin section images. This method was used to analyze thin sections from a south Florida aquifer, and the results were used to verify pore size distributions based on NMR signatures (Parra et al., 2001; Hackert and Parra, 2002). The pore size analysis and thin sections provided a description of the aquifer lithological facies related to porosity and permeability at the borehole scale. The resulting lithology column and well logs were integrated with reflection and velocity tomography imaging, as well as 2D surface seismic attributes (Parra and Hackert, 2002a,b; Parra et al., 2003). As a result of this interpretation, porosity and permeability images were obtained at the field scale.

To differentiate matrix porosity from vuggy porosity at the borehole scale, we must implement new algorithms with which to process well-log information. In fact, correct evaluation of double-porosity heterogeneous media can be based on an integrated analysis of various physical characteristics obtained from core and well log data. Such an interpretation procedure can be considered a petrophysical inversion that allows reconstructing a model of the rock microstructure.

An inversion of laboratory measured elastic-wave velocities was applied by Cheng and Toksöz (1979) to obtain the spectra of pore shapes as a function of pressure and saturation. The authors developed a method based on the iterative inversion scheme applied to a rock model, where the aspect ratio of spheroidal pores in the matrix depended on pressure. An approach for evaluating secondary porosity in vuggy carbonate formations using acoustic velocities and electric conductivity was proposed by Brie et al. (1985), who represented secondary pores as spherical inclusions in a homogeneous matrix and described the acoustic and electric parameters by the Kuster–Toksöz and Maxwell–Garnet models. Effective properties of a matrix with primary porosity were given by Wyllie's relation for acoustic velocities and Archie's law. Markov et al. (2003) proposed the technique of joint inversion of acoustic and resistivity well-log data to determine secondary pore-system type (vugs and cracks) and to estimate matrix and secondary porosity for carbonate formations.

In this paper, we describe the application and feasibility of the petrophysical inversion technique for the characterization of highly porous carbonate aquifers. This technique is based on the unified pore-space model and the self-consistent Effective Media Approximation (EMA) for calculating elastic moduli and electrical conductivity (Berryman, 1980, 1992; Norris et al., 1985). We represent the secondary pore system as ellipsoidal inclusions embedded in an elastic and conductive homogeneous isotropic matrix with primary porosity. The variation of the ellipsoid aspect ratios permits us to describe different shapes of secondary pores as isolated vugs (close-to-sphere inclusions), vugs interconnected by channels (prolate ellipsoids), and cracks or microfractures (oblate ellipsoids). To define the effective properties of the matrix we use statistically obtained regression equations (Mavko et al., 1998; Kazatchenko and Mousatov, 2002) and theoretical simulations by the symmetrical EMA for given mineralogical and structural formation characteristics (Kazatchenko et al., 2004). The solid grains and pores saturated by fluid have an ellipsoidal shape with different aspect ratios. By minimizing the difference between measured and predicted data sets (acoustic velocities and electric conductivity logs), we can estimate the value of the primary and secondary porosities as well as the aspect ratios of the ellipsoidal secondary pores (pore types).

We invert the experimental well log data obtained for a carbonate aquifer in the western Hillsboro Basin of Palm Beach Country, Florida. A characterization of this aquifer at the borehole and field scales is given in Parra et al. (2001), and the hydrogeology is described by Bennett et al. (2002). The inversion results allow us to find the detailed vertical distribution of the primary and secondary porosity values in the carbonate aquifer with high total porosity. The secondary porosity system of this formation has complex micro-