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Characterization of Reservoir Heterogeneity Through Fluid Movement Monitoring With Deep Electromagnetic and Pressure Measurements

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Abstract

Cores, open hole logs, formation testers, pressure transient tests, and production logs are usually used to assess reservoir heterogeneity. A common limitation of these techniques is that they do not provide two-dimensional spatial information of reservoir characteristics. For example, cores and logs have excellent vertical resolutions, but very small lateral radii of investigation, and the pressure transient tests have a large lateral radius of investigation, but very poor vertical resolution. Constructing an appropriate simulation model requires rescaling the data, and that may introduce significant uncertainties. To address these limitations, we explored the use of electrode resistivity array (ERA) measurements in a carbonate formation for reservoir characterization. The ERA was installed on tubing in a barefoot well rather than permanently cemented outside the casing as in previous applications. This notable difference introduced particular issues in the ERA data acquisition and interpretation, but also provided flexibility for device installation and operation. Furthermore, the ERA measurements were carried out in conjunction with low-salinity water injection and production in the same well. It was found that the ERA voltages near a source electrode showed unique characteristics that represented local formation heterogeneity. Although the new technology can be used at any scale, the focus was on characterizing formation heterogeneity within the length of the ERA string in the vertical direction and about 100 ft laterally around the wellbore. The scale of the investigated formation heterogeneity is comparable to grid sizes used in current reservoir simulations. Models were developed to identify stratified permeability heterogeneities from the time-lapse ERA voltages. The stratified heterogeneity estimated from the ERA measurements was compared to and verified by open hole logs and core analyses. The final heterogeneous reservoir model from ERA was subsequently applied to a numerical simulation that integrated the dynamic fluid flow, salt transport, and electrode array responses for water front monitoring and multiphase formation property evaluation and confirmed the first pass estimates of the identified heterogeneities.

Introduction

Permeability heterogeneity, especially that induced by formation stratification, is very important in all aspects of reservoir engineering processes, from well placement to enhanced oil recovery applications. The stratified and interwell heterogeneities dictate fluid movement and waterflooding efficiency, thus significantly affecting hydrocarbon recovery. This is particularly true in carbonates, for which reservoir heterogeneity exists at many different scales. Detailed reservoir characterization is needed to better map the formation heterogeneity for reservoir management. Core experiment, open hole wireline logging, wireline formation tester, pressure build up, injection/fall off test, and production logging are the conventional methods for characterization of reservoir heterogeneity. Although applications and advantages of these techniques in formation evaluation are well established, each has limitations that should not be overlooked. In general, these measurements can be divided into two categories: static and dynamic.

For instance, open hole logs provide continuous, detailed vertical results of porosity, sand face effective resistivity images, lithology compositions, initial fluid distribution, etc. These are static properties of the formation. Correlations are used to link these static properties to dynamic properties, such as permeability. The results are subjective and are limited by the applicability of calibration from core measurements. Moreover, the depth of the investigation of wireline logs is usually