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Modeling and inversion of elastic wave velocities and electrical conductivity in clastic formations with structural and dispersed shales

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ABSTRACT

This paper presents a new approach for simulating P- and S-wave velocities, and electrical conductivity in shaly-sand rocks and determining the shale spatial distribution (dispersed and/or structural shales). In this approach, we used the effective medium method and hierarchical model for clastic formations. We treat shaly-sand formations as porous natural-composite materials containing: solid grains (such as quartz, feldspars and structural shale) and pores completely filled with a mixture of hydrocarbon, water and dispersed shale. For calculating the effective elastic properties and electrical conductivity of this composite, we have applied the multi-component self-consistent effective media approximation (EMA) method. We simulate the elastic velocities and electrical conductivity for clastic formations in two steps. Firstly, we calculate the effective properties of mixture (combination of water, hydrocarbon and dispersed shale) filling the pores. Then we find the effective elastic and electrical conductivity properties of formation constituted of solid grains (quartz and structural shale) and pores with the effective properties determined in the previous step. We considered that all components are represented by ellipsoids. The aspect ratios (shapes) of grains and pores; are defined as a porosity function obtained for the model of clean sand formations. Modeling results have demonstrated that the shapes of both shale components (dispersed and structural) weakly affect the effective elastic velocities and electrical conductivity of shaly-sand formation and can be approximated by flatted ellipsoids. The model proposed has been used to determine the volumes of dispersed and structural shales for two sets of published experimental data obtained from the cores. For determining the shale distribution, we have performed the joint inversion of the following physical properties: P-, S-wave velocities, total porosity, and total shale volume. Additionally, we have predicted the effective electrical conductivity for the second set of data, taking into account the shale distribution obtained by the inversion process. A good agreement between the simulated effective conductivity and measured data confirms the determination of shale spatial distribution, and allows us to validate the proposed model and calculation technique.

1. Introduction

Formation evaluation of clastic shaly-sand rocks is kept as an important petrophysical problem because they represent about 80% of sedimentary formations, and 40% of oil production rocks worldwide. Uncertainty in determining the petrophysical properties of clastic formations is mostly related to the presence of shale and its type of spatial distribution (dispersed, structural and laminar). This distribution influences the evaluation of all principal reservoir characteristics as effective porosity, water saturation, and permeability. Traditional petrophysical models used widely in well-log interpretation associate the rock physical properties with the total shale concentration, and do not allow the shale (clay) position into formations to be determined.

Several authors (Castagna et al., 1985; Han, 1986; Tosaya and Nur, 1982) proposed the relationships between the elastic-wave velocities, total porosity, and shale volume for clastic formations. These dependencies are based on a statistical analysis of experimental data and demonstrate that the velocity decreases when the total shale content increases. Marion (1990) simulated the elastic-wave velocities as functions of clay volume by using a model for non-consolidated shaly-sands, taking into account bimodal distribution of the solid grains (clay and sand). In this model, the P-wave velocity increases while the clay volume goes up to the sand-porosity value and then starts to decrease with the clay-concentration growth.

To describe the velocity behavior in clastic rocks Xu and White (1995) developed a model called sand–clay mixture. The main feature of this model is the dependence of elastic properties on pore geometry.

Kuster and Toksöz (1974) treated theoretically the propagation of elastic waves in two-phase media (defined as an aggregate of two homogenous phases of different properties) where one of them, called the matrix, is a continuum in which inclusions of the other phase are

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randomly embedded. By using this model, Minear (1982) studied the effect of different shale distribution on the effective elastic-wave velocities.

Other authors as Berge et al. (1993), Berryman (1995) and Norris (1985), based on the previous work of Bruggeman (1935), proposed the simulation methods treating the porous formation as the naturally composite material. They developed the bases of the effective medium methods: Effective Media Approximation (EMA) sometimes called Self-consistent Theory (SC) and Differential Effective Medium (DEM). These methods are achievable theories and predict the values of effective physical properties that fall within the Hashin–Strikman limits. Applicability of the effective media methods to simulate the elastic moduli for clastic and carbonate formations has been confirmed by several authors (Aquino et al., 2011; Berge et al., 1995; De Lima et al., 2005; Gelius and Wang, 2008; Han et al., 2011b; Kazatchenko et al., 2004a; Markov et al., 2006; Minear, 1982; Sheng, 1990, 1991). A novel approach that permits to simulate physical properties near to percolation threshold for low porosity formations (tight formations) and mechanical percolation for low consolidated sands (deep water formations) was presented by Markov et al. (2014).

The application of micromechanical methods to simulate different physical properties at the same time, i.e. electrical resistivity and P-wave velocity in clastic rocks was performed by Sheng (1991) and for carbonate rocks were performed by Kazatchenko et al. (2004a, 2004b, 2006a, 2006b). Markov et al. (2012) applied the same approach for the determination of dielectric permittivity of carbonate formations. The study of P-wave velocity prediction for synthetic sandstones performed by Berge et al. (1995) using the DEM and EMA methods demonstrated that the theoretical prediction with the last one is closer to the experimental data. By using the EMA method, Aquino et al. (2011) proposed a model for calculating the effective elastic moduli and electrical conductivity of clean sandstones. In this model grain and pore shapes are introduced as functions of porosity. It is important to mention that the EMA method does not account the electrochemical and electrokinetic phenomena.

Han et al. (2011a) analyzed the experimental data set of the P- and S-wave velocities and electrical resistivity for sandstone brine-saturated samples at differential pressures of 60, 40, 26, 20, 15 and 8 MPa. Based on these experimental data, Han et al. (2011b) developed a three-phase model composed of quartz, brine and pore filling clay minerals. To calculate the effective elastic velocities and electrical resistivity the authors combined the self-consistent approximation and differential effective medium methods assuming that all three components have the same shape approximated by sphere. Jensen et al. (2012) demonstrated a consistent joint elastic-electrical modeling according to the differential effective-medium theory. The proposed petrophysical model takes into account only dispersed clay. The authors considered that their approach is analogous to calibrating a rock physics model to a particular reservoir based on data from possible well logs and core samples.

The conductance and electrochemical behavior of shaly sands and their relation to log interpretation was reviewed by Wyllie (1960). Waxman and Smits (1968) developed an equation that relates the electrical conductivity of water-saturated shaly sand to the water conductivity and the clay content (expressed by the cation-exchange capacities per unit pore volume of the rock). In this paper, we treat the shale as a component with specific physical properties.

In this paper, we propose an approach for calculating the effective P- and S-wave velocities and electrical conductivity of clastic formations, taking into account the spatial distribution of shales (dispersed and structural shale concentrations). In the proposed approach, porous shale–sand formations are treated as a micro heterogeneous material composed of solid grains (sand and structural clay grains) and pores filled with a mixture of water, hydrocarbon and dispersed shale (clay). We consider the shales as agglomerated and have electrical resistivity that is assigned and take into account the surface conductivity. To simulate these effective physical properties we apply a two-step hierarchical homogenization scheme. Firstly, we determine the effective properties of a mixture (combination of water, hydrocarbon and dispersed shale) filling the pores. Then we find the effective elastic velocities, and electrical conductivity of the medium constituted of solid grains (quartz and structural shale), and pores with the effective properties obtained in the previous step. For both steps of homogenization, we use the multi-component self-consistent effective media approximation (EMA) method. The shapes of all components are represented by tri-axial ellipsoids. The aspect ratios (shapes) for grains and pores are introduced as porosity functions obtained for the clean sand formations (Aquino et al., 2011). To find the shapes for dispersed and structural components of shale, we have studied the sensitivity of the effective elastic-wave velocities and electrical conductivity to the shale concentration and spatial distribution. As is used in petrophysics, the shale conductivity can be assigned by using the well log data (the conductivity of clean shale layers) or simulated by applying several published methods which take into account the surface conductivity and water salinity (Revil and Glover, 1998; Revil et al., 1998; Shevnin et al., 2007).

The model proposed has been used to determine the volumes of dispersed and structural shales for two different published experimental data obtained from the cores (Han, 1986; Han et al., 2011a, 2011b). For determining the spatial shale distribution, we have performed the joint inversion of the measured P- and S-wave velocities, total porosity and total shale volume. To validate the proposed model and calculation technique, we have compared the conductivity measured on the samples with the effective electrical conductivity calculated using the concentrations of dispersed and structural shales obtained by the inversion process.

2. Model and simulation method

Shaly-sand formations are an aggregate of minerals that contain mainly quartz, feldspars and shale which are chemically and physically durable. According to several authors (Bassiouni, 1994; Minear, 1982; Neasham, 1977), there are three principal types of the shale spatial distribution in clastic formations: (1) structural, when the shale particles constitute part of the rock-solid skeleton, (2) dispersed, when the shale grains are located into pores, and (3) laminar, when shales form thin layers.

In this paper, we propose a model that corresponds to the microstructure of clastic formations taking into account the structural and dispersed types of shale position into rocks. We treat these shaly-sand formations as a multi-component composite material constituted of the solid grains (quartz, feldspars, and structural shale) and pores filled with a mixture of water, hydrocarbon, and dispersed shale (Fig. 1). To determine the effective elastic-wave velocities, and electrical conductivity of this microheterogeneous material we apply a two-step hierarchical homogenization scheme. Firstly, we have to obtain the effective physical properties of the mixture (water, hydrocarbon, and dispersed shale) filling the pores (homogenization at the pore scale). Then we can perform the second step of homogenization at the rock-sample scale and calculate the effective physical properties of the medium constituted of solid grains (quartz and structural shale) and pores with the effective properties found in the previous step.

For both steps of homogenization, we use the multi-component self-consistent approximation (EMA) method that belongs to the micromechanical effective media methods. The use of this method does not take into account the electrochemical and electrokinetic phenomena. These methods are widely used in the determination of the effective physical properties in sedimentary rocks due to its reliability (De Lima et al., 2005; Gelius and Wang, 2008; Gomez et al., 2010; Kazatchenko et al., 2004a, 2006a, 2006b; Markov et al., 2012; Sheng, 1991). The EMA method is a unique technique that provides the solution of the homogenization problem for our multi-component model because this method, in comparison with the DEM method and Effective Field Method (Kanaun and Levin, 2008) does not require introducing any