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Hydrocarbon saturation in upper Wolfcamp shale formation

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ABSTRACT

Water saturation (S_w) and hydrocarbon saturation ($S_{hc} = 1{-}S_w$) estimates in hydrocarbon-bearing formations are generally derived from Dean-Stark core measurements, NMR log, and electromagnetic (EM) logs, such as induction log, galvanic resistivity (laterolog), or dielectric dispersion logs. In-situ estimation of hydrocarbon saturation in conventional reservoirs primarily rely on the deep-sensing or high-resolution EM logs. However, in the hydrocarbon-bearing shale formations, hydrocarbon saturation estimates obtained from EM logs tend to be unreliable. Conventional EM-log-interpretation models tend to break down for shale formations because they neglect the interfacial polarization effects and the dispersive behavior of EM properties of such geomaterials. This can be addressed by jointly processing the subsurface galvanic resistivity, induction, propagation and dielectric dispersion logs using an integrated model that accounts for the interfacial polarization mechanisms.

One galvanic resistivity (laterolog) and dielectric dispersion logs, comprising 4 conductivity and 4 dielectric permittivity logs measured at four distinct frequencies, were acquired in a 520-feet depth interval of a well drilled in the upper Wolfcamp shale formation. We implement a novel log interpretation technique for the improved estimation of water saturation (S_w), brine conductivity (C_w), textural index/cementation exponent (m), and saturation exponent (n) in the upper Wolfcamp shale. Log processing was performed with an integrated mechanistic model, which combines Complex Refractive Index (CRI) model to analyze the conductivity and permittivity logs acquired at 1 GHz, Stroud-Milton-De (SMD) model to analyze the 3 conductivity dispersion and 3 permittivity dispersion logs in the frequency range of 10 MHz to 0.3 GHz, and Waxman-Smits (WS) model to analyze the deep galvanic resistivity log (RLA5) measured by the EM laterolog tool at 1 kHz.

In the upper Wolfcamp shale, estimates derived from the joint inversion were robust in the presence of pyrite, low water saturation, and low porosity as compared to estimates from the inversion of only four-frequency dielectric dispersion logs. Formation brine conductivity and saturation-exponent estimates are more reliable compared to water saturation and cementation exponent estimates. Water saturation estimates obtained using the proposed methodology are compared against those obtained using multi-mineral inversion and those derived using CRIM model. Average relative errors in fitting the 1 laterolog resistivity and 8 dielectric dispersion logs using the estimates obtained from the proposed method are 10% and 20%, respectively, and their extreme values are 55% and 60%, respectively, in the 520-ft depth interval of the upper Wolfcamp shale formation.

1. Introduction

The Delaware basin forms the western sub-division of Permian Basin of west Texas and southeast New Mexico extending over 10,000 square miles [1]. In the Delaware Basin, the Wolfcamp shale play forms one of the largest and complex unconventional reservoirs in the United Sates. Upper Wolfcamp formation is classified as a tight oil reservoir, with permeability usually in microdarcies and porosities ranging from 0.01 to 0.15 p.u. Upper Wolfcamp formation comprises sequences of carbonate, clastic sand, and shale laminations and beds [2]. Mineral constituents include varying amount of quartz, calcite, dolomite, kerogen, illite, albite, and pyrite. This mix of minerals pose a major challenge when estimating porosity, water saturation, and net pay [3]. Presence of low values of porosity, interfacial polarization effects [21,24], and large clay content and other factors in the Wolfcamp formation also affect resistivity interpretation and saturation [4]. Accurate evaluation of porosity is critical for the estimation of water saturation. Rosepiler [5] observed that errors in estimation of water saturation increased in low-porosity clay-rich formations. Water saturation estimates using Archie-type equations breakdown in organic-rich shales and tight hydrocarbon bearing formations due to low porosity, increase in tortuosity, high connate-water salinity, interfacial polarization effects [21,24], and large clay content.

Sarihi and Murillo [6] proposed a workflow to estimate water

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Nomenclature

Symbols and abbreviations

S_w	water saturation
EM	electromagnetic
C_w	brine conductivity (S/m)
m	cementation exponent
n	saturation exponent
CRI	complex Refractive Index
SMD	Stroud-Milton-De
RLA5	resistivity laterolog measured using galvanic resistivity tool at 1 kHz
WS	Waxman-Smits
B	equivalent conductance of sodium clay exchange cations (mS/meq)
Q_v	cation exchange capacity per unit pore volume (meq/cc)
CEC	cation exchange capacity
kHz	KiloHertz
MHz	MegaHertz
GHz	GigaHertz
R_t	true resistivity of the formation measured using galvanic resistivity tool at 1 kHz
φ_t	total porosity of the formation
LR	Lichteneker-Rother model
ε_b^*	bulk complex permittivity of the formation
ε_m	matrix permittivity
ε_w^*	complex permittivity of water
ε_o	hydrocarbon permittivity
α	geometrical fitting parameter assumed as 0.5
E_b	real value of water permittivity assumed as 80
E_o	vacuum permittivity with universal value of 8.85×10^{-12}
m'	rock textural parameter
IP	interfacial polarization
LMA	levenberg Marquardt algorithm
$\boldsymbol{F(p)}$	cost Function Vector
$\boldsymbol{p}^k$	model parameter vector computed at the k-th iteration of the inversion
$\boldsymbol{J}(\boldsymbol{p}^k)$	Jacobian matrix computed at the k-th iteration of the inversion
V_{py}	volume fraction of pyrite
TOC	total organic carbon
Res_{mod}	modeled resistivity
Res_{meas}	measured resistivity
$Error_{Total}$	total error
$Error_{SMD}$	error for permittivity and conductivity for SMD model
$Error_{CRI}$	error for permittivity and conductivity for CRI model
$Error_{WS}$	error for resistivity for Waxman Smits model
$Perm^{meas,1\,GHz}$	measured dielectric permittivity at 1 GHz
$Perm^{mod,1\,GHz}$	modeled dielectric permittivity at 1 GHz
$Cond^{meas,1\,GHz}$	measured electrical conductivity at 1 GHz
$Cond^{mod,1\,GHz}$	modeled electrical conductivity at 1 GHz

saturation using Waxman-Smits equation in tight-gas formations considering the conductivity and volume fraction of clay minerals. Their results on tight rock samples indicated a proportional relationship between clay content and the clay factor, which replaced BQ_v in the Waxman-Smits equation, and was recommended for shale evaluation. Donadille et al. [7] addressed the limitations in determining high connate-water salinity with dielectric logs. At high salinity of about 70 ppk, the dielectric measurements lose sensitivity to salinity. Joint inversion of neutron sigma measurements and dielectric dispersion logs showed excellent sensitivity to high salinity values in Bakken shale formation. Chen and Heidari [8] proposed joint interpretation of dielectric and resistivity measurements that significantly improves water-filled porosity and hydrocarbon saturation assessment. They introduced analytical model combining conductivity and permittivity measurements for organic-rich source rocks with complex pore structure. They suggested that spatial distribution and tortuosity of water, kerogen, and pyrite networks significantly affect dielectric permittivity and electrical resistivity. Challenges with hydrocarbon saturation estimation in shale reservoirs due to dielectric effects have been reported by Misra et al. (2016) [22].

Han et al. [9] proposed an log processing methodology by combining Lichtenecker-Rother model, Stroud-Milton De model, and PS model, a mechanistic pyrite-clay dispersion model, for the estimation of water saturation, formation water salinity, homogeneity index, and cementation index in clay-lean and clay-rich units of Bakken shale. They carried their interpretation for a 300-feet depth interval in Bakken Petroleum System and compared their estimates with Dean Stark core water saturation, NMR interpretation and service company's inversion results. 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. This methodology has been extended to other shale reservoirs [22,23].

Formation evaluation in conventional reservoirs generally involves the estimation of water saturation from the deep-sensing or high-resolution EM logs, such as laterolog, induction log, and dielectric dispersion logs. In unconventional reservoirs, water saturation estimation is difficult due to complex mineralogy, higher clay content, low porosity, textural features and high salinity. Interpretation with only 1-GHz dielectric permittivity log or with only laterolog or induction resistivity log or with only 8 dielectric dispersion logs in the frequency range of 10 MHz to 1 GHz is sensitivity to model assumptions, noise in data, noise in model inputs, interfacial polarization mechanisms, textural effects, and has low sensitivity to certain petrophysical properties. These challenges can be addressed by performing a joint processing of resistivity and dielectric dispersion logs using an integrated mechanistic model. In this paper, dielectric dispersion logs and laterolog resistivity logs are simultaneously processed to estimate the water saturation, brine conductivity, saturation exponent and cementation exponent in a 520-ft depth interval of upper Wolfcamp shale.

2. Method

2.1. Relevant EM logging tools

Laterolog resistivity tool injects electric currents into geological formations and records the potential drop across a specific length along the openhole well. Laterolog measurements are related to the electrical resistivity of the formation. Laterolog tools are reliable in boreholes drilled with water based muds. Laterolog tool has 2-feet resolution with 10, 20, 30, 60 and 90 in. of depths of investigation and operates at frequencies lower than 10 kHz. On the other hand, dielectric dispersion tool transmits electromagnetic (EM) waves and records the changes in amplitudes and the phases of the propagating wave, which are related to the dielectric permittivity and electrical conductivity of the formation and their dispersive behaviors. Dielectric dispersion tool has 1-inch vertical resolution and operates at multiple discrete frequencies in the range of 10 MHz to 1 GHz.

2.2. Relevant log interpretation models

Interpretation of laterolog tool focuses on the petrophysical controls