[PS]Petrophysical Interpretation of Electromagnetic Induction and Dielectric Dispersion Logs in Bakken Petroleum System*

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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, NMR log, dielectric dispersion log, and Techlog Quanti-ELAN and Dean-Stark core measurements.

We perform an inversion-based interpretation of dispersive electrical conductivity and dielectric permittivity measurements at six EM-log-acquisition frequencies acquired across 1000-feet depth interval in one of the science wells intersecting the BPS. Three geoelectromagnetic mixing models, namely Lichtenecker–Rother model, Stroud-Milton-De model, and Waxman Smits model, are coupled to jointly process the dispersive EM logs to simultaneously estimate oil-in-place, formation water salinity, cementation exponent, and saturation exponent.

Oil-in-place estimates obtained using the proposed interpretation method were compared against those obtained from triaxial induction resistivity, NMR log, Quanti-ELAN solver, Dean-Stark core measurements, and service company's dielectric inversion. Our estimates of water saturation and those obtained using the service company's dielectric inversion exhibit the best match with Dean-Stark's core water saturation in the Middle Bakken, Lower Bakken, and Three Forks formations. However, in the Lodgepole, Scallion, and Upper Bakken formations, our estimates of water saturation are closer to those obtained from NMR logs, which disagrees with the extremely high estimates obtained using the service company's dielectric inversion. The estimated values of water saturation and formation water salinity in Middle Bakken are in the ranges of 0.5 to 1 and 205 kppm to 250 kppm, respectively. The cementation index indicates enhanced tortuosity and cementation in the Scallion and Lower Bakken formations.

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Summary

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, NMR log, dielectric dispersion log, and Techlog Quanti-ELAN and Dean-Stark core measurements.

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Motivation

Figure 1. Inconsistency in water saturation estimates and high salinity formation

Inversion workflow

Figure 2. Inversion workflow for the joint interpretation

DIELECTRIC LOGS
- EPSI_XO_F0
- EPSI_XO_F1
- EPSI_XO_F2
- EPSI_XO_F3
- COND_XO_F0
- COND_XO_F1
- COND_XO_F2
- COND_XO_F3

INDUCTION LOG
- RLA5

φ_t

ε_b^*

250 initial guesses for S_w, C_w, m, n → Modified Levenberg-Marquardt algorithm Error tolerance=10% → Petrophysical properties S_w, C_w, m, n

Synthetic data inversion

Parameters	Values
Total porosity	5 %
Volume fraction of clay	25 %
Cation exchange capacity (CEC) per unit pore volume, Q_v	0.1 meq/cc
Equivalent conductance of sodium clay exchange cations, B	13 mS/meq
Relative permittivity of hydrocarbon	3.5
Relative permittivity of brine	80
Homogeneity index, α	0.5
Bulk conductivity of brine, C_w	10 S/m
Water saturation, S_w	30 %
Cementation exponent, m	2
Saturation exponent, n	2

Table 1. Assumed petrophysical parameters for the synthetic case study

Figure 3. Comparison of synthetic data and the integrated model predictions based on the inversion-derived estimates

Petrophysical interpretation for inversion estimates

Figure 4. Comparison of water saturation estimates with dielectric inversion, NMR, ELAN and Dean-Stark core estimates (Track 3), brine conductivity estimates (Track 4), formation homogeneity index (Track 5), cementation index exponent (Track 6), T2 NMR distribution (Track 7) and errors for estimates (Track 8)

Inversion estimates and data validation

Figure 5. Formation type (Track 1), depth (Track 2), gamma ray (Track 3), Resistivity measured by induction (Track 4), neutron porosity, density porosity and ELAN total porosity (track 5), water saturation estimates (Track 6), brine conductivity estimates (Track 7), cementation index exponent (Track 8), saturation exponent (Track 9), measured and modeled dielectric permittivity at four frequencies (Track 10), measured and modeled dielectric conductivity at four frequencies (Track 11), measured and modeled resistivity (Track 12),

Conclusions

- Dielectric dispersion logs and deep induction log can be jointly inverted to estimate water saturation, brine conductivity and cementation exponent
- High uncertainty estimates for water saturation in Lodgepole Formation is primarily due to small pore size and low porosity formation
- Upper section of Middle Bakken has high uncertainty, which could be due to wide range of pore-size distribution
- Enhanced cementation exponent/tortuosity observed in Upper and Lower Bakken Formation could be attributed to wide range of pore-size distribution

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