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Advances in Electromagnetics for Reservoir Monitoring

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Summary

Increasing production efficiency and monitoring water/steam/CO^2 *floods are key issues to be addressed with borehole and surface technologies and measurements. At the same time linking the information to 3D surface and borehole seismic data requires extrapolation to the inter-well space. Evaluating several methods and technologies for reservoir dynamics monitoring leads to a practical concept of Full Field Fluid Monitoring with electromagnetics. The implementation includes marine and land sources and receivers, surface-to-borehole arrays and single well systems that can look up to 100 m around the wellbore and ahead of the drill bit.*

The enabling technology is built around a multi-component cable we are building for marine applications, which can measure magnetotellurics as well as controlled source EM signals. It allows much denser data collection, enhanced operational cost efficiencies, and semi-permanent or permanent operation, and it can also be combined with nodes to cover a larger footprint with wider spacing. Similar technology with a variety of fit-for-purpose telemetry can be used onshore. For borehole use we combine our EM sensor packages with a borehole seismic acquisition system or purpose-built LWD subassemblies.

One of the major lessons from the various projects was that surface electromagnetic methods alone are ambiguous if they are not used in combination with surface-to-borehole measurements. The reason lies in the up-scaling issues associated with the inherent averaging nature of EM methods.

Introduction

During the 1990s an oil company consortium identified monitoring of reservoirs as one of key technology areas of the future (www.deeplook.com).

While numerous technologies were investigated, it was not until recently that the business environment was established and the industrial technology sector emerged. These awaited the time required to establish a baseline level for 'smart well' completion installations. Such smart wells are required to react to monitoring results.

Table 1: Summary of the resolving powers of various geophysical methods w.r.t application

SENSOR CAPABILITY	RESOLVING POWER				
	Distance	Fluid	Surface-to-surface	Borehole-to-surface	Borehole
Seismic	Excellent	Poor	Excellent	Excellent	OkK(more noise)
EM	OK (5% of depth)	Excellent (water to HC)	Ok	Excellent	Excellent (less noise & distance)
Gravity	Poor	OK (oil to gas)	Poor	Poor (passive)	Poor (passive)
Strongest Synergy	Seismic	EM/seismic	Seismic/EM/ gravity	Seismic/EM	Seismic/EM/ gravity

Today it is recognized that geophysical methods can help with monitoring as long as they are calibrated to borehole information. Among the geophysical techniques are gravity, electromagnetics and various seismic methods. Gravity senses density changes or overall mass contrasts, seismic responds to impedance changes, which occur mostly as layer boundaries, and electromagnetics responds to fluid in the pore space of the rock. To define changes in commercial quantities does usually not require detection of the actual fluid but only the change in a time-lapse mode, which is significantly easier.

We evaluated the various resolving capabilities of the different techniques with the purpose of finding the best combination. The results are shown in table 1. The best method to sense targets at a distance is seismic because of the linear signal decay with distance. Fluid changes in the pore space are best sensed by electromagnetics as the resistivity of a rock depends primarily on the fluid conductivity. In the borehole-to-surface or surface-to-borehole mode electromagnetics and seismic combined give the best response, because seismic can define the geometric boundaries while the fluid content comes from electromagnetics. The individual methods are used during different parts of the reservoir life cycle. During exploration, surface methods are favored and a 3D seismic data cube is built. Then borehole measurements are acquired and more detailed reservoir models are derived and part of the surface measurements are calibrated. The real calibration occurs when the data is scale matched using borehole-to-surface measurements.

The monitoring concept

The monitoring concept is based on several facts:

- Most fluid fronts are associated with a resistivity contrast (Zhou et al., 2002).
- Many reservoirs are more than 1 km depth below the surface and too deep for surface based monitoring.
- Boreholes are available for most reservoirs that need monitoring (as they are being produced)
- While detecting the small response from the fluid front is difficult, it is easier to detect fluid front changes with time.

We thus choose, as general approach, to start with surface monitoring and to add borehole measurements to overcome the lack of sensitivity of surface measurements (Strack, 2004). The best approach would be to install subsurface sensors from the very beginning of field development. While the industry is getting ready to adopt these concepts, it is safe to assume that the industrial application will grow through semi-permanent installations first as it did with 4D seismic.

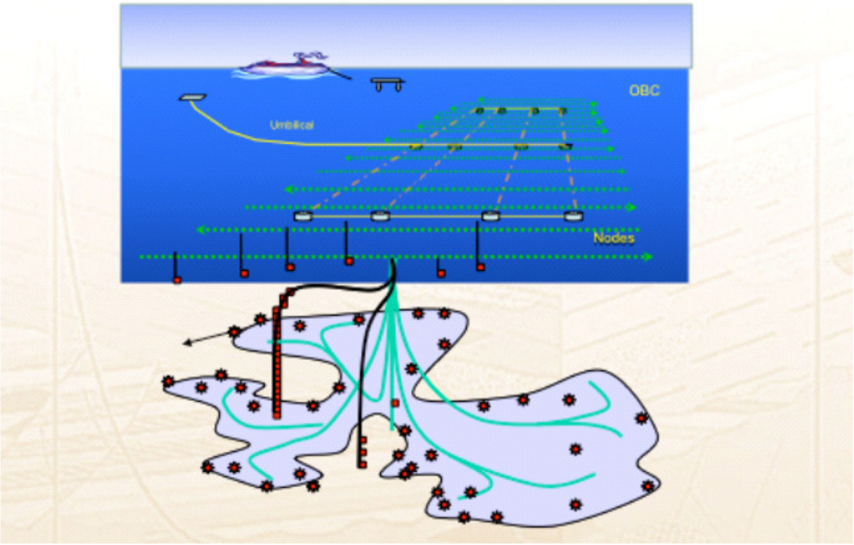


Figure 1: Cartoon of a full field sensor installation including surface, borehole and permanently- installed sensors.

Case histories

Long-term case histories applying EM monitoring have not yet been published; we thus selected a feasibility study as one of the first field trial results. The first case history is from Prudhoe Bay, Alaska and is courtesy of BP. It is the same reservoir that has been discussed extensively for gravity monitoring (Brady et al., 2006). Figure 2 shows a map of the oil field and the time-lapse results for the EM measurements. The map shows a profile, which is the seismic line that was used to derive accurate layer boundary information. Together with the well logs we derived various petrophysical models along that profile. In general one can simplify the reservoir model as shown on the left side of the map. The reservoir is an apex water flood, which means water, is injected from the top of the reservoir. The water then pushes the gas below and the gas displaces the oil that is produced from the flanks.

We then calculated the fluid substitution model for a fully oil saturated reservoir and a fully brine saturated reservoir. The reservoir itself is more complex and consists of multiple reservoirs in a 60 m thick section at approximately 2700 m depth. On the right of the map and below are the time lapse sections for two type of electromagnetic measurement, magnetotellurics (MT) and Controlled Source Electromagnetics (CSEM) (in this case time domain). For the magnetotellurics on the upper right, we have displayed apparent resistivity and phase information; for the CSEM we have displayed apparent resistivities. Both time-lapse results show anomalous behavior and on the right side of the profile the anomaly gets weaker when the reservoir thickness gets thinner, interpreted as a threshold value. For the magnetotellurics (MT), the time lapse difference is around 3 % and for the CSEM around 15%. This means the MT would be a riskier method to apply. In both cases the difference is small and given the amount of logistics required for field measurements, it would not be advisable to do this as first EM field trial.

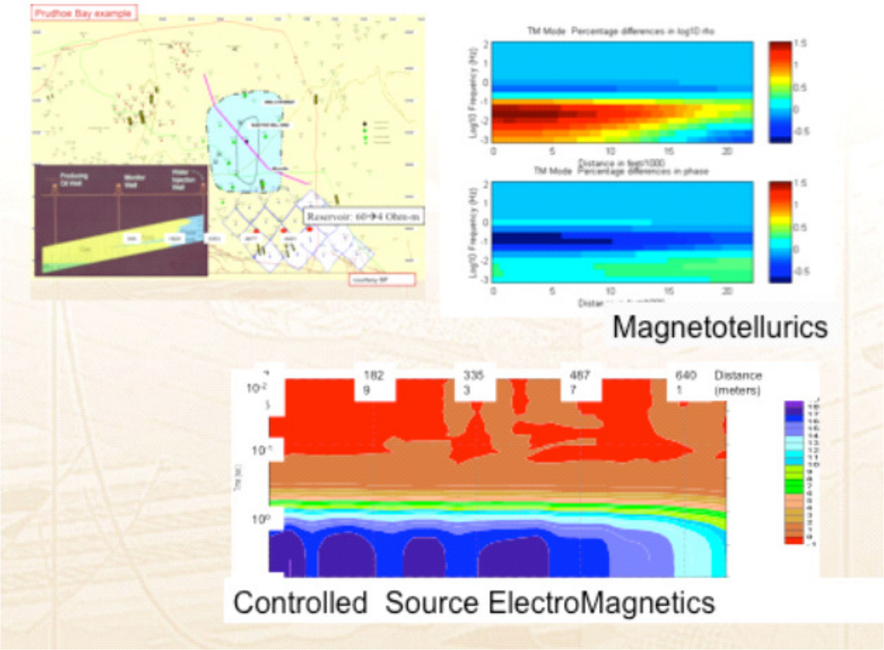


Figure 2: Results from the feasibility study for Prudhoe Bay, Alaska. On the top left is the survey map with the seismic profile that yielded the a priori information. The insert in the map is the reservoir model cartoon. On the right and the bottom are the time-lapse results from EM monitoring numerical experiments.

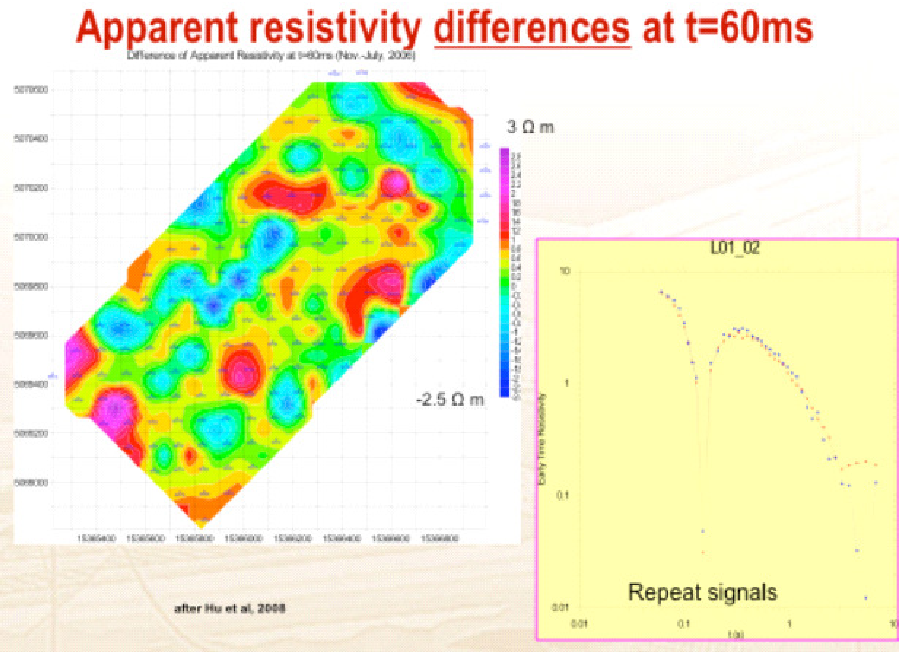


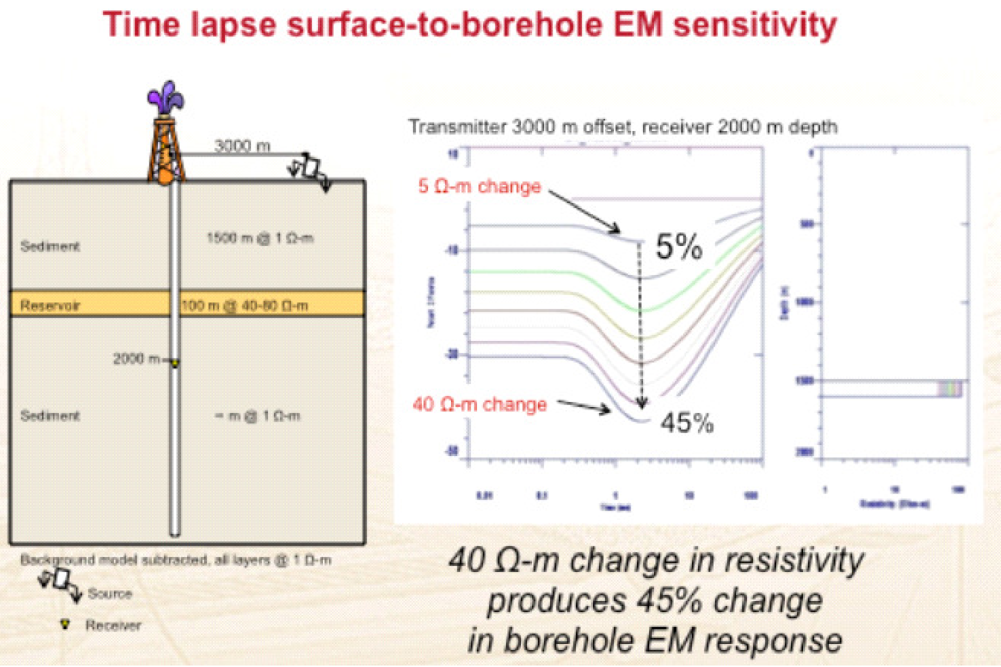
Figure 3: Time lapse difference map (apparent resistivities) from the steam flood example from China. On the right are two individual signals from the same location.

The next example is from China (Hu et al., 2008) where after successful feasibility study several test measurements were carried out in an oil field. The method selected was CSEM using time domain measurements, a grounded dipole transmitter of 2 km length and offsets between 5 – 10 km. Measurements were repeated after about 5 months during 2006. Many receiver sites were occupied and the resulting difference map is shown in figure 3. Two time-lapse recordings are also in the figure on the right displayed as apparent resistivities. An example for two recordings for the different times is shown on the right side of the figure. The time-lapse apparent resistivity difference was then color coded, positive meaning hydrocarbon influx and negative brine influx. As we are dealing in this case with a steam injection it means for negative (blue) that the steam is moving fast and for red/purple that the steam is moving slow.

In this case the bottom of the reservoir was at 400 m depth, which is the reason why it was successful. In many case the reservoir is deeper and surface measurements won't see much of an anomaly as the signal decays the offset to the third power.

The next obvious step is to use surface-to-borehole measurements where the transmitter is at the surface and the receivers in the borehole. This overcomes cultural noise issues with the receivers when at the surface and safety issues when lower high voltage and high current transmitters in the borehole. Figure 4 shows some modeling results for a reservoir that is representative for many reservoirs in the Middle East. In this case the fluid substitution yielded resistivity changes from 5 to 40 ohm-m for brine or oil saturated reservoir. When modeling this we can see appreciable differences on the right of the diagram.

A next step would be to add single well measurements. Single well measurements and even time lapse measurements will require recording of very small signals in the Pico-volt range. Present technology is just starting to be able to measure these type of small signals and the first laboratory tests have just been made.



Time lapse surface-to-borehole EM sensitivity

40 Ω-m change in resistivity produces 45% change in borehole EM response

Figure 4: Feasibility models and results for surface-to-borehole EM monitoring. On the left is the model and on the right of the diagram the various curves for different reservoir fluid saturations.

Conclusions

Geophysical reservoir monitoring can help predict flood front arrival and thus allow control of the smart well production completion. This saves operating costs and increases the recovery factor of a reservoir. The use of these types of measurements is slowly increasing as infrastructure and technology understanding is put in place.

Acknowledgements

I would like to thanks Hu Wenbao and Gang Yu for their support throughout the years. Hu Wenbao made a successful project from initial discussions and carried out many surveys in China that yielded successful results. The data from Alaska was provided by BP, and Jerry Brady was instrumental in getting the project organized. I thank KMS technologies for permission to publish this.

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