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Hydrocarbon saturation in Bakken Petroleum System based on joint inversion of resistivity and dielectric dispersion logs

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ABSTRACT

Bakken Petroleum System (BPS) is composed of both conventional and unconventional units, which exhibits significant variations in lithology, rock texture, clay content, total organic carbon, accompanied by high connate water salinity, presence of disseminated pyrite grains, and low values of porosity. These petrophysical attributes of the BPS lead to inconsistency in the oil-in-place estimates for those obtained from Electromagnetic (EM) induction log, Nuclear Magnetic Resonance (NMR) log, dielectric dispersion log measured by Array Dielectric Tool (ADT), and Dean-Stark core measurements. For purposes of improved hydrocarbon saturation estimation and petrophysical characterization in the BPS, a joint-inversion-based interpretation was performed on dispersive electrical conductivity and dielectric permittivity measurements at 4 dielectric-log-acquisition frequencies and 1 induction resistivity acquired at 20 kHz. This analysis was performed across a 350-ft depth interval in one of the science wells intersecting the BPS. Three geo-electromagnetic mixing models, namely Complex Refractive Index model, Stroud-Milton-De model, and Waxman Smits model are integrated and coupled to the inversion scheme to simultaneously estimate water saturation, formation brine conductivity, cementation exponent and saturation exponent in BPS.

Water saturation estimates obtained using the proposed interpretation method were compared against those obtained from NMR log, Dean-Stark core measurements and service company's dielectric inversion. In Middle Bakken from depth XX720 to XX750 ft, our estimates of water saturation are in better agreement with those estimated by service company's mineral inversion method and service company's dielectric interpretation as compared to those obtained from NMR interpretation and Dean Stark core measurement. Water saturation and formation brine conductivity estimates in Middle Bakken are in the ranges of 0.5–1 and 25–45 S/m, respectively. Inversion-derived brine conductivity and saturation exponent estimates are most uncertain in Lodgepole and Three Forks 2 formations, which exhibit a wide range of pore size distribution. Average relative errors in matching the 1 induction resistivity and 8 dielectric dispersion logs using the inversion-derived estimates are 33% and 20%, respectively, in the 350-ft depth interval of BPS. The proposed inversion achieves high certainty for the estimates when the formation has low clay content, low electrical anisotropy, and high porosity.

1. Introduction

The Bakken Petroleum System (BPS), one of the largest tight oil deposits in the world, is situated in the Williston Basin that covers parts of North and South Dakota, Montana, and southern Canada [1]. BPS consists of two layers of organic-rich shale (the Upper and Lower shales) sandwiching a dolomitic-siltstone interval of 45 ft thickness called the Middle Bakken. The Lodgepole formation overlying the Upper Bakken Shale mainly consist of limestone. Specifically, Scallion is the basal member of Lodgepole formation which overlies the Upper Bakken Shale. Included in the BPS below the Lower shale is the Three Forks formation, composed of laminations of dolostone and dolomitic-mudstone. There exist multifold complexities in formation evaluation, including hydrocarbon saturation estimation. Reservoirs in the Bakken Formation are characterized with low porosities and permeabilities, ranging from 5 to 15 pu and 1 to 20 mD, respectively [2]. Mineral constituents in BPS include varying amount of quartz, calcite, dolomite, kerogen, chlorite, illite, montmorillonite and pyrite [3]. A complex distribution of reservoir and clay mineralogies, formation fluids, and reservoir quality are present in these formations. Additionally, low-resistivity pay, laminated sandstones and shales, and micro-porosity pose problem while estimating water saturation [4].

Water saturation estimation in organic-rich shale reservoirs is challenging due to effects of clay and conductive minerals on the

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resistivity-based saturation analysis. Adverse effects of clay minerals on saturation estimation can be addressed by using Dual Water or Waxman-Smits (WS) equation. Interpretation of induction tool measurements focuses on the petrophysical controls on charge transport through porous media. The frequency of operation for induction tools is low; as a result, conductivity component dominates the permittivity components, unless there are clay and conductive mineral grains in the formation. Interpretation of dielectric dispersion tool measurements is based on the large contrast between permittivity of water and that of oil and rock minerals. Interpretation of induction measurements are highly sensitive to formation water salinity, whereas that of dielectric dispersion measurements tends to be less sensitive to the salinity [5]. For the frequency range of dielectric dispersion logs, both the real and imaginary components are dominant.

Pirie et al. [6] compared water saturation estimates obtained from triaxial resistivity induction log, NMR log, dielectric dispersion log, Techlog Quanti-ELAN, and Dean-Stark core measurements. S_w evaluated with the petrophysical model using R_h from induction resistivity logs at 2-ft vertical resolution compared very well with S_w obtained from dielectric measurements in Middle Bakken. The Dean-Stark core water saturation ranged from 40 to 60% in lower portion of Three Forks formation while dielectric measurements suggested 100% water saturation. The Bakken formation water salinity from core measurements tend to be large values in the range of 240–360 ppk; therefore, there is a need for more robust method to estimate the formation water salinity. Dielectric measurements lose their sensitivity at high salinity values greater than 70 ppk. Donadille et al. [7] demonstrated the limitations in accurately determining high connate-water salinity with dielectric logs. Joint inversion of neutron sigma measurements and dielectric dispersion logs provides stability to petrophysical results and excellent sensitivity to high salinity values in Bakken shale formation. Water saturation estimates agreed with the core water saturation measurements and salinity estimates were from 100 to 400 ppk for Bakken formation. Water saturation and brine resistivity were estimated by combining wireline induction and sigma logs in several wells in Middle East carbonate fields [8]. The comparison of water saturation derived from the joint processing of resistivity-sigma logs against those obtained from carbon-oxygen (CO) logs was reasonably good in high porosity formation, whereas water saturation estimated from joint processing of resistivity-sigma logs was more robust in tight formations. The proposed resistivity-sigma interpretation technique requires the values of cementation exponent, tortuosity factor and saturation exponent to be known a priori.

Han et al. [9] combined Lichtenecker–Rother model, Stroud-Milton De model, and PS model to process 8 dielectric dispersion logs for estimating water saturation, formation water salinity, homogeneity index, and cementation index in clay-lean and clay-rich units of Bakken shale. They compared their estimates with Dean-Stark core water saturation, NMR interpretation and service company's inversion results for a 300-ft depth interval in BPS. This integrated model technique generated range of possible values for estimates and assumed a homogenous formation. Misra and Han [10] carried out joint interpretation using conductivity and permittivity values obtained from EM induction at 26 kHz, EM propagation at 400 kHz and 2 MHz, and dielectric dispersion logs at 20 MHz, 100 MHz, 260 MHz, and 1 GHz to estimate the water saturation, bulk conductivity of brine, surface conductance of clay, and radius of spherical clay grains in European shale formation. This proposed inversion was performed assuming isotropy and homogeneity of the investigated volume. Glinskikh et al. [11] implemented two algorithms, Nelder-Mead non-linear error minimization and pseudo-inversion of sensitivity matrix coupled for petrophysical inversion of high frequency induction logs acquired in a shaly sandstone formations of West and East Siberia to estimate water saturation, porosity and clay fraction in the formation. The mixing model accounted for conductive dispersed clay assuming a three-component mixture of nonconductive quartz grains, conductive clay particles, and host fluid. Results of numerical inversion showed high quality for water saturation and porosity as compared to clay fractions. Ramirez et al. [12] implemented a probabilistic approach with Bayesian stochastic inversion of gamma ray, density, and resistivity logs to estimate porosity, water saturation and volumetric shale concentration in thinly bedded formations. Their estimates were consistent with deterministic inversion approach and provided uncertainties of layer properties and hydrocarbon reserves.

There are several challenges in characterizing Bakken system due to complex mineralogy, low-pay resistivity, high salinity, and high clay content [13] [14]. Formation evaluation in conventional reservoirs at low frequencies with deep-sensing or high-resolution EM logs, such as laterolog, induction log is dominated by the conductivity of the formation and affected by polarization of clay and conductive minerals. At higher frequencies, the dielectric effects due to pore morphology and water content dominate. Dielectric measurements at multiple frequencies helps to evaluate both permittivity and conductivity of a geological formation at multiple frequencies; thereby capturing the dispersive dielectric effects due to conductive minerals, clays, interfaces, and water content. In contrast, interpretation with only 1-GHz dielectric permittivity log or with only laterolog or induction resistivity log or with only 8 dielectric dispersion logs is sensitive to model assumptions, polarization mechanisms, textural effects, noise in data, and noise in model inputs. These challenges are addressed in this paper by performing a joint processing of 1 resistivity and 8 dielectric dispersion logs using an integrated mechanistic model. Eight dielectric dispersion logs and one induction resistivity log acquired in 350-ft depth interval of BPS are simultaneously processed to estimate the water saturation (S_w), brine conductivity (C_w), saturation exponent (n) and cementation exponent (m).

2. Method

2.1. Relevant EM logging tools

The induction log uses a high frequency current flowing in a coil to induce a current in the formation that flows circumferentially around the tool axis. Induction measurements are related to the electrical conductivity of the formation. Induction tools are generally recommended for wells drilled with oil-based muds. Array Induction Tool (AIT) generates resistivity logs at five different depths of investigation (DOI), namely10, 20, 30, 60, and 90 in., with vertical resolution ranging from 1 to 4 ft. The differences between these curves enable accurate assessment of true formation resistivity, R_t, free from the effects of shallow invaded zone [15]. Dielectric dispersion tool transmits electromagnetic (EM) waves and records the changes in amplitudes and the phases of the propagating wave, which are then related to the dielectric permittivity and electrical conductivity of the formation. Dielectric dispersion tool has 1-inch vertical resolution and operates at multiple discrete frequencies in the range of 10 MHz–1 GHz.

2.2. Relevant EM log interpretation models

In this study, the joint inversion technique processes low-frequency induction measurements using WS model, the two 960 MHz conductivity and permittivity logs using CRI (Complex-refractive index) model, and the three-conductivity dispersion and three permittivity dispersion logs acquired in the range of 22–350 MHz using SMD (Stroud-Milton-De) model. Waxman and Smits [16] introduced a resistivity-based model for clay-rich geomaterials to estimate water saturation by accounting for additional conductivity due to the presence of clay with high cation exchange capacity (CEC). WS model is expressed as

$$\frac{1}{R_t} = \varphi_t^m S_w^n \left(C_w + \frac{B.\, Q_v}{S_w} \right) \tag{1}$$