Electromagnetic methods for development and production: State of the art

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Electrical and electromagnetic methods are a natural addition to the toolbox of a development and production geophysicist because formation resistivity is a strong function of the reservoir fluid saturation and temperature. Unfortunately, the high degree of cultural noise in developed oil fields has limited the use of surface electrical techniques, and the preponderance of steel well casings has limited the deployment of borehole tools in completed wells. The result is that, with the exception of open-hole logging, electrical methods are not routinely used in oil fields after the exploration phase is complete.

Recently, however, several experimental applications of electromagnetic techniques for water and steam flood monitoring have yielded impressive results (see *TLE*, March 1995). Crosshole EM measurements, made in fiberglass-cased observation holes, have yielded images of interwell resistivity structure and bed continuity in several California oil fields. Repeated application of EM tomography was used to obtain images of resistivity variations during steam-flooding operations. These data were in turn used to track the flow of injected steam.

In this short article we discuss the relative merits of electrical methods as applied to oil-field development and production. We then briefly describe several new technologies that apply EM methods in innovative ways to the hostile oil-field environment.

Advantage of electrical methods. Electrical and electromagnetic data are analyzed primarily to yield the electrical resistivity of the rock formation where currents have been injected or induced to flow. The resistivity is in turn a strong function of the porosity and pore fluid saturation. In fact, resistivity data obtained through electric logging are routinely used by log analysts in calculating the porosity and saturation of pay zones.

Although surface and borehole seismic have been the preferred geophysical technology for D&P applications, Figure 1 provides an excellent illustration of why field developers should consider collecting EM in addition.

Here we plot seismic velocity and electrical resistivity as a function of temperature, porosity, and water saturation in water-flooded sandstone cores. The plots indicate a high sensitivity of the electrical resistivity to variations in reservoir conditions, and a smaller sensitivity of seismic velocity to the same reservoir variations. Typically, the resistivity varies up to an order of magnitude over the range of typical reservoir conditions whereas the seismic velocities vary by no more than 10-20%. The contrast is most pronounced in Figure 1b where the seismic data indicate a very small change due to fluid saturation, and the electrical data are greatly affected.

Of course these plots do not tell the whole story. Although the electrical data are sensitive to variations in storage and saturation of reservoir liquids, seismic techniques are more sensitive to the presence of reservoir gases. In addition, the higher resolution offered by seismic techniques is superior in mapping reservoir structure. These core data suggest that combination of the two technologies can improve estimates of reservoir conditions offered by either method.

Some new technologies are emerging to extend the range of EM methods into reservoir spaces between wells. Below we give brief summaries of three: extended induc-

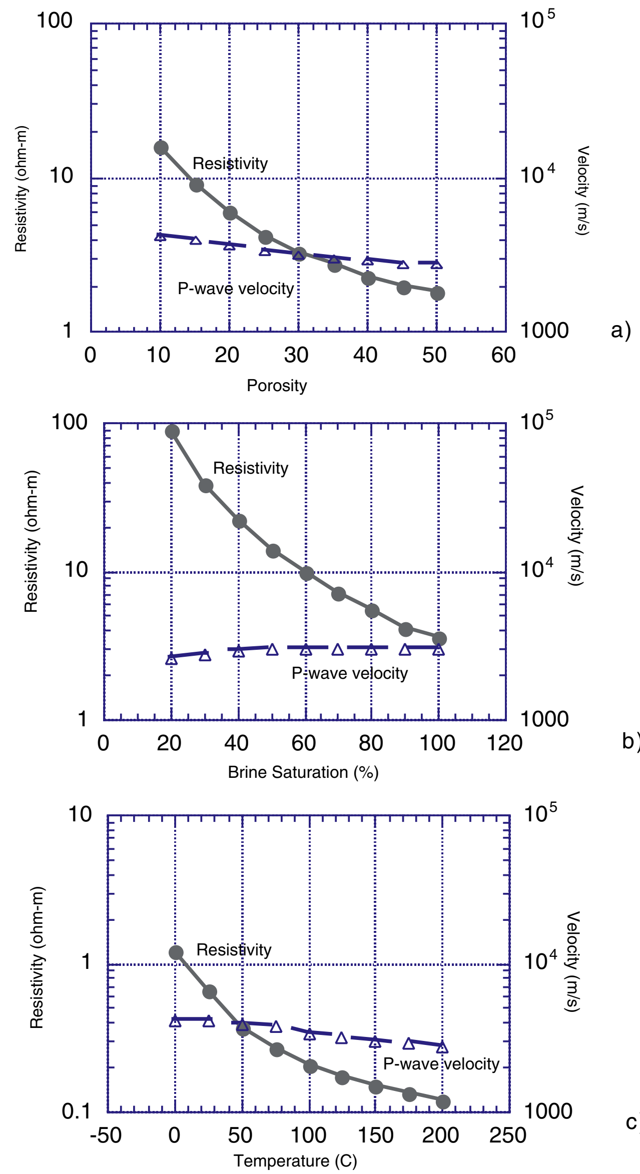


Figure 1. Variation of resistivity and *P*-wave velocity with porosity, brine saturation, and temperature for a sandstone core.

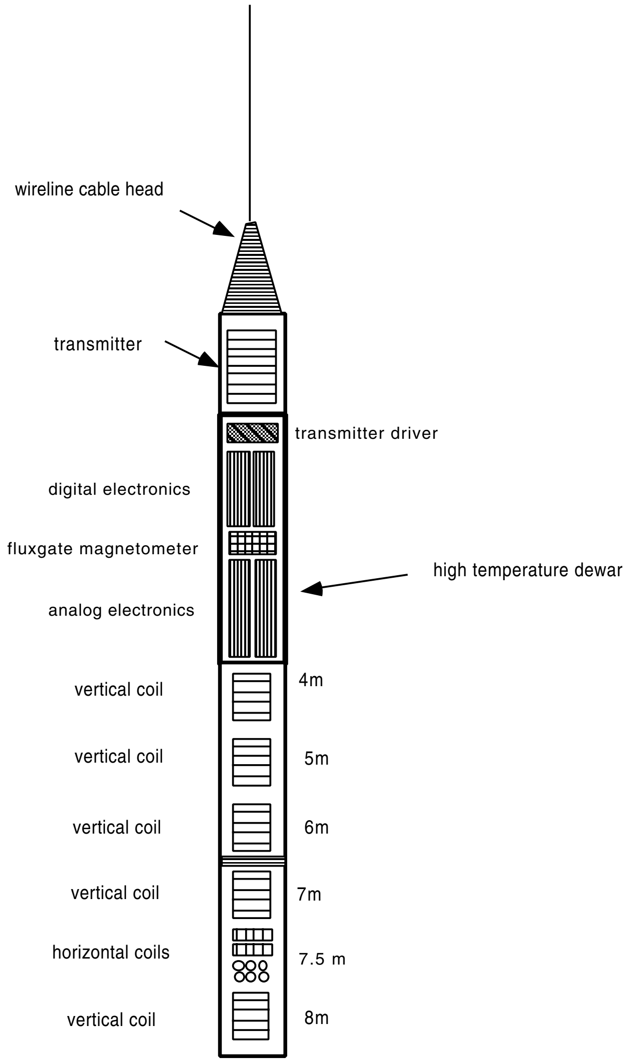


Figure 2. Schematic diagram of the MAIL tool.

tion logging, application of crosshole EM in steel-cased wells, and earth's field nuclear magnetic resonance (NMR).

Single borehole imaging. Commercial induction logging technology is designed for detailed formation evaluation in stratigraphic beds at least a meter thick. The investigation depth of such devices is also a meter or less. An extension of this same technology using large and variable source-receiver separations and three-component receivers would permit more extensive structural and stratigraphic mapping from a single borehole. This has utility in 3-D geology and in deviated boreholes. Below we describe a prototype device with some of these features.

Recently, the experimental Multi-Frequency Array Induction Logging (MAIL) tool has been developed for the New Energy Development Organization (NEDO) of Japan by Electromagnetic Instruments of Richmond, California. The tool was designed for fracture mapping in high-temperature geothermal exploratory boreholes and has been tested in wells with temperatures exceeding 26° C.

Figure 2, a schematic drawing of this tool, indicates the basic concept — a multifrequency transmitter section in one end and an array of induction coil and fluxgate sensors distributed throughout the rest of the tool. Five vertically oriented induction coil sensors are spaced 4-8 m from the transmitter; two horizontal field sensors are situated at 7.5 m, and a three-component fluxgate magnetometer (used for tool orientation) lies 3 m from the source. The tool operates at four frequencies in the range of 3-40 kHz. Signal detection, synchronous stacking, and A/D conversion are accomplished within the tool before transmission to a PC-controlled surface station. The subsurface station controls data collection, applies calibration corrections, and displays/stores results.

The tool was operated at the Lost Hills Field in central California where Mobil Exploration and Production is operating a shallow steam flood for enhanced oil recovery. We deployed the tool in a fiberglass-cased observation well 30 m from a steam injector. The observation well has several nonuniform high-temperature zones due to the recent steam flood. In the past we have used this and a companion observation well for crosshole EM studies that have tracked the injected steam plume over the past several years. We therefore have a good idea of the electrical resistivity structure in the region between the boreholes.

Figure 3a shows the commercial induction-resistivity log from the borehole, collected immediately after drilling in 1992, together with a 1996 resistivity log from the MAIL tool using the 5-m offset vertical sensor. The two responses are quite similar in the upper reaches of the well, but notice that the newer log is smoother than the previous log, due to the longer source-receiver offsets. Below 60 m, however, the resistivity measured with the MAIL tool is significantly less than the commercial 1992 log. This difference is primarily due to the high-temperature zone in the borehole (in excess of 130° C) caused by the nearby steam injector. The replacement of insulating oil with hot water and steam is consistent with the 50-80% reduction in resistivity observed with the logs.

An interesting feature of this tool is the ability to measure horizontal fields in addition to the vertical field component. In a single hole EM logging tool horizontal fields are zero for homogeneous or horizontally layered formations. Sizable horizontal fields therefore indicate geological heterogeneity adjacent to the borehole such as throughgoing fractures, dipping beds, or irregular structures.

Figure 3b is a plot of the horizontal fields from the MAIL in the same borehole. Notice that the fields are small in shallow sections of the well but become significant at depths greater than 60 m where they display a crossover anomaly with peaks roughly corresponding to the boundaries of the high-temperature zone. Numerical models show that this is consistent with a low resistivity zone (steam plume) that is more pronounced east of the well, toward the steam injector.

We have shown that extended induction logging data are useful for indicating reservoir conditions and heterogeneity well away from the borehole. The next generation of such tools will likely include three-component sources, in addition to the three-component receivers, and a larger selection of sensor offsets and operating frequencies. These richer data sets will be sufficient for creating a deep 3-D resistivity image around the well, not just an induction log.

Water-flood monitoring with crosshole EM in steel-cased wells. Steel casing severely attenuates electromagnetic signals transmitted or received from within the pipe. The casing typically acts as a low-pass filter, attenuating sig-

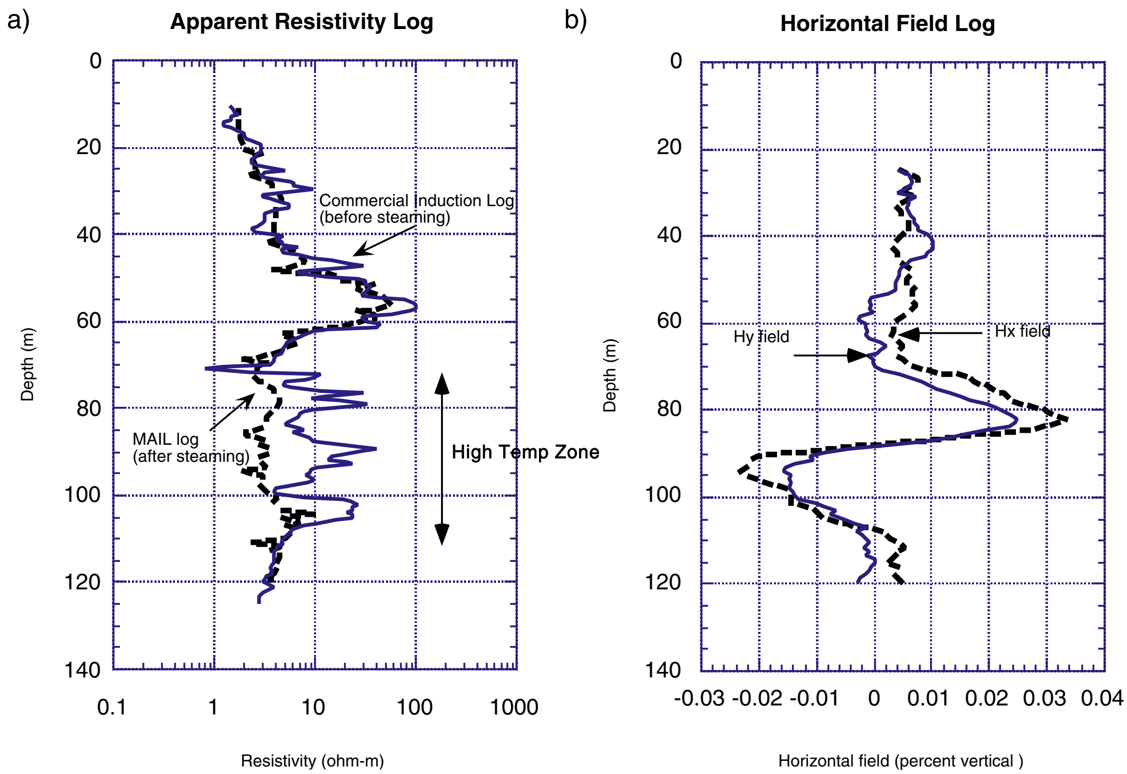


Figure 3. Induction resistivity logs and horizontal field response in an observation well near a steam injector at the Lost Hills Field.

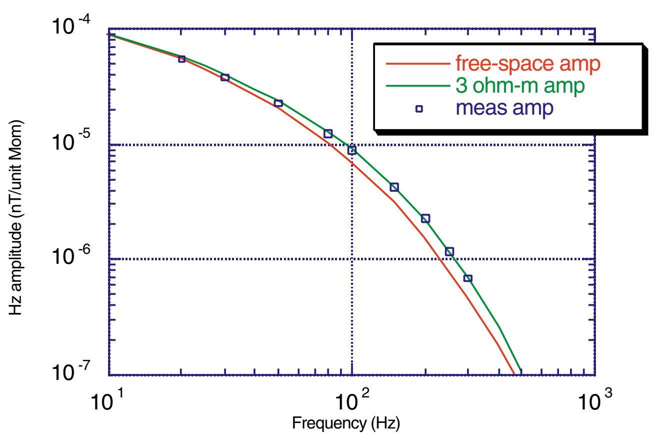


Figure 4. Crosshole EM frequency sounding in steel casing.

nals above 10 Hz and virtually eliminating signals above a few hundred Hz. At lower frequencies, where through-casing measurements are possible, the total measured field is substantially less and the affect of formation resistivity smaller as compared to measurements made through non-conducting casing. This means that field measurements are more difficult in steel casing, and field data predominantly reflect casing effects.

Current research suggests, however, that the shielding effect of the steel pipe is a fairly simple function of the thickness, electrical conductivity, and magnetic permeability of the steel-pipe segment surrounding the sensor. Although EM fields are severely attenuated by the steel pipe, the response may be calculated with fairly simple numerical models and separated from the formation effect using straightforward techniques. In addition, numerical calculations suggest that for widely separated boreholes the formation response is a considerable portion of the total measured field. Thus, if the properties of the steel casing are obtained, the response due to the casing may be easily separated from the total field, leaving the formation response as a residual.

Recently, the crosshole EM technique was tested in a field application utilizing one steel-cased well and one fiberglass well. The fiberglass monitoring well is 10 m from a water injector and 90 m from a steel-cased oil production well. Induction resistivity logs in the observation well show that the average formation resistivity varies between 1.5 and 4 ohm-m in the production interval (550-770 m). Repeated induction logs show that the water injection has decreased the resistivity in the oil-bearing zone between 20 and 40%.

For the initial test we positioned both source and receiver tools at the same vertical level and adjusted the frequency of the transmitter beginning at the lowest frequency detectable with our receiver (20 Hz) until the signal was attenuated by the casing to below the detection threshold of our tool (about 500 Hz). These frequency soundings were made at 10 different levels, corresponding to different casing segments and small differences in formation resistivity. The sounding data were found to repeat over time to about 3%.

Figure 4 shows a crosshole frequency sounding from a depth of 550 m. The data are plotted with numerical calculations for steel-casing models with and without a 3 ohm-m formation. The electrical conductivity, magnetic permeability, and thickness of the steel casing were obtained by using the Schlumberger METT casing evaluation log and by trial and error fitting of the lower frequency section (< 50 Hz) of the crosshole soundings to numerical models.

At frequencies above 50 Hz, the formation effect causes the total response curve to deviate significantly from the curve with the casing alone. The observed data seem to much more closely correspond to the model with the formation present. This promising result, coupled with other research, strongly suggests that the formation resistivity may be obtained with crosshole EM even in steel-cased wells.

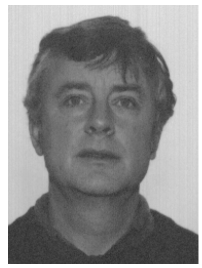
In future surveys our goal is to obtain a complete tomographic resistivity section using one well with a steel casing and one with fiberglass casing. In addition, we expect that the ongoing EM monitoring will yield information on the subsurface resistivity changes due to water flooding within a year or two.

Earth's field NMR. Recently, a series of experiments involving the use of earth's field NMR resulted in successful application of this technology to groundwater exploration in arid regions. This technique involves locally perturbing the direction and amplitude of the earth's ambient magnetic field to affect the dipole moment of hydrogen-based molecules (i.e., water or oil) within the pore structures. After the perturbing field is shut off, a decay signal is generated in regions containing mobile hydrogen atoms. These data can be used to estimate the porosity, saturation, and possibly even permeability of these volumes.

The technology, originally developed by Russian scientists, involves a variation of the time domain or transient EM method. It is typically applied using large surface-based loop antennas and is capable of exploring for groundwater resources at depths up to 100 m or so.

Recently, a project has been initiated through the DeepLook consortium to study the feasibility of extending this technology to oil and gas exploration. The attraction of the technique is that it allows for determination of mobile saturation at distances up to tens of meters from a single borehole. This contrasts sharply with the present generation of borehole NMR devices which produce high-resolution data but at limited penetration depths.

Conclusions. EM techniques have great potential in development and production applications due to their sensitivity to variations in subsurface fluid saturation and temperature. Initial applications have been promising, and ongoing research suggests that the techniques are viable even in steel well casing. At present, however, the methods are little used in D&P, and no commercial tools are available. The future application of electromagnetic techniques to oil-field D&P requires continued technological advancement on the part of the research community and continued application and investment on the part of oil-field developers.



Michael J. Wilt received his bachelor's (1973) and master's (1975) in geophysics from the University of California Riverside, and his doctorate (1991) from the University of California Berkeley. He was employed as a staff scientist at Lawrence Berkeley Laboratory from 1977 to 1984 and worked on employing electrical and electromagnetic methods for geothermal and petroleum exploration. He pursued his doctorate over the next five years with research in electromagnetic sounding, resistivity monitoring, and the application of the self potential method to engineering problems. He worked at Lawrence Livermore National Laboratory from 1989 to 1997 where he applied electrical and electromagnetic methods to oil and geothermal field characterization. He joined EMI as vice president and director of the borehole geophysics division. He is currently leading research and development projects in crosshole EM and extended induction logging.

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