DIRECT HYDROCARBON PROSPECTING USING ELECTROMAGNETIC METHODS

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Abstract

In this report the electrical transient method for direct hydrocarbon detection is analyzed. The method uses a Schlumberger electrode arrangement with a pulsed square wave source, which was modeled in the present study using plane waves in a stratified medium. It is found that hydrocarbon-bearing rocks cannot be distinguished from background clastic or background massive carbonate rocks except at very shallow depths, unless the background rocks are extremely homogeneous. The method also cannot distinguish between hydrocarbon-bearing rocks and massive carbonates when they are modeled separately with clastic rocks as background. It appears that the electrical transient method may only be useful for hydrocarbon pools with extremely homogeneous overlying rocks.

Introduction

The reflection seismic method dominates petroleum exploration, but unfortunately most of the time it provides structural information only. "Bright spots" are helpful direct hydrocarbon indicators, but they are often ambiguous and in deep hydrocarbon pools do not show up at all. Electrical methods have been tried before in the oil industry, with little success. This method, if it works as claimed, would be a very effective direct hydrocarbon indicator and would play an important role in all future petroleum exploration.

Electraflex Method

This method was pioneered by Jamil Azad of Electraflex Surveys Ltd., Calgary, Alberta, Canada. A preprint of his talk given at the 1977 SEG meeting in Calgary can be obtained, which is entitled "Direct Detection of Hydrocarbons with Electrical Transients". A shortened version of this was published in the September 12, 1977 edition of "Oil and Gas Journal", page 83. For details one should consult these references, as I only intend to outline his method here.

The method uses a Schlumberger electrode arrangement (as in resistivity surveys) with a pulsed square wave current source of frequency .125 - 1 Hz. The skin depth for typical clastic rocks of resistivity 100 ohm-m is of the order of ten km, so the energy gets deep enough. The voltage as a function of time is observed between each pulse and then the readings are averaged for interpretation. According to Azad, one then obtains a voltage vs. time curve with a standard induced polarization time decay superimposed on reflections from hydrocarbon-bearing rocks and other high resistivity bodies. One separates these two effects and uses the maximum amplitude of the reflection part for anomaly determination. The reflections are primarily caused by the large resistivity contrasts between ordinary sedimentary rocks and hydrocarbon-bearing rocks. This can be summarized in the following table.

Material	Resistivity (ohm-m)
clastic rock	100
massive carbonate	10,000
gas	almost ∞
oil	3×10^{11}
oil or gas-saturated rock	at most 10^{11}

Azad's experimental results show that the method gives strong anomalies for average-sized hydrocarbon pools down to at least 10,000 feet.

Electromagnetic Theory

I assumed stratified media and imparted a vertically incident plane wave down into the earth. The theory is exactly as found in Keller and Frischknecht, "Electrical Methods in Geophysical Prospecting", pages 210-212 and 303-305, so I will just sketch it here. Essentially one specializes Maxwell's equations to a vertically incident plane wave and then solves the resulting ordinary differential equation for the electric vector, using the continuity of the electric and magnetic vectors at the stratified media interfaces as boundary conditions. I calculated b_o/a_o , which is the ratio of E_r , the upcoming electric vector, to E_s , the downgoing electric vector. E_r/E_s basically measures the ratio of the amplitude of the reflected wave to that of the incident wave, as seen just below the ground surface.

Results

I chose $\mu=\mu_o$ for all rocks and $\varepsilon=\varepsilon_o$ for oil-bearing rocks, $10\varepsilon_o$ for massive carbonates, and $8\varepsilon_o$ for clastic rocks, though ε does not matter much, since $\mu\omega^2\varepsilon << \mu\omega\sigma$ in the expression for γ at the bottom of page 303, Keller and Frischknecht. The linear frequency was chosen to be .5 Hz . The values for E_r/E_s are correct to within a scale factor $e^{-\gamma_1 z_1}$, where γ_1 is γ for the first layer and z_1 is the thickness of the first layer. Multiplying each value of E_r/E_s by this will change the absolute values but not the relative ones.

Typical Models

Rock of Interest at 13,000 feet

layer	Oil Model		Limestone Model		Background Model	
	resistivity p(ohm-m)	thickness z(ft.)	p(ohm-m)	z(ft.)	p(ohm-m)	z(ft.)
1	50	2000	50	2000	50	2000
2	100	2500	100	2500	100	2500
3	200	2000	200	2000	200	2000
4	800	2250	800	2250	800	2250
5	400	2250	400	2250	400	2250
6	800	2000	800	2000	800	2000
7(rock of interest)	10^{11} oil	500	10,000 ℓs	1000	500	2050
8	500	2100	500	2100	800	2100
9(half-space)	1000		1000		1000	

All of the unlabeled rocks above are clastic. The parameters were varied in a minor way without being noted, e.g., if layer three above were 2200 feet thick and had a resistivity of 400 ohm-m it would not effect the results enough to be worth considering. For all models below, except when noted otherwise, $z=500$ feet for oil-bearing rock, 1000 feet for limestone, and $p=10^{11}$ ohm-m for oil-bearing rock, 10,000 ohm-m for limestone. The clastic rock resistivities are always about as in the above models.

Data

Layer # of Rock of Interest	Approximate Depth (ft.) of Rock of Interest	Model Type (z in ft., p in ohm-m)	Re $\frac{E_r}{E_s}$	Im $\frac{E_r}{E_s}$	$\left\lvert\frac{E_r}{E_s}\right\rvert$
2	2000	oil-bearing rock	.490	-.0894	.498
2	2000	ℓs(p=1000)	.488	-.0902	.496
2	2000	ℓs(z=500, p=1000)	.488	-.0909	.496
2	2000	ss or sh(clastic rocks)	.416	-.131	.436
3	4500	oil-bearing rock	.422	-.128	.441
3	4500	ℓs(p=1000)	.422	-.127	.440
3	4500	ss or sh	.365	-.148	.394
4	7000	oil-bearing rock	.357	-.0931	.369
4	7000	oil-bearing rock(z=1000)	.361	-.0918	.373
4	7000	ℓs	.361	-.0919	.373
4	7000	ss or sh	.353	-.0952	.365
5	9000	oil-bearing rock	.410	-.132	.431
5	9000	ℓs	.412	-.132	.432
5	9000	ℓs(z=500)	.410	-.132	.431
5	9000	ss or sh	.403	-.134	.425
6	11,000	oil-bearing rock	.418	-.144	.442
6	11,000	ℓs	.419	-.144	.443
6	11,000	ss or sh	.416	-.145	.441
7	13,000	oil-bearing rock	.378	-.107	.393
7	13,000	ℓs	.380	-.107	.395
7	13,000	ss or sh	.379	-.107	.394

These models for the Electraflex method do produce positive anomalies for average-sized hydrocarbon pools shallower than about 6000 feet, but massive carbonates at those depths produce similar anomalies, so the method is inherently ambiguous. One must know something about the stratigraphy of an area in order to get unambiguous results. Below 6000 feet the hydrocarbon-bearing rocks and carbonates could not be distinguished from the background clastic rocks.

Limitations of My Models and Conclusions

My figure of 10^{11} for oil or gas-saturated rock is probably high, as the interstitial water undoubtedly drives the resistivity down quite a bit. However, my plan for doing this modeling was to deliberately make things extremely favorable for the method, and if it did not work then, it probably never would. Having a very large resistivity contrast clearly favors the method. I used plane waves, while in the Electraflex method a dipole source is used, which does not produce plane waves, and I also assumed stratified media, which is not always the case. Both of these approximations favor the method and are additionally the easiest to handle mathematically.

My non-hydrocarbon resistivities should be in the 10-200 ohm-m range and should be varied more frequently, with layers around 100' thick, as shown by well logs. I found that in general, the greater the number of layers between the surface and a certain depth, the lower the resolution of the method. Some sedimentary sequences are more homogeneous than my models, though, especially in Alberta, where there are thick sequences of limestone. I did a quick check of this and found that for these exceptional cases where the carbonates are the background rocks, the method would work better than for my models, which would explain many of Electraflex's results.

One must in addition take into account the square wave source, which has all frequencies in it, with low ones dominant. However, I tested the response for several frequencies and found little difference, i.e., if I received a response of x for background rocks using a frequency z and a response of $2x$ for oil-bearing rocks at that frequency, then if I tried a frequency q and received a response of y for background rocks, I would necessarily receive a response of $2y$ for oil-bearing rocks using that frequency. Therefore, my results for the relative responses for oil-bearing rocks versus clastic rocks and massive carbonates should still hold.

Finally, the induced polarization effect has been neglected, but that should not be too important here.

Much more work could be done on this method, but was not because of the discouraging results. Considering the favorable conditions on which the method was tested, I seriously doubt if it works as claimed. The only possible exception is the special case of extremely homogeneous rocks overlying the hydrocarbon-bearing stratum.