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Array TEM Sounding and Application for Reservoir Monitoring

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Summary

Theoretical and numerical modeling results show the feasibility of residual oil mapping and dynamic monitoring of steam or water driven reservoirs by using the electric source TEM method. A pilot survey of customized array TEM was carried out over a steam driven heavy oil reservoir. Field results confirm that the resistivity anomalies are well correlated with residual oil saturation.

Introduction

Formation resistivity is closely related to reservoir porosity, pore fluid saturation and properties. In general, reservoir formation shows strongly heterogeneity after long term water or steam-driven recovery.Especially in the dominant pathway where the formation has better porosity and permeability, the distinct resistivity differences between oil-bearing and water-bearing formation lay the physical foundation for reservoir monitoring by electromagnetic sounding methods. While seismic method is difficult to direct detecting changes of formation fluid due to the little difference of seismic velocity of oil-bearing or water-bearing formation. Based on their special features, electromagnetic methods with improved resolution should be applied to better mapping the oil-water contact interfaces, monitoring the water or steam-driven front, and dynamically picturing reservoirs and optimizing the developing plans.

Among electromagnetic methods, the time domain or transient electromagnetic method (TEM) is the first choice for hydrocarbon prediction of known structures in exploration and for reservoir dynamic monitoring in a producing field. This is due to its advantages of higher resolution, interference rejection ability and sensitivity to formation resistivity variations. Theoretical studies for TEM methods have a long history and various observation systems, such as methods adopting electric source or magnetic source, long offset or common center transmitter-receiver configurations, or operations on ground, well to surface or between wells. (Kaufman and Keller, 1983; Strack, 1992, Hoerdt et al, 2000) These methods have been broadly used in shallow geological structure mapping, underground mineral, geothermal and hydrocarbon resource investigations (Yan et al., 1998).

Survey Setup

Multi-channel TEM array observation layout is shown as in Figure 1. Source current is delivered into ground by transmitter through grounded wires and the electrical field is built up in earth media at current on time. The decay of secondary field components induced in earth at the moment of source current off time are observed and recorded. Electrical properties of subsurface media varying with depth can be deducted by analyzing the electromagnetic decay responses at different delay time since the early time signal reflects electric properties of shallower depth and late signal reflects electric properties of deeper section of earth media. TEM method has advantages of high working efficiency, better vertical resolution, less static distortion and easy data processing attributed to time domain responses and secondary magnetic component observation. Exploration depth coverage from several meters to several thousand of meters can be achieved by choosing proper observation parameters according to exploration tasks.

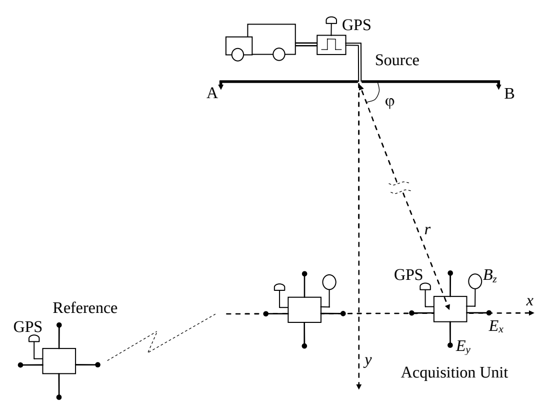

Figure 1 Array TEM survey setup

Suppose the exciting current by grounded wire source is along *x*-direction, and the grounded wire can be treated as an electric dipole if the source-receiver offset is much longer than the length of source wire or as finite dipole if the offset is closer (Stoyer, 1990). Observed electric field and induced electromotive force (EMF) by vertical magnetic induction field can be used to derive apparent resistivity for data processing and quantitatively interpretation.

Forward Modeling of Reservoir Monitoring by TEM

Electromagnetic response of a 3D reservoir model in layered Earth is studied by forward modeling using volume integral equation algorithm (Newman et al., 2002) to investigate the feasibility of detecting the variation of deep buried reservoir by LOTEM method. Designed reservoir model is located 1000 m deep with parameters setting to simulate water or oil bearing formation. Survey configuration is set to stimulate by grounded wire and observe data by receiver on earth surface. Detectivity of reservoir boundaries is analyzed and evaluated by studying the variation of TEM responses as the different components and different site locations (Tang et al., 2004).

Model is setup as shown in Figure 2, a 3D horizontal plate in homogeneous earth is to simulate the reservoir formation. Parameters for homogeneous earth is set to be conductivity 0.05S/m and dielectric constant = 1.0. Electric dipole source (Tx) in *x*-direction is centered at (0,-500,0) and 50 receiver (Rx) sites are setup along *y*-direction at locations from *y*=500-3000m. The size of the 3D anomalous body is 200×200×25m and set resistivity = 0.2S/m and dielectric constant = 10.0 to simulate the water bearing formation. Models of anomalous body centered from *y*=0-1400m with step of 200m to simulate reservoir at different locations.

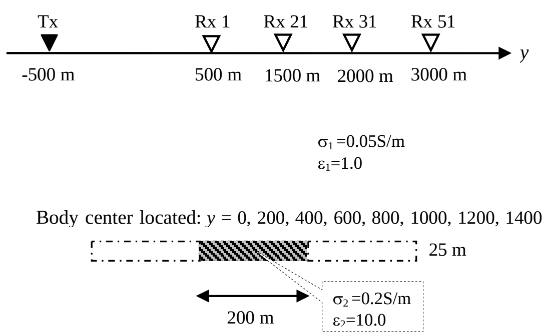

Figure 2 Model setup for water bearing reservoir

Figure 3 shows the secondary transient response of electric field e_x.The amplitude of secondary e_x anomaly is positive and keeps almost no change in the early time (t< 10 ms), and shows maximum at right top of the anomalous body and decays with the distance of the receiver to the center of the body.This anomaly retains for a period of time and then decays rapidly, and forms a steep step zone with dense contours in plot. A local negative anomaly is whereafter shown at about t=30 ms, the center of this negative anomaly is also corresponding to the center of the anomalous body. Modeling results for anomalous body at different locations show that contours of this negative anomaly well define the locations of the anomalous body.

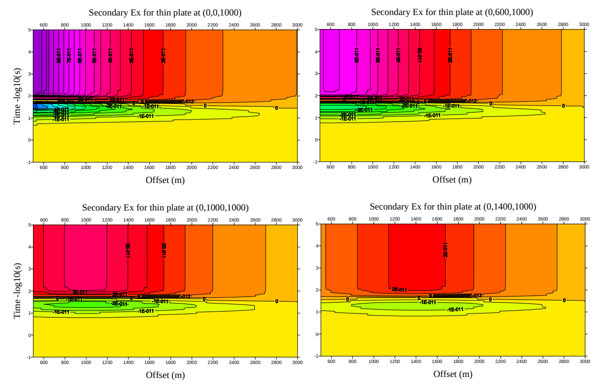

Figure 3 Secondary e_x responses for simulated water-bearing reservoir at y=0, 600, 1000, 1400m

Field Trial for Reservoir Dynamic Monitoring

Based on these considerations we designed a pilot survey and carried out field measurement at several times from 2006 to 2007.

Geological and Reservoir Settings of Testing Area

The testing area is a heavy oil reservoir in northwest of China. The reservoir bed is braided river delta facies with formation thickness of 20~60 m and thinning gradually westward.The tectonic setting is relatively simple, the substructure is a monocline from northwest toward southeast with small gradient, the formation dip is 4~6° and the average depth of the lower boundary of the reservoir formation is about 400 m.

The oil and water relation in reservoir is complicated due to that large amount of water may trapped in formation owing to the heterogeneous and insufficient substitution of water by oil in the late stage of secondary heavy oil reservoir formed up, and oil and water in formation may not segregated sufficiently for the similar density of heavy oil and ground water.It is confirmed by drill core analysis and oil testing that some areas of this heavy oil reservoir have low resistivity feature.Among various effect factors to formation resistivity, main factors are formation lithology, mineralogical composition, type of cementation, water salinity and oil saturation.Low resistivity of this heavy oil reservoir is mainly attributed to the formation grain size become small and shale content increases, and the bound water content increases thereafter. Low resistivity areas are mainly located in the west part where the grain size is small and the east part which is the shallow river-way deposit region.

Acquisition Parameters and Site Setup

A high power transmitter is used to deliver large current (~25A) to the ground through a ground wire of 2km in length， and offset (transmitter -receiver distance) is 5~10 km. Source waveform is square wave with period of 8~32s. Distances between survey sites and survey lines are 100~150 m, totally 13 survey lines and 180 sites were carried out. Field setup and site locations are shown in Figure 4.

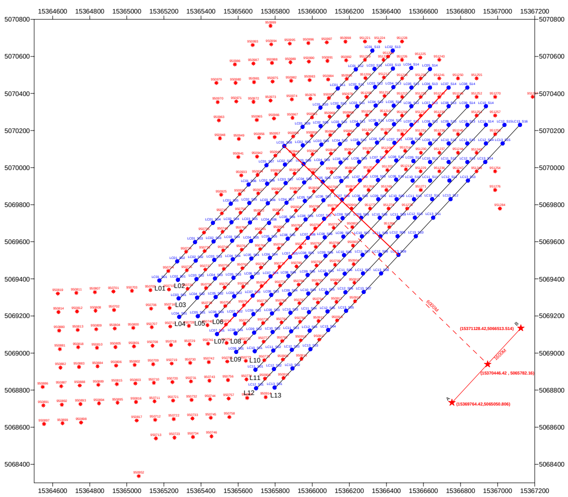

Figure 4 Survey setup and site locations

Two surveys had been carried out for same sites in same area with possible same survey parameters setup for 4D dynamic monitoring purpose. First survey was carried out in July, and second survey was carried out in November of 2006.

Data Processing

Figure 5 shows transient e_x curves of one site for two surveys at different time. It is obvious that the observed results at different time has good consistency except that data points in late time (last 5 points) shows discrepancy due to the low signal to noise ratio after 2s. We chose this approach which does not apply the usually low pass filter (which gives smoother results) to be sure that we see all remaining noise in the data.Figure 6 shows the cross sections of early time apparent resistivity of survey line #12 measured at two different times. In general, the cross section plots show good consistency for two surveys, some variation can be distinguished directly from the plots which may be the contribution of the steam movements. Detail interpretation will be given by difference plot of early time resistivity for whole survey area.

Data Interpretation

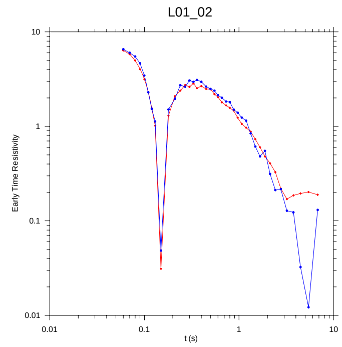

Figure 5 Comparison of observed e_x transients for two surveys at different times

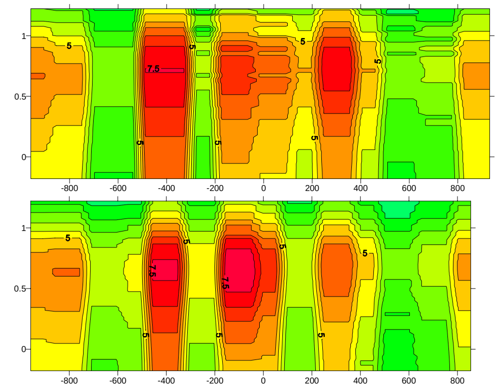

Figure 5 Cross sections of apparent resistivity for survey line #12 observed in July (below) and in November (above)

Figure 7 is the time sliced plan plot of early time resistivity at 60 ms derived from data of second observation, which is approximately the depth of 400 m if take average resistivity of overburden layer to be 5 Ωm. The production wells are labled as blue dot and the steam injection well are red dots. This plot will give a plan view of resistivity distribution of the reservoir layer. Boundary lines are drawn to delineate area of low (<4 Ωm) and high (>4 Ωm) resistivity areas. It can be inferred that the high resistivity areas are the areas of high satuation of oil and contacted with the steam front. And the low resistivity areas are mixed with production and injection wells and are inferred to be water flooded.

Figure 8 shows the apparent resistivity differences by subtracting the apparent resistivity data of the first survey from that of the second survey. The differences are expressed as percentages, with positive values representing the resistivity increasing from first to second observation and negative values indicate resistivity decreasing.

In general, the maxima and minima of difference of resistivity derived from two time lapped measurements occurred in regions of producing wells except in the

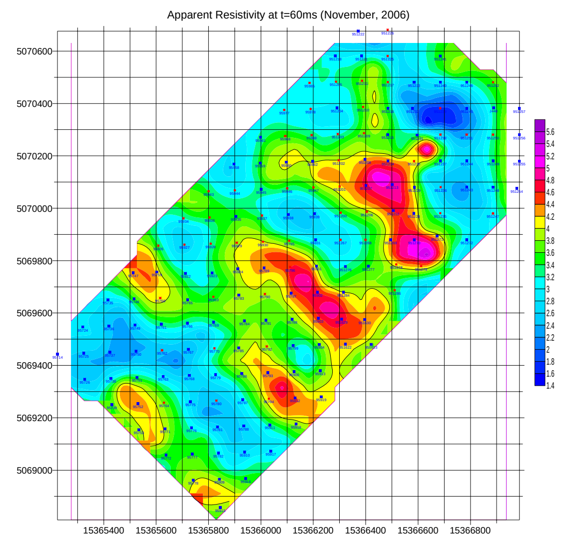

Figure 7. Apparent resistivity distribution at t=60 ms from second survey (Nov. 2006)

channels of steam. Three regions with different speed of steam movement can be clasified qualitatively from the residual map. However, more work need to be done for detail interpretation to take into account of complicate relationship between resistivity variation and steam phase

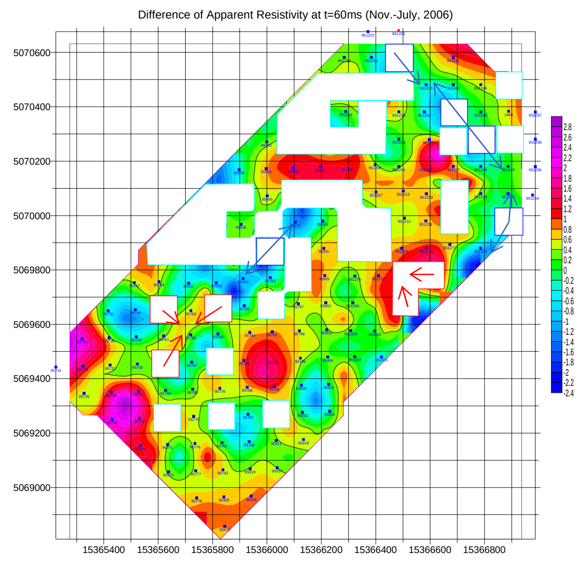

Figure 8. Apparent resistivity differences at t=60ms and qualitative inferred interpretation.

□ Steam moving fast　　□ Steam moving slow

□ Injection channeled through　　→ Main moving directions

change in reservoir. According to this interpretaion results, some measures can be taken to optimized the production schedule for enhancing the output ratio.

Conclusions

This study has shown the feasibility of dynamic monitoring of steam or water driven reservoirs by employing TEM method with electric dipole source. Field trials had made successful measurement of electromagnetic field and preliminary processed results show resistivity anomalies well correlated to the steam front and residual oil. Further detail interpretation combined with geological and petroleum engineering information is needed for future studies.

Acknowledgments

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EDITED REFERENCES

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