A multi-physics, integrated approach to formation evaluation using borehole geophysical measurements and 3D seismic data

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Summary

This paper describes a methodology for formation evaluation based on the integration of multi-physics borehole geophysical measurements and 3D seismic data. The objective is to estimate in-situ petrophysical parameters that honor the physics of multi-phase mud-filtrate invasion taking place in the immediate vicinity of the wellbore. Examples are shown of the estimation of porosity, absolute permeability, permeability anisotropy, and initial water saturation using combinations of electromagnetic logs, formation tester data, P- and S-wave sonic logs, and magnetic resonance measurements. A procedure is also described to estimate petrophysical parameters based on the use of time-lapse logging and in-situ permanent pressure and DC resistivity sensors. Finally, 3D seismic data, post-stack and pre-stack, are used to ascertain lateral extent and continuity of lithology and flow units.

Introduction

Borehole geophysical measurements are customarily used in conjunction with core data to estimate in-situ rock formation properties. The economical assessment of hydrocarbon flow units requires of accurate estimates of effective porosity, absolute permeability, permeability anisotropy, relative permeability, capillary pressure, fluid saturation, PVT fluid properties, thickness, and lateral extent. Most estimation procedures rely on independent assessments that fail to fully integrate the notion of a common petrophysical model. For instance, estimates of total porosity are obtained via active gamma ray density tools. Porosity estimates are subsequently used together with resistivity measurements to provide estimates of in-situ water saturation. Formation tester measurements, on the other hand, are primarily used to estimate formation pressure, absolute permeability, and fluid properties. On occasion, magnetic resonance measurements are used to assess irreducible water saturation, effective porosity, and absolute permeability. Similarly, sonic logs are used to assess mechanical compliance, porosity, presence of gas, presence of fractures, and in-situ stress. Nuclear spectroscopy tools (e.g. nuclear and gamma-ray activation tools) are used to assess mineralogy and volumetric composition of solid materials. Fully integrated interpretation of multi-physics borehole geophysical measurements is difficult because of their substantial differences in geometrical support (vertical resolution and depth of penetration).

Techniques used for the interpretation of borehole geophysical measurements are often based on simple assumptions concerning the phenomenon of mud-filtrate invasion. Even though such a phenomenon is commonly regarded a technical nuisance by well-log analysts, it can serve as a working template to quantitatively integrate borehole geophysical measurements. This paper summarizes work performed by the authors to quantify and constructively make use of the phenomenon of mud-filtrate invasion to estimate spatial distributions of petrophysical parameters that honor all of the available borehole measurements. The same model is used to integrate P- and S-wave sonic measurements with 3D post-stack and pre-stack seismic data and to estimate lateral extent of flow and lithology units away from existing wells.

Numerical Simulation of Mud-Filtrate Invasion: Immiscible and Miscible Fluid Phenomena in Complex Porous Media

Numerical simulation of the phenomenon of mud-filtrate invasion can be performed with commercial multi-phase and compositional reservoir simulators. Likewise, the physics of mudcake growth and time-varying rates of mud-filtrate invasion can be coupled with formation properties to accurately replicate dynamic invasion (Wu et al., 2001). Figure 1 shows a cross-section of a simple example of horizontal permeable rock formations drilled with a deviated well. Rock formations are assumed saturated with oil and salty irreducible water. Porosity of these formations is assumed constant and equal to 20%; the corresponding absolute permeability values are indicated on the cross-section. Drilling is assumed performed with a fresh water-base mud. A cross-section of water saturation across the formations is shown in Figure 2 after 4 days of mud-filtrate invasion. Because of differences between salt concentration in the mud (40,000 ppm) and in the connate formation water (100,000 ppm), salt mixing takes place within the formations as mud-filtrate traverses the mudcake. Depending on the nature of relative permeability curves, the salt front may trail or precede the water saturation front, hence causing unexpected behavior to the spatial distribution of electrical resistivity (George at al., 2003). Figures 3 and 4 show the corresponding cross-sections of salt concentration and electrical resistivity, respectively. Electrical resistivity was computed using the simplest form of Archie's law and water resistivity values consistent with the spatial distribution of salt concentration (Alpak et al., 2003). Based on these cross-sections, it becomes clear that the common assumption of a piston-like radial distribution of electrical resistivity could lead to significant interpretation errors. To further understand this very important remark, Figure 5 shows the corresponding cross-section of electrical resistivity simulated under the assumption of a 10:1 ratio of permeability anisotropy (horizontal-to-vertical permeability) in the center formation layer. This cross-section exhibits significant differences with respect to the simulated resistivity cross-section of electrical resistivity in the absence of permeability anisotropy, especially in the proximity of layer boundaries.

Automatic Inversion of Petrophysical Parameters: coupling the physics of mud-filtrate invasion with the physics of electromagnetic scattering

Considerable emphasis has been given to the numerical simulation of borehole electromagnetic measurements. The advent of tri-axial tools has also spearheaded a great deal of work to understand the role played by electrical conductivity anisotropy. However, interpretation of rock formation properties based solely on borehole electromagnetic measurements often fails to honor the physics of mud-filtrate invasion. The authors have developed inversion procedures to estimate petrophysical parameters that honor the physics of mud-filtrate invasion and the physics of electromagnetic scattering. Electromagnetic modeling is performed using 3D finite-difference staggered grids, fast integral equation solvers, and novel approximations based on integral equations. Even though these methods can efficiently reproduce the effect of electrical anisotropy and complex 3D distributions of electrical resistivity, work remains to be done to consistently integrate permeability anisotropy phenomena with electrical anisotropy phenomena. Presence of salt mixing usually obscures the interplay of the two physical properties. The inversion of borehole electromagnetic data can assume either single-time or time-lapse data (e.g. LWD and wireline data) when coupled with the physics of mud-filtrate invasion. This yields multi-layer estimates of porosity, absolute permeability, and water saturation.

Formation Tester Measurements

Borehole formation testers can sample pressure, fractional fluid rates, and fluid properties. They perform a local fluid withdrawal experiment under controlled flow-rate conditions. The measured time evolution of pressures and fractional fluid rates can be used to ascertain formation properties such as porosity, permeability, relative permeability, and capillary pressure (Wu et al., 2002). However, accurate and reliable estimation of petrophysical properties requires proper account of the physics of mud-filtrate invasion. Because of the large CPU times required by the simulation of mud-filtrate invasion, inversion of formation tester measurements poses significant numerical and computer challenges. Moreover, borehole electromagnetic measurements are necessary as ancillary information to constraint variables such as time of invasion and total volume of mud-filtrate. Examples are shown in this paper of the joint inversion of formation tester and borehole electromagnetic measurements that honor the physics of mud-filtrate invasion.

Borehole Sonic Measurements in the Presence of Mud-Filtrate Invasion

The authors have also developed numerical procedures to quantify the influence of mud-filtrate invasion on measurements of P- and S-wave velocities acquired with borehole logging tools. Examples are described of the analysis of time records simulated numerically for arrays of borehole sonic sensors using monopole and dipole sources. The assessment of the effect of mud-filtrate invasion provides a quantitative method to improve the consistency between surface seismic amplitudes and rock formation properties estimated with sonic borehole tools.

Additional Borehole Geophysical Measurements

The physics of mud-filtrate invasion can serve as working template to integrate measurements performed with nuclear (e.g. density and neutron measurements) and magnetic resonance tools. This strategy also embodies a natural way to assimilate differences in length of penetration and vertical resolution inherent to a particular measurement. Moreover, reverse modeling of the process of mud –filtrate invasion can be used to interpret borehole measurements performed behind casing, such as those normally used to assess fluid saturation changes resulting from reservoir production.

Recently, in-situ permanent sensors have been prototyped and field-tested to measure and interpret real-time changes in the dynamic behavior of hydrocarbon reservoirs. Sensor prototypes include pressure gauges and DC electrodes deployed behind casing. The advent of in-situ permanent sensors also opens the interesting possibility of controlling hydrocarbon production with a feedback loop aimed at optimizing recovery and sweep efficiency. This paper describes several examples of the use of in-situ permanent sensors to estimate spatial distributions of porosity and permeability.

Stochastic Inversion of Borehole Measurements and 3D Seismic Data

Seismic data are sampled along regular and closely spaced surface grids. Even though the vertical resolution of surface seismic data is far from that of borehole measurements, the former can be used to quantitatively fill the spatial gap between sparse well locations. A procedure has been developed by the authors to extrapolate petrophysical properties laterally away from wells. This procedure is based on the concept of geostatistical inversion put forth by Haas and Dubrule (1994). The vertical resolution of the seismic extrapolated petrophysical properties is midway between that of well logs and 3D seismic data. As opposed to standard geostatistical simulation methods, petrophysical properties interpolated with geostatistical inversion honor not only the borehole measurements but also the 3D seismic data between them. Figure 6 shows an actual field example of the spatial distribution of stochastically inverted acoustic impedances together with spontaneous potential logs. The resolution of the inversion is 0.5 ms, i.e. four times that of the vertical resolution of the input seismic data (2 ms) and provides an excellent indication of the lateral continuity of existing sand units. More recently, the authors have developed a stochastic inversion procedure that honors surface pre-stack 3D seismic data and borehole measurements. This procedure considerably increases the range of possibilities for the accurate estimation of petrophysical parameters between existing wells. Stochastic inversion of borehole measurements and 3D seismic data has also been used to construct high-resolution hydrocarbon reservoir models amenable to numerical simulation of multi-phase fluid flow.

Conclusions

The physics of mud-filtrate invasion provides a natural interpretation model to fully integrate multi-physics borehole geophysical measurements. Inversion procedures can be formulated to jointly honor several types of borehole geophysical measurements. Although naturally appealing, this is a highly challenging task: efficient numerical solvers are necessary to replicate mud-filtrate invasion phenomena in the presence of both oil- and water-base drilling mud. Similarly, rock physics models are necessary to deterministically (or statistically) link effective medium properties with multi-phase petrophysical parameters. While many technical issues still remain to be addressed, this paper provides a survey of preliminary results that address some of the salient physical and mathematical concepts.

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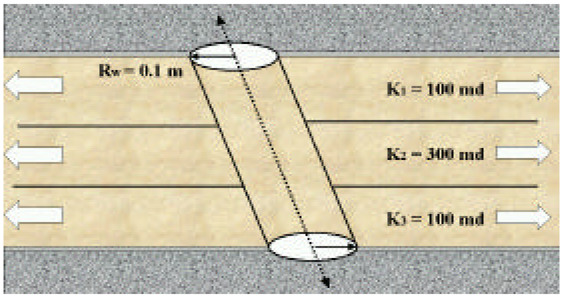

Figure 1. Cross-section of a generic three-layer formation model drilled with a fresh water-base mud. Permeable rock formations are assumed saturated with oil and salty irreducible water. Permeabilities for each layer are as indicated in the figure. Porosities are assumed constant and equal to 20%.

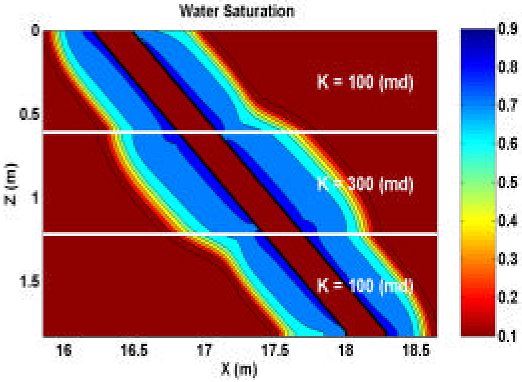

Figure 2. Cross-section of water saturation after four days of invasion. The cross section was obtained via numerical simulation of the process of mud-filtrate invasion.

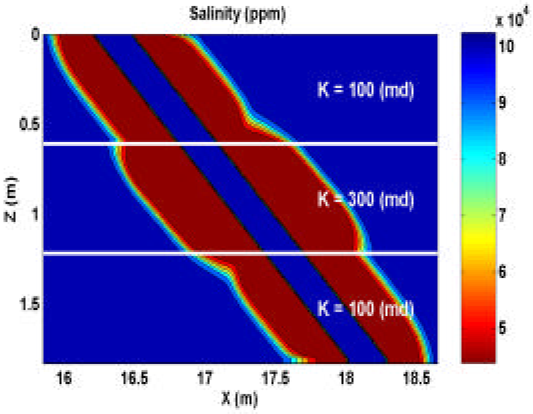

Figure 3 Cross-section of salt concentration after four days of invasion.

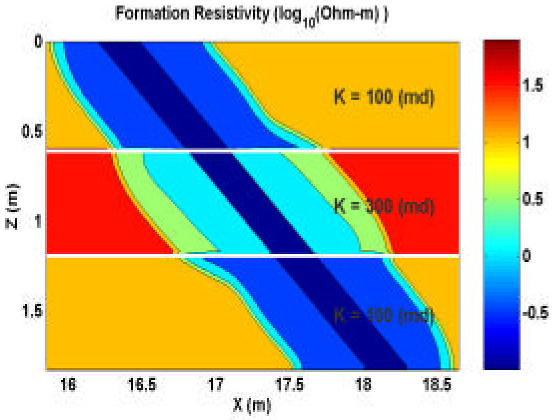

Figure 4. Cross-section of electrical resistivity after four days of invasion. The cross section was obtained through the use of Archie's law.

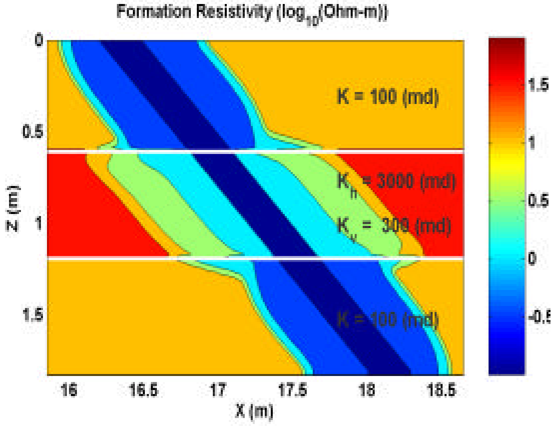

Figure 5. Cross-section of electrical resistivity after four days of invasion in the presence of a large contrast of permeability anisotropy.

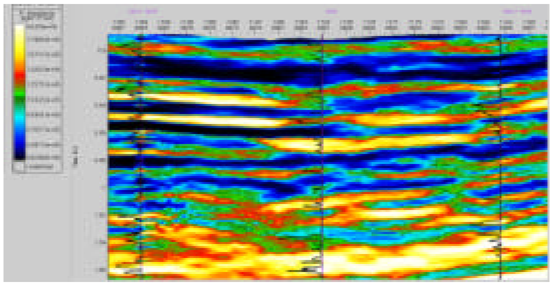

Figure 6. Cross-section of acoustic impedance stochastically inverted by honoring borehole measurements and surface 3D post-stack seismic data. The vertical axis is two-way seismic travel time. Well locations are shown together with spontaneous potential logs.