Simulation of physical properties using empirical equations and micromechanical methods in a unified petrophysical model for sand-clay formations

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Abstract

The petrophysical evaluation in sand-clay reservoirs is an important worldwide issue due to the presence of hydrocarbons in this type of formation. The calculation of physical properties in sand-clay formations depends mainly on the petrophysical model used and must consider the spatial distribution of clay. For this reason, in this work the simulation of physical properties is carried out with a hierarchical unified petrophysical model for sand-clay formations that consists of three levels of homogenization: 1) pores that contain fluids and clay 2) sandstone composed of quartz grains, structural clay 3) formation composed of sandstone and layered clay intercalation. Physical properties, such as transit time of P and S waves, electrical resistivity, density, neutron porosity and gamma rays were simulated with two different techniques, the first; from micromechanical methods (Effective Medium Approximation, EMA), characterized by taking into account the size, shape and modeling various physical properties at the same time, and the second; with empirical equations that are applied in the conventional evaluation of geophysical well logs characterized by applying different models to estimate a single physical property. Finally, particular cases of the unified petrophysical model are presented to analyze the differences in simulated physical properties with respect to sand porosity.

OBJECTIVE.

Analyze the differences between simulated physical properties from a hierarchical petrophysical model, with different simulation techniques and establish relationships between simulated physical properties.

RESUME.

The petrophysical evaluation in sand-clay reservoirs is an important issue worldwide due to the presence of hydrocarbons in this type of formation. The calculation of physical properties in sand-clay formations depends mainly on the petrophysical model used and must consider the spatial distribution of clay. For this reason, in this work the simulation of physical properties is carried out with a petrophysical model

unified hierarchical structure for sand-clay formations consisting of three levels of homogenization: 1) pores containing fluids and clay 2) sandstone composed of quartz grains, structural clay 3) formation composed of sandstone and layered clay intercalation. Physical properties, such as transit time of P and S waves, electrical resistivity, density, neutron porosity and gamma rays were simulated with two different techniques, the first; from micromechanical methods (Effective Medium Approximation, EMA), characterized by taking into account the size, shape and modeling various physical properties at the same time, and the second; with empirical equations that are applied in the conventional evaluation of geophysical well logs characterized by applying different models to estimate a single physical property. Finally, particular cases of the unified petrophysical model are presented to analyze the differences in simulated physical properties with respect to sand porosity.

INTRODUCTION.

The estimation of petrophysical properties such as clay volume, water saturation, oil saturation in sand-clay formations is not adequate due to the uncertainty of the simulation of physical properties (electrical resistivity, acoustic velocities), the uncertainty increases due to because different petrophysical models for different physical properties are used to characterize the same medium. The erroneous results in the determination of physical properties in the determination of petrophysical properties in clastic rocks are related to conventional interpretation techniques that do not consider the spatial distribution of clay: dispersed, structural and laminar. Most of the "conventional" models that are currently applied in well log interpretation were developed for specific methods such as sonic, electrical or neutron logs that are not compatible and each model is applied to determine different petrophysical properties (Aquino, 2015).

The first model to estimate water saturation in clean sands was proposed by (Archie, 1942). Subsequently, different models have been developed for clayey sands that only consider electrical resistivity. Poupon proposed an equation for the distribution of laminar shale, the equation of (Simandoux, 1963), represents a type of distribution of structural and dispersed clay, Waxman and Smits (1968) developed a

model for the presence of dispersed clay. However, these equations do not consider different clay distributions at the same time.

Based on the propagation of elastic waves, (Wyllie, 1956) proposed a volumetric approach to determine the porosity of the formation, (Raymer et al., 1980), carried out an empirical algorithm and obtained a non-linear relationship to improve the porosity determination. (Han, 1986) performed empirical linear regressions relating velocity to porosity and clay content.

Some authors applied micromechanical methods for the petrophysical evaluation of clastic rocks (Sheng, 1991), (Aquino, 2015), and carbonate rocks (Kazatchenko, 2004) using different physical properties simultaneously. In addition (Lechuga, 2018) simulated physical properties using empirical equations (Archie, Wyllie, Raymer Hunt Gardner) and micromechanical methods from a petrophysical model for unconventional shale oil and gas reservoirs.

There are physical properties that are not a function of the shape of the components, such as density, this is because this record is sensitive to electron density, the number of electrons per cubic centimeter, which is directly related to volume density. (Bassiouni, 1994) , (Lettuce, 2018). The neutron porosity response is sensitive to the hydrogen index and is associated with the presence of medium fluids and clay with bound water. (Schon, 2011).

In this thesis, the simulation of physical properties using micromechanical methods and empirical equations is shown considering a hierarchical model that considers three levels of homogenization: 1) pores containing water, gas and dispersed clay, 2) sandstones formed by quartz, structural clay and pores (with the effective physical properties estimated at the first level of homogenization) and 3 formation composed of layers of sandstone and laminar clay.

The EMA (Effective Medium Approximation) micromechanical method was applied to simulate effective physical properties at the first two levels of homogenization using the IMP-PILD® software. The stratified formations (third level of homogenization) are transverse isotropic media and the elastic moduli and electrical resistivity aretensioners. EMA allows the simulation of physical properties such as electrical resistivity, acoustic velocities, density, neutron porosity and gamma radioactivity.

For the case of the simulation with conventional equations, various petrophysical models were used that are used in the conventional evaluation of geophysical logs for the separate calculation of physical properties such as electrical resistivity, acoustic velocities, density, neutron porosity and gamma radioactivity in the three levels. homogenization of the Hierarchical model.

Micromechanical methods

Theory of the effective medium

The effective medium theory implicitly assumes that the effect of heterogeneity exists in the studied medium and this can be represented by a basic morphological unit. This approach considers that an elementary cell contains a spherical heterogeneity embedded in a matrix. This physical conceptualization does not explicitly calculate the size of the heterogeneity but rather its shape (Cosenza, 2009). This theory is applied in the proposed model, where it is also considered that the anisotropy of the medium affects the measured physical response (Kazatchenko., 2007) (Aquino, 2015). Each of the physical properties of the model components are homogenized and integrated to the next corresponding level (Figure 3.2).

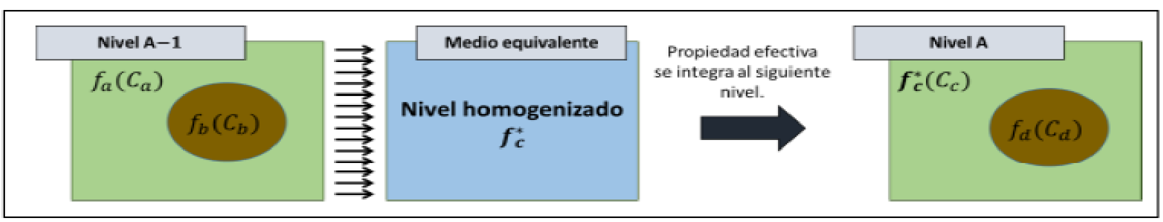


Figure 3.2 Scheme that describes the homogenization process of the effective properties of the medium. At level A-1 an element a and an element b are considered. the physical property fa(ca) are homogenized with the physical property fb(cb). The homogenized physical property f*c is introduced at level A and the process is repeated. (Lettuce, 2018)

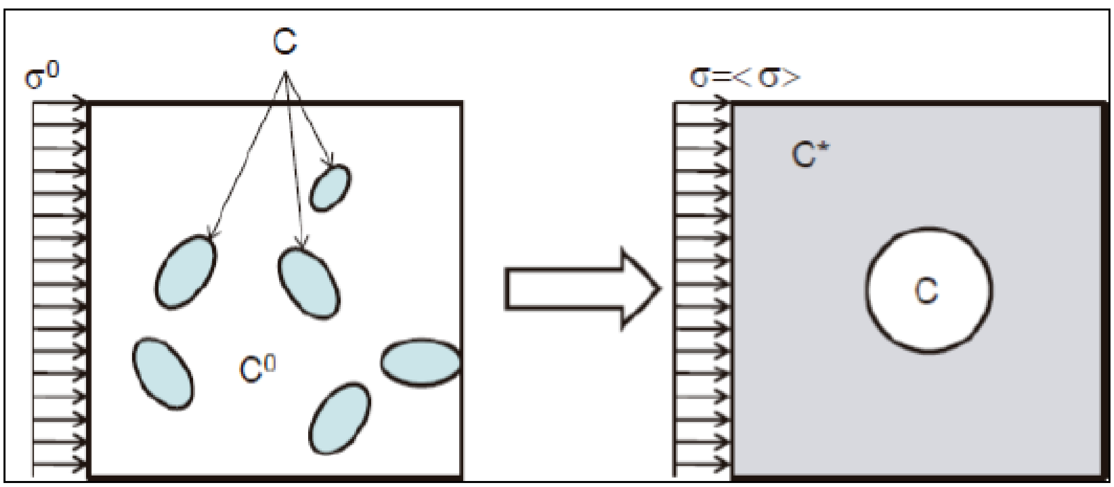
There are different methodologies developed to determine the effective properties of the medium depending on the different components that make up the rock. These methodologies are called self-consistent, which use the concept of effective field to take into account the iteration between particles. Such methodologies require a "host", which for practical purposes of this research is not applicable (Aquino, 2015). An example is the “Differential Effective Medium” (DEM) method, which cannot calculate the resistivity when the host is a solid without water, nor the transit time of the shear wave when the host is solid. a fluid.

The method used to model the effective properties of the medium is "Effective Medium Approximation" (EMA), which allows considering a multicomponent system when all the components are treated equally, with which no material is considered as " host” (Kazatchenko, Markov, & Mousatov, 2004).

Effective Mean Approximation (EMA)

There are several methods of effective medium, in this thesis it is proposed to use the so-called EMA (Effective Medium Approximation). The EMA method was originally proposed by Bruggeman in 1935 and remains a popular approach for determining the physical properties of compounds (Torquato S. a., 2011). Since its invention, it has been the basis for a vast number of studies of macroscopic inhomogeneous media and has been generalized by numerous authors to treat a wide variety of problems (Stroud, 1998). Each inclusion in the composite is assumed to behave as if isolated in a homogeneous medium with properties that match the general properties of the composite material. The field acting on each inclusion in the compound is the external field ε0 applied to the heterogeneous field. The assumed hypothesis reduces the problem of interaction between many inclusions in the compound to the problem of an isolated inclusion embedded in a homogeneous medium (Figure 2.5).

Figure 3.3 Scheme of the Effective Means Method (Kanaun & Levin, 2008).



EMA is generally used for symmetric configurations since no matrix is required to be entered. The expressions that result for the estimation of the effective properties depend on the properties of the phases involved and their volumetric fractions, in addition to the shapes of the inclusions (Torquato S., 2000). This method assumes that the medium is composed of N components that are treated equally (Kazatchenko., 2007).

(Kazatchenko et al., 2004) used the AMS approach for carbonate rocks because the method takes into consideration the real physical requirements that the matrix simultaneously have a non-zero shear modulus and electrical conductivity. Additionally, EMA makes it possible to solve the homogenization problem of a multicomponent system such as a matrix composed of grains of different minerals.

The homogenization problem using the EMA method approach can be performed for multicomponent systems by treating each component equally (not identifying any of the components as a solid or fluid host medium) (Berryman, 1995) ; (Norris et al., 1985).

The general EMA equations for the elastic properties of a medium composed of N constituents used for the simulation are: (Kazatchenko et al., 2004).

3.3 Method for calculating model parameters. Joint investment technique

The application of joint inversion can be carried out for the determination of different parameters, depending on the experimental data available. For example, the determination of the shapes of pores and grains that make up the rock matrix (fundamentally quartz), in the case of clean sands. For the case of more complex formations, it is necessary to estimate the volumes of the different types of spatial distribution of clay (dispersed, structural and lamellar) (Aquino, 2015).

The fundamental idea in the use of joint inversion is to take into consideration at the same time all the physical properties that are measured and by means of an equation to couple these properties in such a way that we minimize the difference between the measured and simulated physical properties. For this, it is necessary to consider, in the discrepancy function, weights for each of the properties. These weights can be estimated from the dispersion of the input data (Aquino, 2015).

The determination of the weights is a good idea because there are different physical properties that vary in different ranges and where in many cases, these variations indicate changes in the petrophysical properties, but in other cases they are affected by measurement problems that make measurements are not reliable (Aquino, 2015). Well log interpretation using the joint inversion technique has recently been used to determine the petrophysical parameters of formations. The first commercialized log interpretation technique using inversion of three different physical properties, called ELAN, was developed by the Schlumberger company (Mitchell & Nelson, 1988); (Schlumberger, 1987).

The ELAN (Elemental Log Analysis) terminology refers to the standard processing of well logs where the inversion technique is used to determine petrophysical properties using information from different well logs (Schlumberger, 1987).

The ELAN processing is a probabilistic model that allows the calculation of properties of the petrophysical model considering that the equations that simulate the physical responses of the tools are linear.

The main application of this model is related to the determination of the elements that make up the rock matrix and its porosity.

The multi-physics or time-share investment technique compared to conventional investment creates an additional problem. This problem consists of equalizing the influence (sensitivity) of different physical properties in the discrepancy function that is minimized in the inversion process (Aquino, 2015).

The discrepancy function must be formulated in order to determine the parameters of the model based on the information available. Equation 3.16 shows a discrepancy function that takes into account the information of the different physical properties measured. Note that on the left side of the equation are the parameters to be searched for.

$F(p1,p2,\ldots pi)$=$Wm1(m1-m1*)2$+$Wm2(m2-m2*)2$+…+$Wmn(mn-mn*$)

(3.6)

Where F is the discrepancy function that must be minimized to estimate the parameters sought, $p1,p2,\ldots pi$ are the parameters to be sought from the model, $Wm1$, $Wm2$,…, $Wmn$are the weights assigned to each of the physical properties that are measured, $m1$, $m2$,…, mn are the physical properties measured and, $m1*$, $m2*$,…, $mn*$ are the physical properties estimated by micromechanical methods.

The coupling of the terms of the discrepancy equation for different properties is done with the weighting coefficients Wmi. These coefficients can be selected in two different ways: as inverse values of the sensitivity of each property to the model parameters (Zhdanov, 2002) or as the standard deviation of the measured properties (Kazatchenko et al., 2007). The investment comparison results show that both types of weighting coefficients can be applied for timeshare investment. However, the use of the inverse values of the standard deviations is preferable since they do not require a priori knowledge of the model for sensitivity calculations for each property and, in addition, take into account the influence of measurement errors for properties used in inversion. . Based on the analysis of the discrepancy distributions between the measured and simulated values for each property, the weighting coefficients can be adjusted, for example, in the case of low quality of a record or measured property (Aquino, 2015).

To minimize the discrepancy function it is necessary to apply a certain technique. Parameter estimation can be seen as an optimization problem in which the discrepancy function represents the difference between the measured and simulated data that must be minimized (Mead, 2008). There are different methods that allow solving the minimization problem, such as the Newton-type methods or those of rapid descent or gradient (Kool et al, 1987). There are fundamentally two different optimization methods, those based on the local calculation of the function to be optimized (eg gradient-based methods) and those based on random search. The advantage of gradient-based methods is that when they work they are very efficient and the disadvantage is that if the function to be optimized is very complex, then the local properties of the function to be optimized may be of little interest (Tarantola, 2005). .

Taking into account that the surface topology of the discrepancy function for the joint inversion of different properties can be complicated, both optimization techniques are used in practice.

Simulation of physical properties of the unified hierarchical model for sand-clay formations

The previous chapter described the unified hierarchical model for sandy-clay formations and the equations used by the EMA (Effective Mean Approximation) method to simulate physical properties simultaneously. This chapter describes the empirical equations to model physical properties by level of homogenization, these equations were proposed using the petrophysical models mentioned in chapter 2, and were adapted to simulate the physical properties of the components of the proposed petrophysical model.

Finally, the numerical simulation of physical properties is presented from the hierarchical model using the empirical equations and micromechanical methods (EMA). The simulation is presented in graphs of porosity vs simulated physical properties of the proposed cases. The proposed cases represent various geological scenarios, in this work a sand saturated with water, a sand saturated with water and gas, sand saturated with water with intercalation of lamellar clay, sand saturated with water and the presence of structural clay, and finally a water-saturated sand and dispersed clay. These geological scenarios help us to observe the sensitivity of the physical properties by modifying the components of the petrophysical model.