V002 MONITORING RESERVOIR FLOW USING MAGNETOMETRY

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Introduction

It is well known that fluid flow in porous rocks has a concomitant electrokinetic effect (Morgan *et al.* 1989; Sprunt *et al.* 1994). The principal electrokinetic effect occurring in a flowing reservoir (i.e. reservoirs undergoing production) is the development of a streaming potential, due to the applied pressure drop across the reservoir. Wurmstich and Morgan (1994) have investigated the possibility of detecting pumping operations using streaming potential measurements at the surface and in nearby monitoring wells. Fitterman (1979) showed that streaming potential can give rise to a magnetic field under special circumstances. Fenoglio *et al.* (1995) have successfully modelled observed magnetic anomalies, associated with pressured fault zones, using the streaming potential distribution as the magnetic source. It is suggested in this paper that electrical potential distribution, associated with streaming potential effects in producing petroleum reservoirs, can give rise to observable magnetic anomalies, and it is proposed that these anomalies can be used to monitor hydrocarbon-water contacts.

Theory

The conventional theory for streaming potential (ΔV) states (Levine *et al.* 1976)

$$\Delta V / \Delta P = [\epsilon \zeta R_f] / [4 \pi \mu_f], \quad (1)$$

where ΔP is applied pressure difference, ϵ is the dielectric constant, ζ is the zeta potential, R_f is the pore fluid resistivity and μ_f is the fluid viscosity. Jouniaux and Pozzi (1995) have shown that this simple relation can change significantly with confining pressures greater than about 50 MPa (burial depths greater than about 2 km), but this complication will be ignored for the present paper, as petroleum reservoirs are generally shallower than this.

The present theory is based on a modification of that proposed by Fitterman (1998).

The magnetic field (**B**) produced by a current density (**J**), due to an electrical potential distribution, is described by the Biot-Savart Law

$$\mathbf{B} = \nabla \times \iiint_V dv [\mu_0 \mathbf{J} / 4 \pi r], \quad (2)$$

where v is volume, μ_0 is the magnetic permeability of a vacuum, r is distance, $(\nabla \times)$ indicates the curl operator, and $(\iiint_V)$ indicates a volume integral. Proceeding in the same fashion as Fitterman (1979, p. 6033-6035), but without the source image, an expression is found for the magnetic field due to the horizontal contact shown in Figure 1:

$$B \approx B_0 \ln\{[(d^2 + a^2)^{1/2} - h][(d^2 + b^2)^{1/2} + h] / \{[(d^2 + a^2)^{1/2} + h][(d^2 + b^2)^{1/2} - h]\}\}, \quad (3)$$

where $B_0 = \{\mu_0 \epsilon \zeta \Delta P / \mu_w\} \{R_{hy}(\mu_w / \mu_{hy}) - R_w\} / \{16 \pi^2 (R_r + R_0)\}$, and $d^2 = h^2 + z^2$, R_{hy} is the resistivity of the hydrocarbon, μ_{hy} is the viscosity of the hydrocarbon, R_w is the resistivity of the formation water, μ_w is the viscosity of the formation water, R_r is the resistivity of the hydrocarbon-filled rock and R_0 is the resistivity of the water-filled reservoir rock, and the other petrophysical

constants as in equations (1) and (2). The magnetic field due to the conductive contacts of the sides and top of the reservoir can also be calculated using equation (2), see also Fitterman (1979, p. 6033), and may be of the same order of magnitude. Figure 1 shows the total magnetic field anomaly, measured in the well, due to the base of the reservoir alone (equation 3) in an hypothetical well drilled 100 m beyond an oil-water contact. For this example, $R_w=0.1 \Omega\text{m}$, $R_{hy}=500 \Omega\text{m}$, $R_r=50 \Omega\text{m}$, $R_o=2.5 \Omega\text{m}$, $\epsilon \zeta / \mu_w=50 \text{ mV}/\Omega\text{m atm}$, $\mu_w/\mu_{hy}=1.7$ and $\Delta P=100 \text{ psi}$. It is seen that the magnetic response due to the contact is approximately 300 nT, which is well within the resolution of current magnetometry, and also that the contact is centred on the anomaly peak.

Conclusions

The theory and example shown in this paper strongly suggests that the monitoring of gas-oil and oil-water contacts within an hydrocarbon reservoir can provide valuable information on the fluid distribution within the reservoir. In keeping with the vision of "Reservoir Geophysics - The Road Ahead", magnetic monitoring of fluid flow presents an exciting future development area for geophysical applications in the hydrocarbon production sphere.

References

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Figure 1: Model of streaming potential induced magnetic anomaly at oil-water contact.