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Feasibility study of surface-to-borehole CSEM for oil-water fluid substitution in Ghawar field

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Saudi Arabia, Geo 2010, poster

Feasibility study of Surface-to-Borehole CSEM for oil-water fluid substitution in Ghawar field, Saudi Arabia

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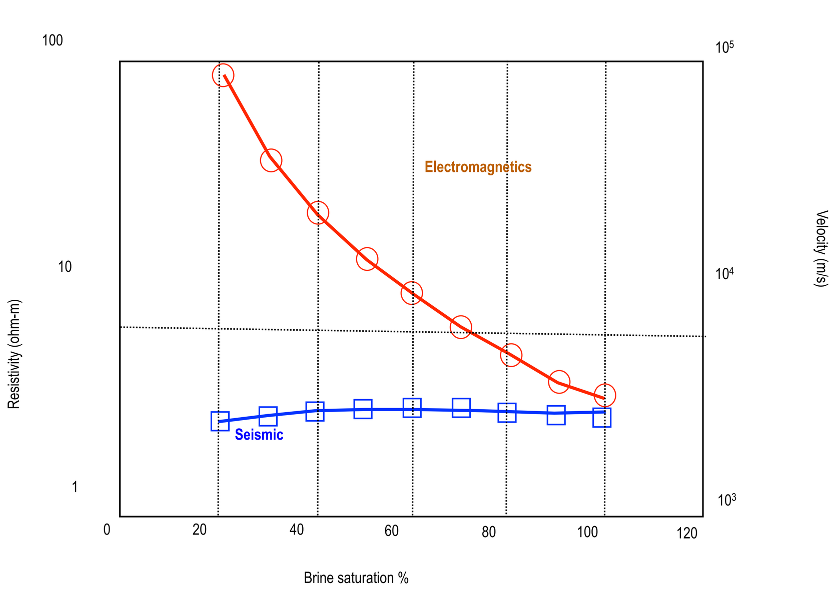
Electromagnetics → more direct reservoir monitoring

Monitoring the advancement water fronts after injection in carbonate reservoirs is a major challenge for production efficiency. 4D seismic has limited applicability to Middle East reservoirs with low gas-oil-ratio in carbonate rocks. On the other hand, electromagnetic (EM) methods hold the largest potential in such reservoirs due to the large resistivity contrast (over one order of magnitude) between oil-saturated and water-saturated reservoir rocks. Electromagnetic measurements are noise sensitive thus special configurations need to be implemented to enable the detection of the extremely small variations of the electromagnetic field that are induced by oil being replaced by injection water. Controlled source EM transmitters on ground surface and borehole receivers represent the most effective layout configuration to improve the signal-to-noise ratio and to augment the aperture of investigation while addressing the signal-to-noise challenge through long recording times (Strack, 2004). Time-domain controlled-source EM techniques provide broadband EM measurements and adapt to most geologic scenarios and to the conditions characterizing the Ghawar field.

An advanced 3D modeling study was carried out for real reservoir geometry from 3D seismic interpretation, anisotropic resistivity logs and time lapse reservoir simulator results. The study shows EM field sensitivity to fluid saturation changes in the reservoir. Results indicate the vertical component of the electric field (E_z) is the most sensitive parameter to fluid replacement for this survey layout. Time lapse EM modeling is used to effectively monitor in 3D resistivity changes in the reservoir's water flood front. EM field estimates yield a quantitative noise floor required for signal detection. These estimates are used in studies where actual noise measurements and noise cancellation techniques will be field tested.



Sensitivity of EM to brine saturation when compared to seismic. Resistivity changes are in the range of one order of magnitude or more (from: Wilt, M.J., and Alumbaugh, D.L., 1998)

Taking the sensors in the borehole

3D feasibility modeling carried out to evaluated the effectiveness of **surface-to-borehole** controlled source electromagnetic technolog to detect reservoir fluid changes during production at the North Ghawar test site. Our selection from all EM technologies is based on the strongest coupling to the reservoir response. Key elements of the feasibility study are:

- Sources: Surface grounded dipole and wire loop
- Receivers: Downhole vertical electric and magnetic
- Reservoir Simulator to predict time lapse changes
- Reservoir Geometry from 3D seimic interpretation
- Resistivity background infered Tri-axial resistivity logs

A minimum of a three year flood front monitoring program is considered in this feasibility study with repeated time interval for each monitoring survey of six months. The objective being the design of optimum surface transmitter locations and downhole receiver deployment.

The reservoir

The reservoir geometry is from 3D seismic interpreted horizons yielding the current oil-water distribution from the reservoir simulator (Figure 1). Flood front changes progressing from the West are modeled for the next three years (Figure 2). Resistivity logs indicate an average water saturated a resistivity of about 5 ohm-m for a 75% water-saturated reservoir. Therefore we expect a factor 10 in resistivity change between a fully oil-saturated reservoir and a fully water-flooded reservoir

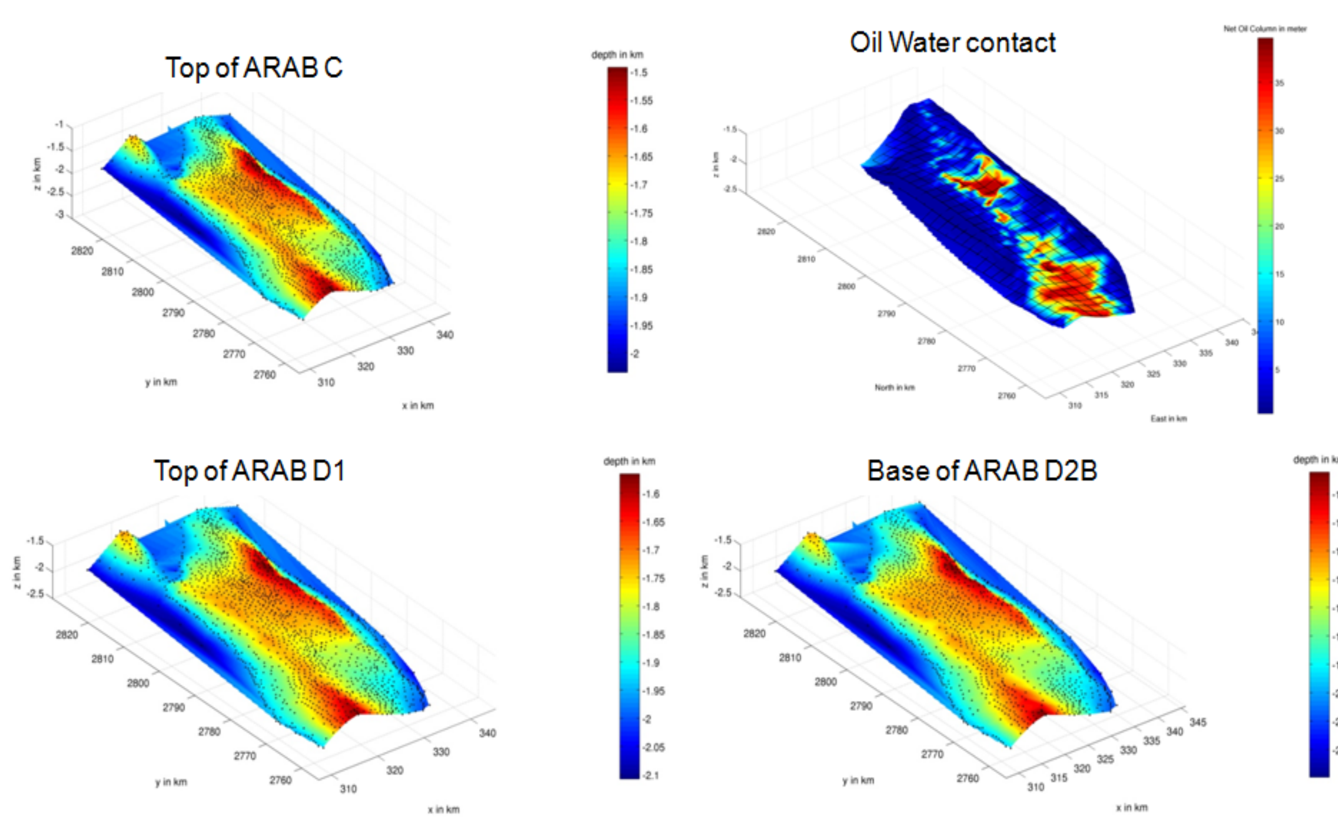


Figure 1. Reservoir surfaces of the Ghawar field and current distribution of Oil-Water from reservoir simulator.

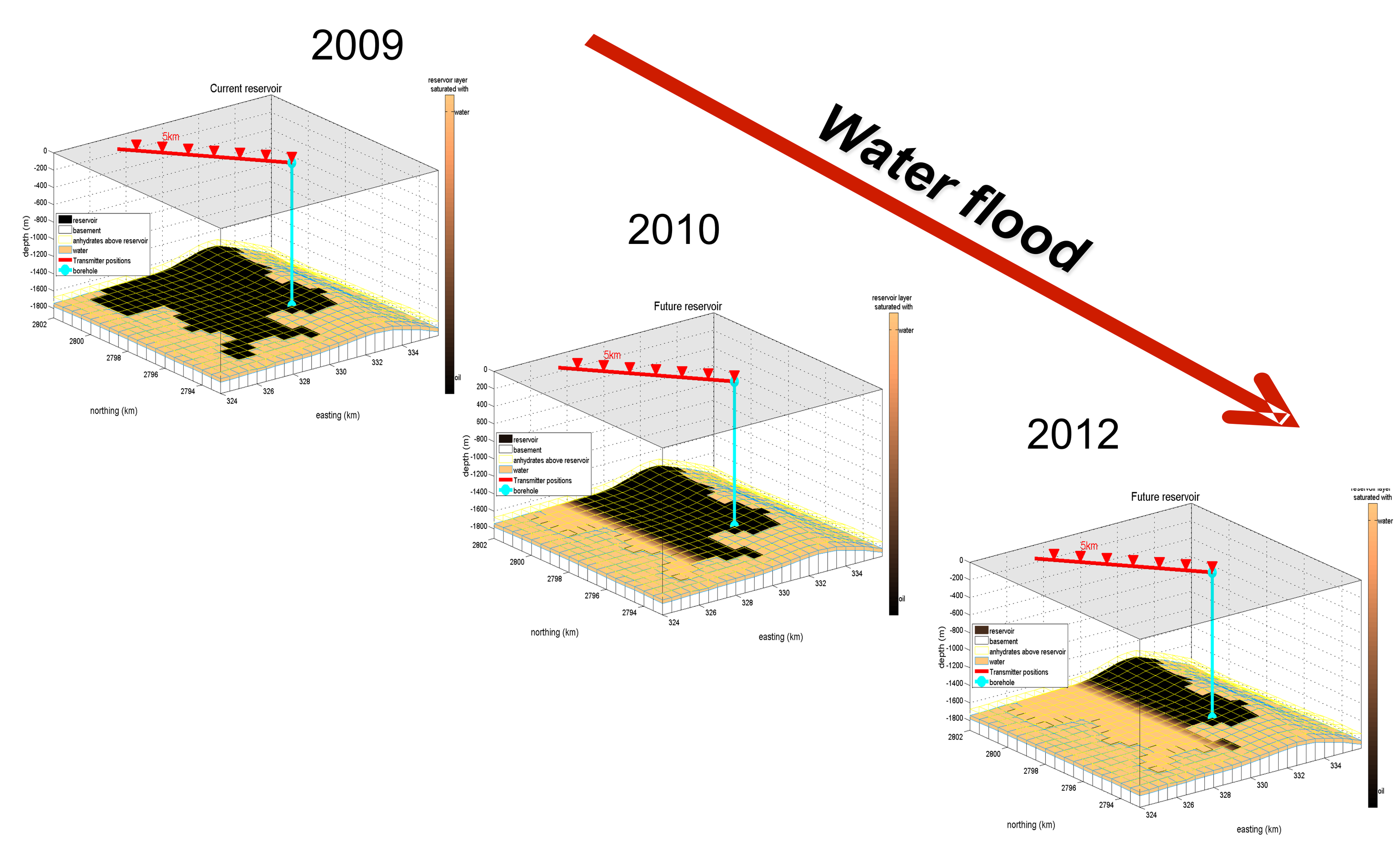


Figure 2. Simulated changes of the flood front over a period of three years.

Flood fronts from EM modeling

For a hypothetic water flood front coming from the west (Figure 2), we have computed the EM response at reservoir level (1968 m) using the survey setup.

Among all possible source and receiver configurations, the surface electric current dipole source and downhole vertical electric field are optimum to track the water flood front.

Results are in Figure 3.

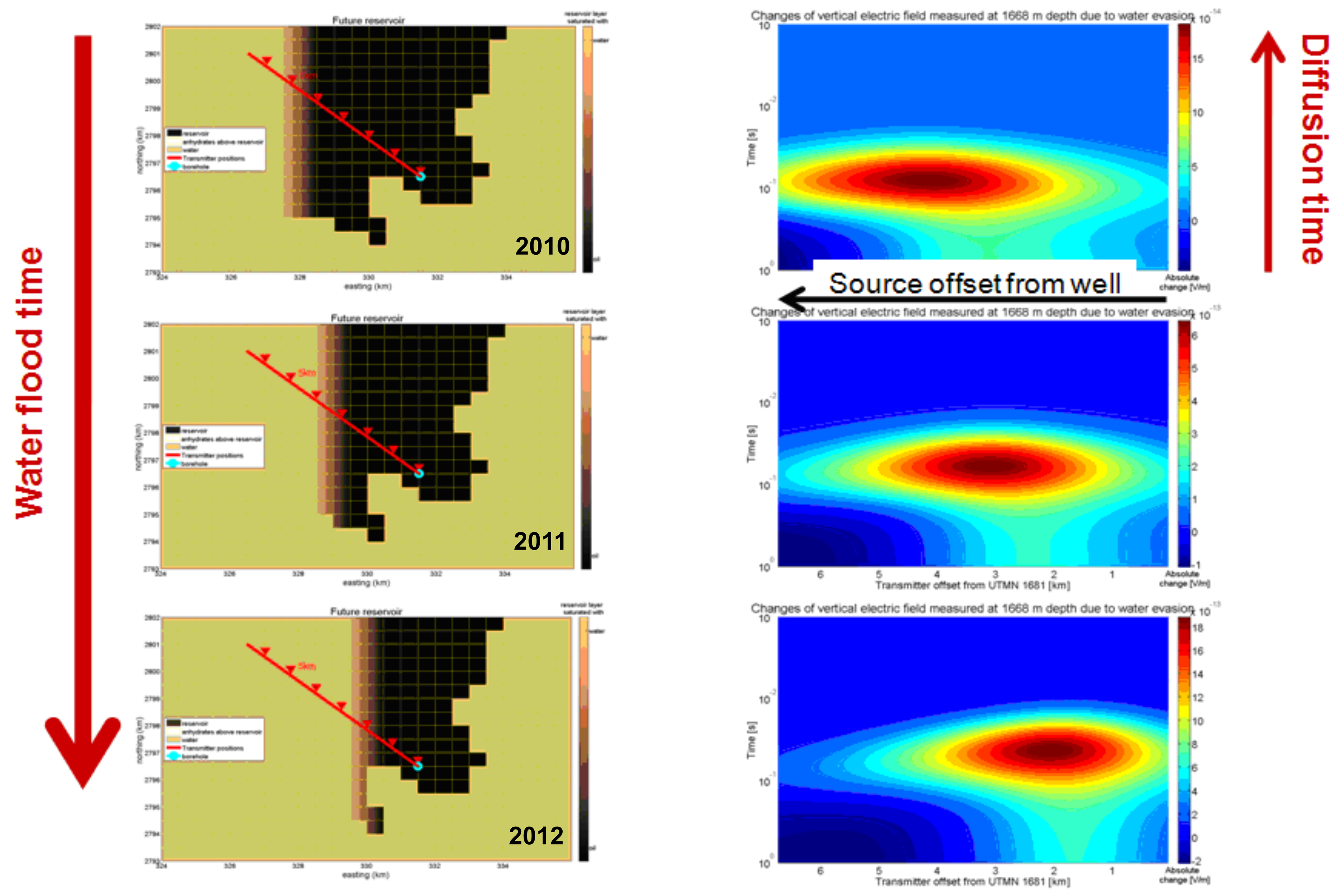


Figure 3. For a predicted reservoir depletion from the West (shown in the left panel), the measured vertical electric field changes due to an electric dipole source excitation at the surface are on the right. As the water front moves to the west, the maximum tracks it. The horizontal axis denotes the source offset from the monitoring borehole and the vertical axis denotes transient. The transmitter are deployed along the profile in red.

The normalized field strength is around 0.3 nV/m. For this the field changes from flood movement are around 0.6 pV/m. For a practical scenario with realistic sources and sensors, the vertical voltage is in the range of 120 µV. The water flooding will cause signal variation in the order of 240 nV. If the the systems can achieve noise levels below 120 nV, we can track signal changes from water flooding better than 2:1.

Vertical electric field changes are different for different transmitters. This behavior will be used in the inversion to decompose water flood front movement from different directions and at various offsets. With the surface transmitter sites shown in Figure 4, we can measure vertical electric field water flood front changes during production.

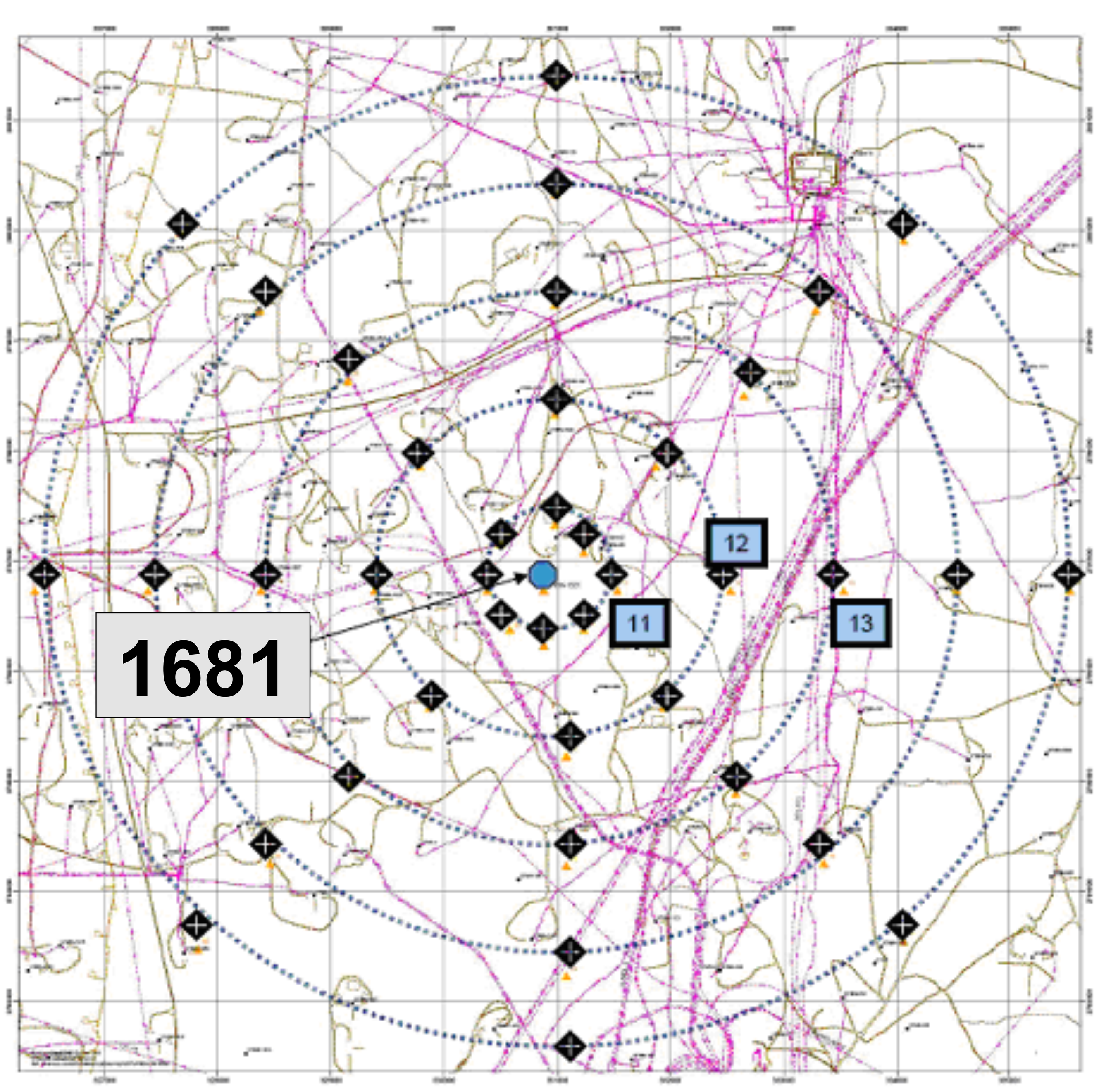


Figure 4. Planned of transmitter positions around test well. Each diamond represents an electric dipoles position..

For near borehole water coning, the caustic response is independent of the transmitter azimuth. The water coning effects can be removed using this independency (Figure 5).

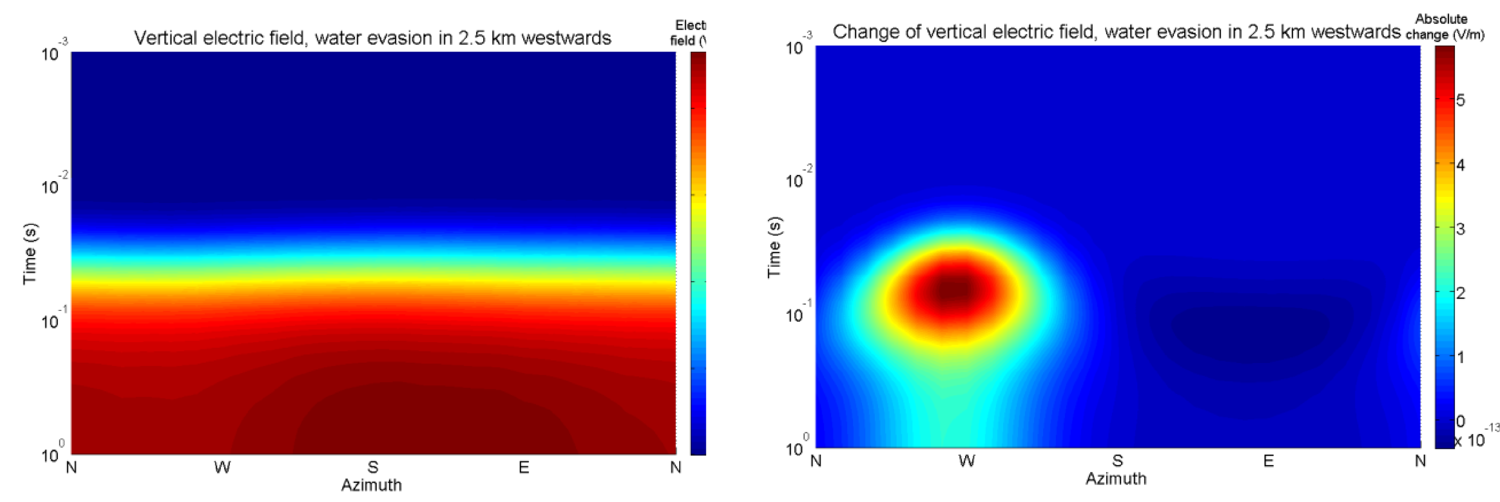


Figure 5. Vertical electric field and its changes as a function of source azimuth. When source and invasion direction align, maximum change occurs.

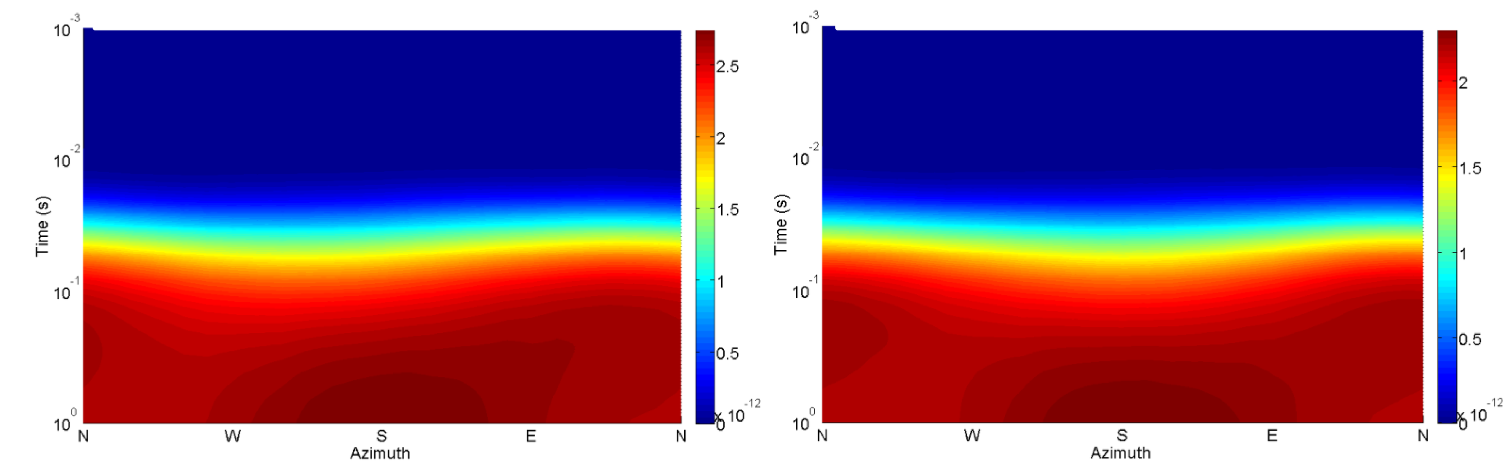


Figure 6. Downhole electric field response from transmitters on a circle for the flat reservoir model (left panel) and response for a coning model (right panel). The transmitter circle center is at the monitoring well with 2,000 m radius. The coning response (right) is different from water flodding (Figure 5 right). It has low azimuth dependence and shows at later times.

NOTE: Figure 5 and 6 can be combined together. The purpose here is to show that the water invasion has an azimuth dependence that can be used to map the invasion direction whilst coning has no azimuth dependence (i.e. it is not affecting the prediction far from the well).

I would envisage a figure showing the normalized change of Ez due to water invasion from West (Figure 5 – right) compared to an equivalent figure showing the non-azimuth dependence of normalized Ez due to coning at the well.

Next steps

Electrical anisotropy --- show examples of cumulative conductance and cumulative resistance for Rh & Rv (i.e. show how the total conductance or transverse resistance change if Rh or Rv are used).

Anything else?.. I am ok with this as next steps

Conclusions

Water flood front movement during hydrocarbon production generates measurable electromagnetic (EM) response for all source and receiver type combinations. Among source and receiver combinations, the surface electric current dipole source and downhole vertical electric field measurements have strnogest coupling to water flood front changes. Other source and receiver combinations provide also operational advantages. Best monitoring results are expected using all combinations of sources and receiver.

Bibliography

1. Wilt, M.J., and Alumbaugh, D.L., (1998) "Electromagnetic Methods for Development and Production: State of the Art," The Leading Edge (1998), 17, 4, 450-548.
2. Strack, K.-M., 2004, Surface and borehole integrated electromagnetic apparatus to determine reservoir fluid properties, US patent 6,739,165,

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