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Cross-Borehole and Surface-to-Borehole Electromagnetic Induction for Reservoir Characterization

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Abstract

Audio-frequency cross-borehole and surface-to-borehole electromagnetics (EM) are interesting alternatives to existing techniques for petroleum reservoir characterization and monitoring. With these methods signals may be propagated several hundreds of meters through typical sand/shale reservoirs and data may be collected at high accuracy with a high sensitivity to the subsurface resistivity distribution. Field systems for cross-borehole and surface-to-borehole EM measurements have been designed and built by Lawrence Livermore and Lawrence Berkeley Laboratories for reservoir evaluation and monitoring. The cross-borehole system utilizes vertical axis induction coil antennas for transmission and detection of sinusoidal signals. Data are collected in profiles with the source coil moving continuously while its signal is detected by a stationary receiver coil located in a separate well. Subsequent profiles are collected using a different receiver depth and the same transmitter span until a suite of profiles is obtained that cover the desired interval in the borehole. The surface-to-borehole system uses a large diameter surface loop transmitter and a vertical axis borehole receiver. Due to its high signal strength this system operates using a sweep frequency transmitter waveform so that data may be simultaneously collected over several decades of frequency. After extensive local testing these systems were deployed at the British Petroleum test facility in Devine, Texas for further testing and technique evaluation. The Devine site is in a region of simple, flatlying geology so that collected data could be unambiguously interpreted with layered models. The results of the field exercise showed that crosshole EM data collected in 1000m deep wells spaced 100 meters apart are smooth and continuous profiles that can be repeated in 24 hours to better than one percent. These data were then closely fit to layered models using a least squares inversion algorithm. The results show a close correspondence to the borehole induction logs. Sensitivity analysis shows that the crosshole EM data from boreholes separated by 100 meters can detect subsurface layering as thin as one meter. The surface-to-borehole profiles are equally repeatable and although this data is less sensitive than cross-borehole EM, it can also be fit to a resistivity section consistent with the borehole log. One advantage of the surface-to-borehole data is that he signal is sufficiently strong to propagate through steel well casing. Although data collected in steel-cased wells is strongly affected by the casing this affect can be removed using simple algebraic methods.

Introduction

The electrical resistivity of most sedimentary rock is a function of pore fluid type, its saturation and the porosity of the rock. For these reasons borehole resistivity logs have long been used by reservoir geologists and engineers to distinguish between rock types, map variations in pore fluid and to determine completion characteristics in boreholes.

There is an obvious need to extend our knowledge of the electrical resistivity distribution from the immediate vicinity of the borehole, as is the case in induction logs, to the region between boreholes. Although this may be accomplished using a variety of surface and borehole configurations we have found that the greatest sensitivity is achieved when measurements are made within boreholes. This is simply because the data are collected closer to the region of interest.

Recent cross-borehole electrical/electromagnetic research has concentrated at opposite ends of the frequency spectrum. Daily et al. (1990) and Shima (1990) have reported success using cross-borehole resistivity methods utilizing grounded sources and receivers. In both cases they have shown that high resolution images could be obtained from inversion of cross borehole voltage and current measurements. Previous applications of the high frequency electromagnetic method (HFEM) to the cross-borehole problem have yielded mixed results. In high resistivity rocks (hard rocks or rocks with low salinity pore fluids) applications of HFEM have provided high resolution tomographic images of gas fire-fronts and fractures in coal seams (Davis et. al., 1979, Lytle et. al., 1974). In regions of lower resistivity (soft sedimentary rocks or rocks with high salinity pore fluids) HFEM results have been disappointing due to severe attenuation of source waves by the medium. Experimental results for enhanced oil recovery operations (EOR) reported by Harben and Pihlman (1988) at the Texaco Kern river site showed that 20 Mhz HFEM signals did not propagate more than a few meters through the sand/shale host rock before attenuation to undetectable levels.

An interesting alternative to these methods is the EM induction method. This method differs from HFEM chiefly by operating at audio rather than radio frequencies (0.25 - 20 Khz vs 2-200 Mhz) and utilizing magnetic dipole rather than electrical dipole antennas. At these lower frequencies the energy propagation is diffusive rather than wave-like, tending to spread and disperse with propagation.

The EM induction method offers several significant advantages over HFEM in through-the-earth imaging applications. 1) At audio frequencies the signals may be detected at far greater distances than HFEM. In typical sand/shale petroleum reservoir rocks it is practical to make high accuracy cross-borehole measurements from wells spaced up to 400 meters apart. 2) The induction measurements are simpler to make and interpret. External interference and "sneak path" wave propagation are major problems at high frequency but they are relatively insignificant at these lower frequencies. 3) A final advantage is that the data may be unambiguously interpreted in terms of resistivity or changes in resistivity of the rock through which the signal has passed. With HFEM it is often difficult to separate resistivity from permittivity effects.

In 1989 researchers from Lawrence Livermore Laboratory (LLNL), Lawrence Berkeley Laboratory (LBL) and U.C Berkeley jointly began addressing the problem of collecting and interpreting audio-frequency cross-borehole and surface-to-borehole EM data. In this program we have developed a field system, written numerical codes to interpret data and have deployed our system in a field environment where the geology is simple and well known. In this report we will describe our system, show some results from the field test and discuss the deployment of this system in steel-cased wells.

Description of the EM Systems

Cross-Borehole System

The LBL/LLNL cross-borehole EM system is a vertical component induction EM system designed for cross-hole imaging from boreholes spaced up to 400m apart. The system operates in the frequency domain from 1-20,000 Hz.

Transmitter and Receiver modules for this system are essentially separate entities. That is, the receiver may be used with separate transmitters, as is the case for surface-to-borehole measurements, and several separate receivers could be operated using the same transmitter. The modules are connected only via electrically isolated cables. A requirement of the instrumentation from each module is that it be locally grounded, have its own power supply and be electrically isolated from other modules. Such grounding and isolation is vital for the elimination of stray currents and ground loops that degrade data quality.

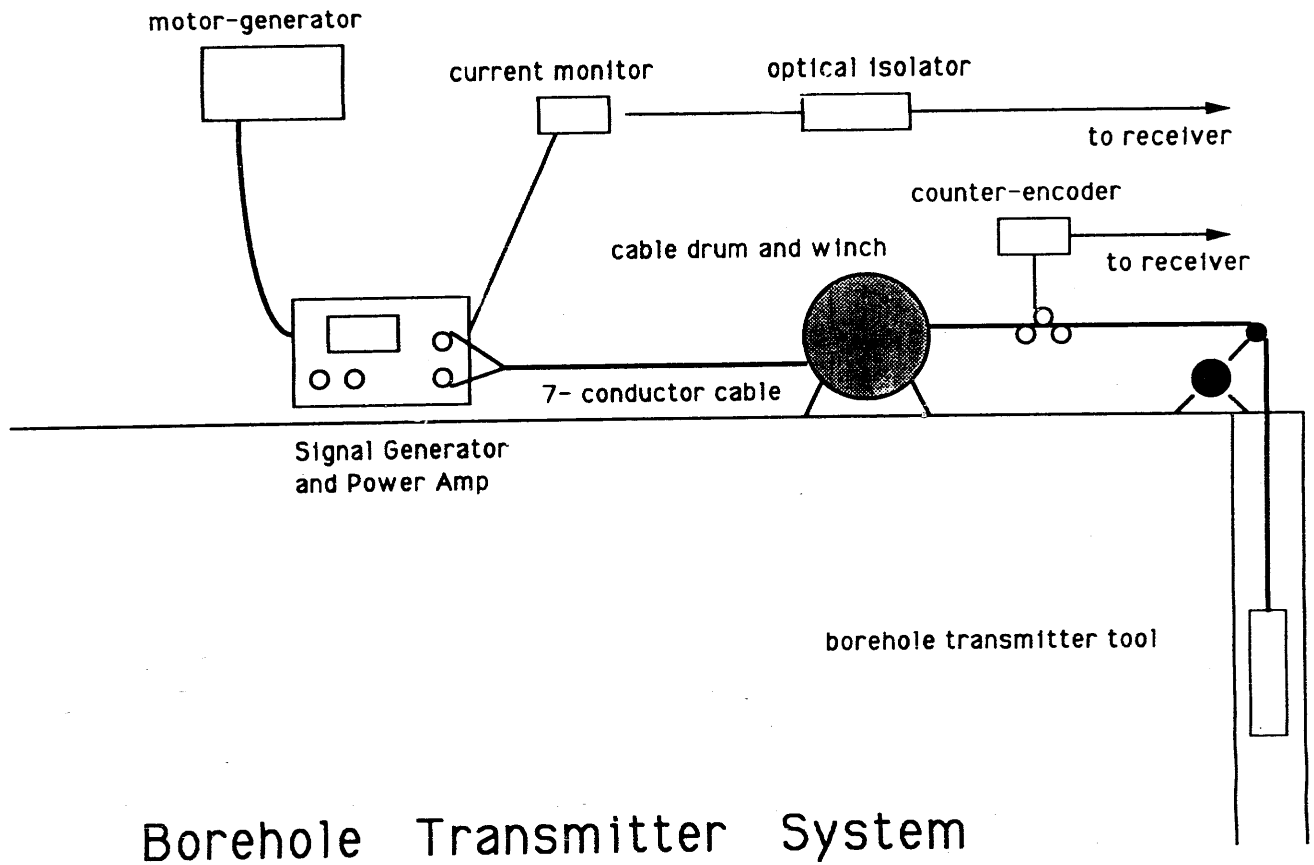


Figure 1 Schematic diagram of the cross-borehole transmitter.

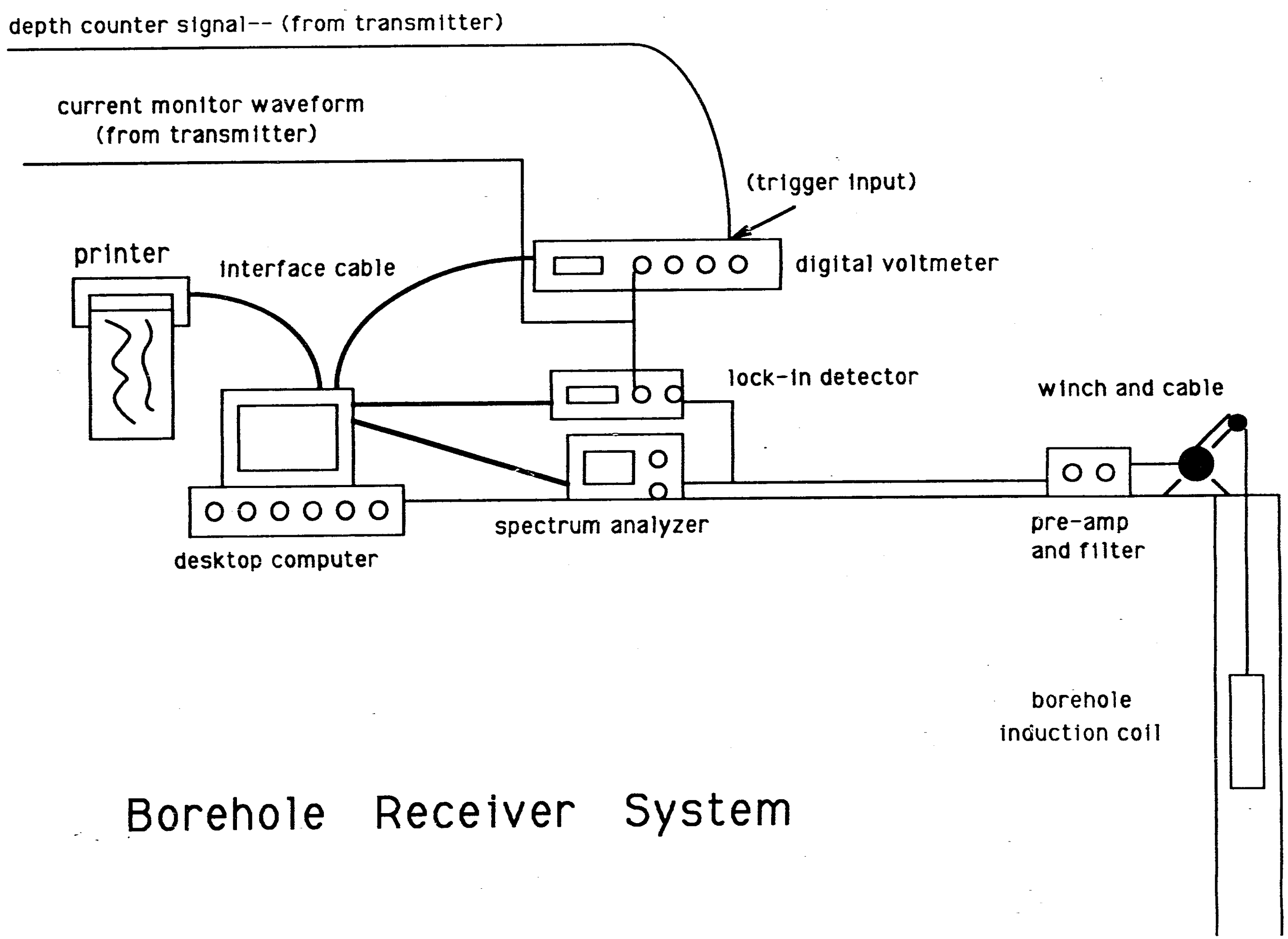


Figure 2 Schematic diagram of the cross-borehole and surface-to-borehole receiver

Transmitter Section:

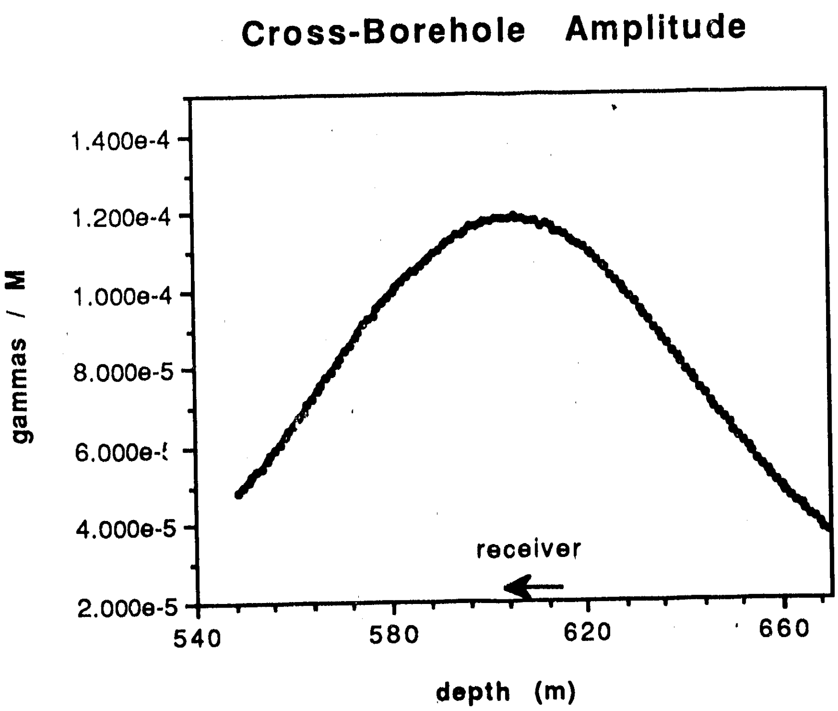
The transmitter section, shown schematically in Figure 1, consists of a custom-designed vertical coil driven by a commercially available EM transmitter; ie the Zonge GGT-25. The coil is 8cm in diameter and 4m long weighing approximately 100 kg. At a current of 15 amps it theoretically supplies a maximum transmitter moment (product of the effective coil area, the number of turns and the current) of 3000 A-m^2 which is sufficient for transmission through the earth at distances more than 500m. In practice, due to the current and voltage restrictions of the logging cable we rarely drive the coil with more than 6 amps. The coil consists of a laminated mu-metal core wrapped with 300 turns of high temperature wire and connected in series with a capacitor board. The capacitors serve to tune the coil, ie counterbalance voltage drop due to the inductance. Such tuning is indispensable at frequencies above 100 Hz to preserve the transmitter moment. Above 100 Hz a different value of capacitance is used for each frequency. The capacitor boards are designed so that frequencies are selectable in factors of 2, from 256 to 8192 Hz.

The coil and cable are moved with a hydraulic, diesel powered winch which is capable of moving the coil at a steady rate ranging from several to several hundred meters per minute. The cable drum presently holds about 800m of seven conductor logging cable although it may hold over twice this amount. The position of the coil and rate of movement are monitored with a wheel-driven encoder/counter. This device provides a visual display of the depth and rate and also gives a synchronous pulse output which is used at the receiver site to provide depth readings of the transmitter coil.

The transmitter current is detected with an inductive-type current meter connected to the transmitter output. This analog record of the transmitter current is sent to the receiver via an isolated line. A second isolated line provides an analog record of the encoder pulse.

Receiver Section:

Signals are detected at the receiver using a vertical-axis custom-designed borehole coil. This sensor coil is an ultrasensitive device (maximum sensitivity of 10^{-13} teslas), operable in the frequency range from 1-100,000 Hz. (For reference the main magnetic field of the earth is approximately 0.5 teslas). The tool is housed in a pressure vessel designed for depths up to 2 km. Detected signals are amplified within the coil then transmitted to the surface up the logging cable. At the surface they are further amplified and filtered before



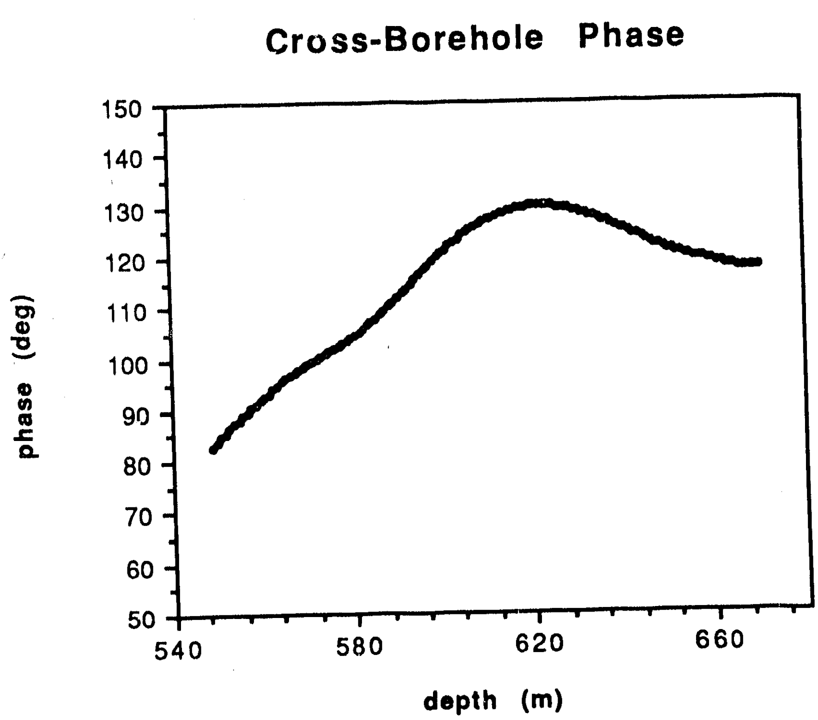


Figure 3 Sample cross-borehole amplitude and phase plots.

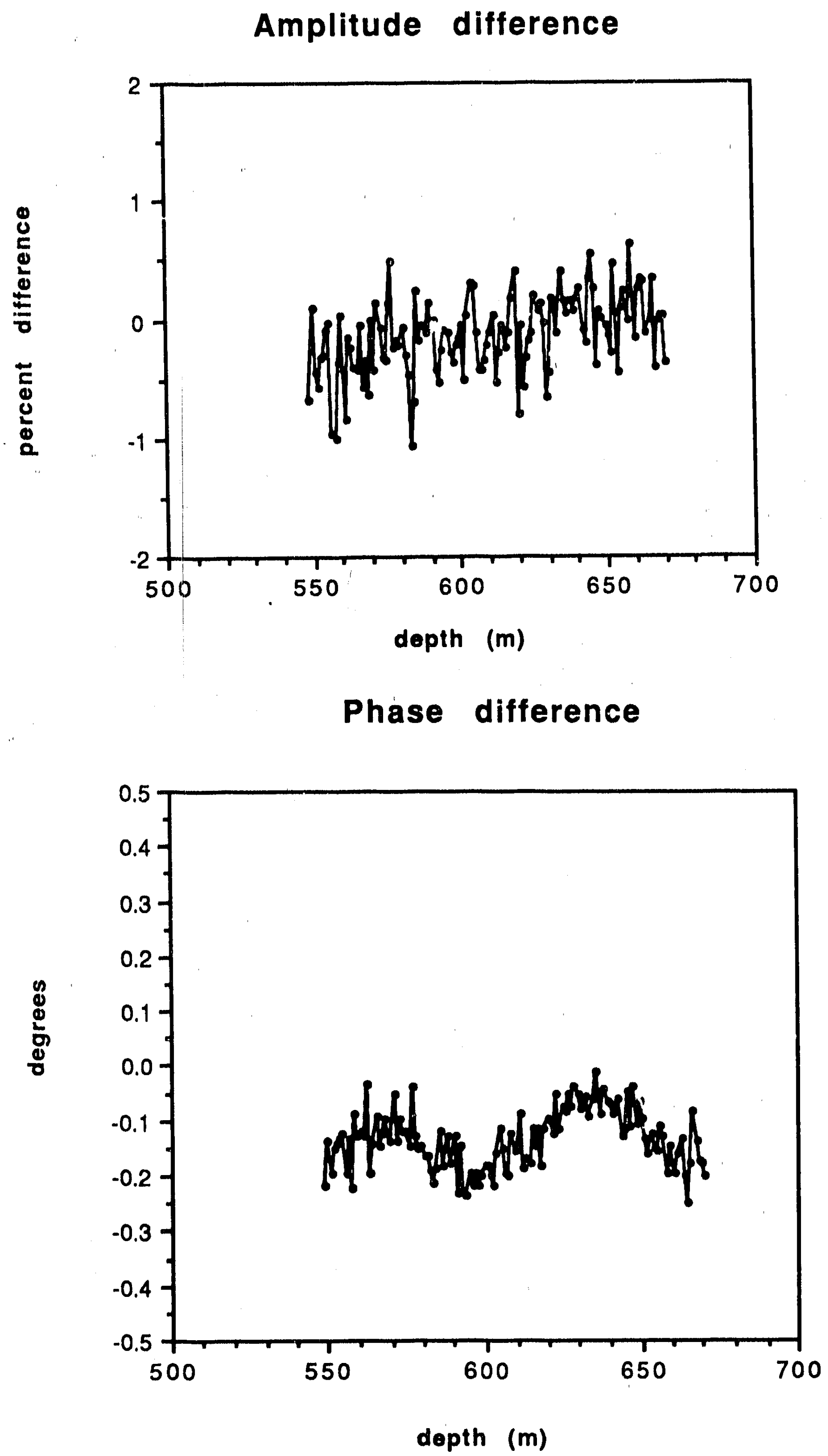


Figure 4 Percent difference of amplitude and phase measurements for a 24 hour repeat

input to the receiver van (Figure 2). In the van all instruments are controlled from an Hewlett Packard desktop computer via the GPIB interface. The computer can adjust instrument gains and sensitivities as well as select sample and averaging rates for the logging system.

The receiver system is triggered by encoder pulses originating at the transmitter. The computer counts the incoming pulses until one corresponding to a pre-selected measurement depth is received. When this occurs the computer collects transmitter current data from the digital voltmeter and magnetic field data from the lock-in detector.

The lock-in detector uses the transmitter current waveform as a reference signal and detects receiver signals in phase and out of phase with this signal. It is a very effective device for accurately discriminating low level signals in a noisy background.The spectrum analyzer depicted in Figure 2 is used as a debugging tool to verify readings and to trace noise sources. It is also used to calibrate system components.

Cross-Borehole Logging :

A particular borehole segment is logged by moving the transmitter coil upwards at a fixed rate while the receiver remains stationary in another borehole. Although equivalent information could be collected by moving the receiver coil rather than the transmitter, doing so results in very noisy data due to the motion of the sensitive detector in the earth's magnetic field. The source coil is typically moved at a rate of 3-5 m /minute. This allows sufficient time for signal averaging but is still a reasonable rate for data collection.

Data is typically collected at approximately one meter intervals within a logging span. At each measurement point five readings are averaged as the transmitter moves past. For cross-borehole logging we typically log over a 100-150 meter interval. Logging intervals greater than this needlessly reduce the signal to noise ratio and lessen the sensitivity to the formation conductivity.

Sample cross-borehole magnetic field plots are given in Figure 3. These results are taken from the Devine test site experiment explained in the following section. The plots show the amplitude and phase of the vertical magnetic field at a frequency of 512 Hz as the transmitter moves between 550m and 670m in one borehole while the receiver is fixed at 598m in a second borehole 100m away. The amplitude plot shows a smoothly varying

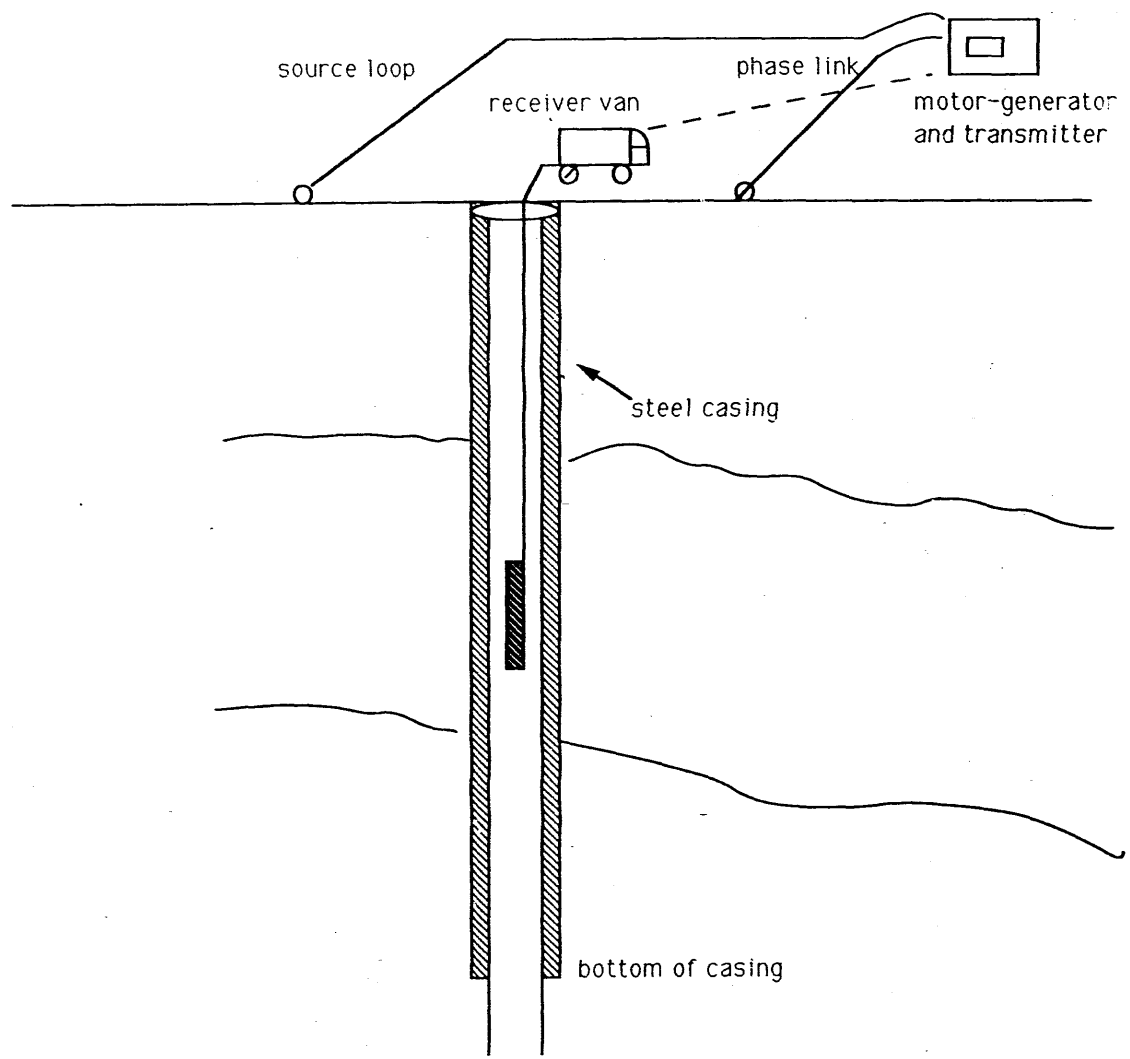


Figure 5 Schematic diagram of the surface-to-borehole system.

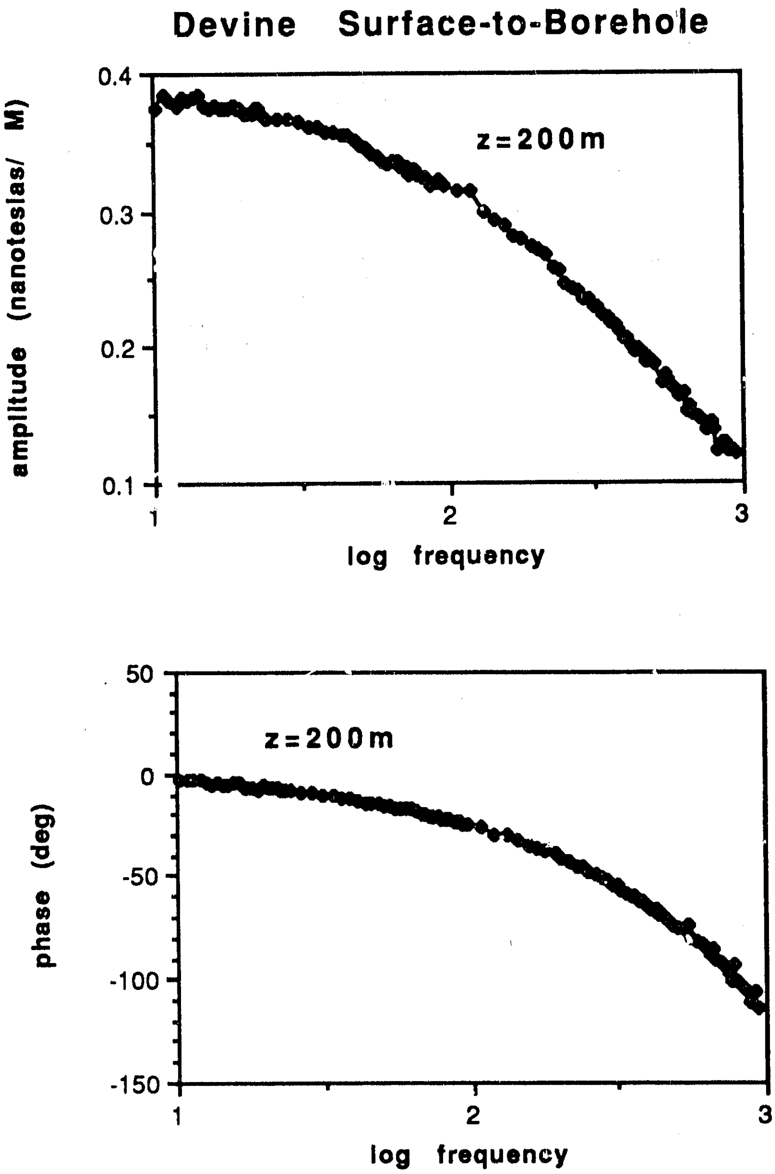


Figure 6 Sample surface-to-borehole sounding plots.

magnetic field, given in picoteslas per unit magnetic moment, that forms a peak where the source and receiver coils are in closest proximity and an approximately symmetrical decrease in field strength away from the peak. The transmitter moment is approximately 1000 so the detected fields are at the level of tens of picoteslas. (Note that the system noise level is approximately .001 pictoteslas). The phase data are also smooth but they display more character than the amplitude results. Near a depth of 600m the phase forms a peak and it "rolls off" sharply above this. This sharp phase rotation correlates to a decrease in subsurface resistivity as the transmitter passes from resistive limestone below 600m to less resistive sands and shales above this depth.

The above profile was measured twice on successive days to establish the precision level of the system; the difference between the data sets is displayed in Figure 4. This figure shows that the amplitude difference over the 24 hour period was less than 1.0 percent for all points with an average of 0.3 percent. The difference in phase averaged less than 0.2 degree. Both of these are well within the guidelines of 1.0 percent for amplitude variations and 0.5 degrees for phase established for imaging requirements (Zhou,1989).

In many ways the borehole environment is benign for EM measurements. At depths more than a few hundred meters the influence of cultural electromagnetic noise and vibration is greatly diminished. In addition, the often variable and troublesome surface layer does not affect interpretation since measurements are made at depths considerably beneath it.

Surface-to-Borehole System:

In cases where only one borehole is available for measurement we can utilize our system in a surface-to-borehole (STB) configuration. Although not as sensitive as cross-borehole measurements, these data offer a marked improvement over surface configurations. With the STB system large, surface-based, loop transmitters are deployed. These are many times more powerful than the borehole transmitters, which effectively extends the range of the system to 1000m meters or more through moderately conductive ground.

The surface-to-borehole system (Figure 5) utilizes a transmitter loop situated at the surface and a receiver probe within a borehole located either inside the loop or offset from it. With the STB configuration data is collected while both source and receiver are stationary. Signal is applied to the transmitter coil by a function generator connected to a power amplifier. Our system can supply up to 15 A of current to a 100 square meter multiturn loop, typically yielding transmitter moments approaching 1x 10^6, or about 1000 times more powerful than our borehole transmitters.

Due to the strength of the source we can apply a random noise source signal to the loop antenna, which disseminates power uniformly within a frequency band, and still achieve excellent results. The random noise source is attractive because it provides signal simultaneously to an entire frequency band thereby greatly reducing data acquisition time. When the random source is used we collect data with the spectrum analyzer shown in Figure 2. At higher frequencies, where the transmitter is less efficient, we tune the source coil with capacitors and transmit discrete sinusoids. For these frequencies we use the lock-in detector for measurement. A complete sounding may be made in the band from 1-1000hz in about 20 minutes per station.

A sample surface-to-borehole sounding is shown in Figure 6. These data were collected at the Devine site with the transmitter loop centered over the borehole and the receiver at a depth of 200m. The data show smooth continuous amplitude and phase spectrum in the frequency range from 10-1000Hz. Although these data may be collected at similar accuracy to the cross-borehole measurements we find that they have a much lower sensitivity to small-scale subsurface structure due primarily to the greater source-receiver separations.

An added benefit of the STB system is that due to the high source strength, data may be collected in steel-cased wells. Although the steel-casing can severely attenuate the signals at higher frequencies we showed in earlier work that the attenuation is independent of the receiver depth (Wilt and Ranganayaki, 1990). This attenuation and related phase shift due to the steel casing is similar to an analog filter and the effects may be removed either mathematically or from field measurements (Wilt and Ranganayaki, 1990). Note that at frequencies greater than 1000hz the casing attenuation is too great to recover any useful signal. This implies that high resolution imaging is especially difficult through steel-cased boreholes.

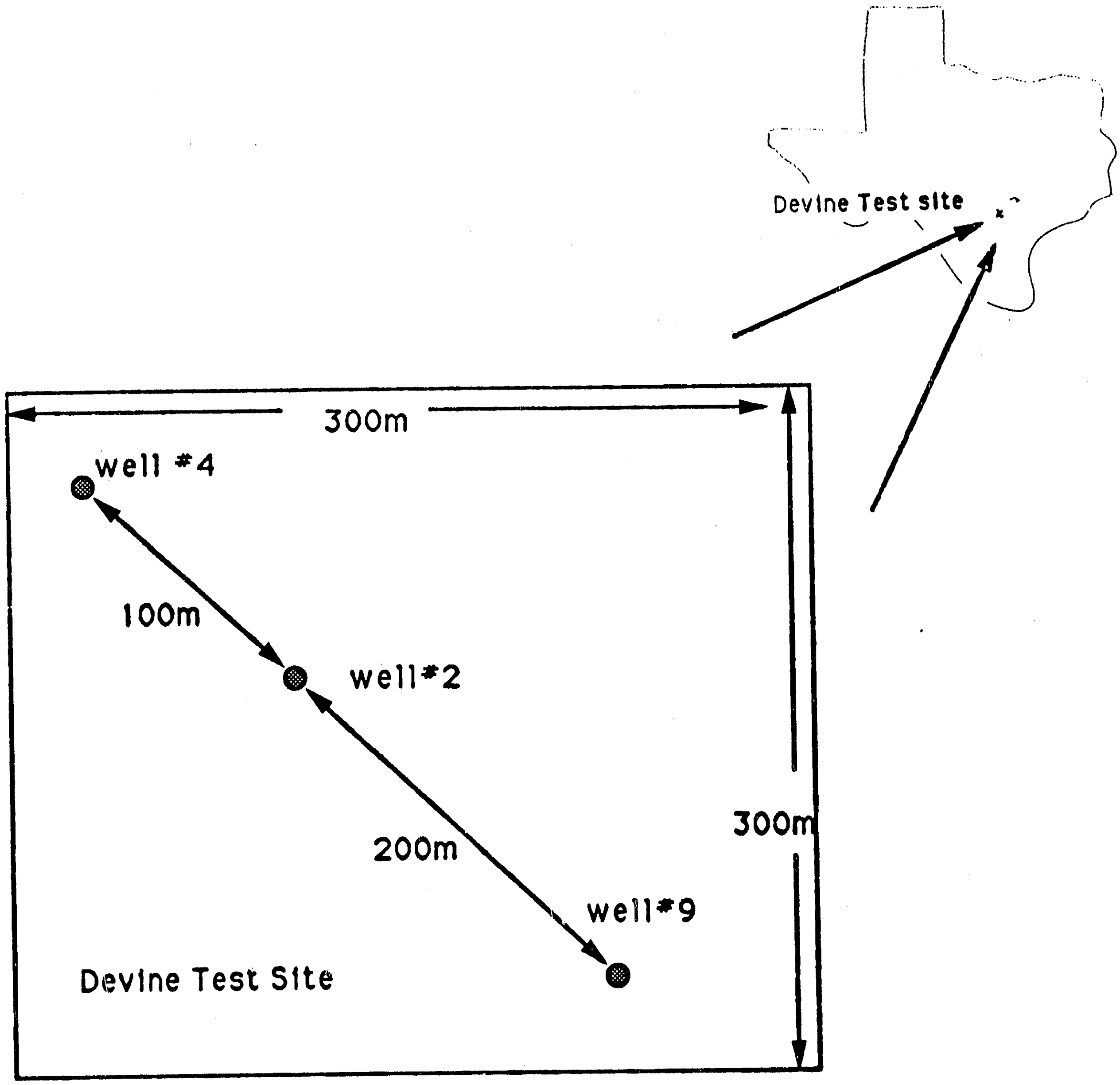


Figure 7. Location map for the Devine, Texas experimental facil:ty

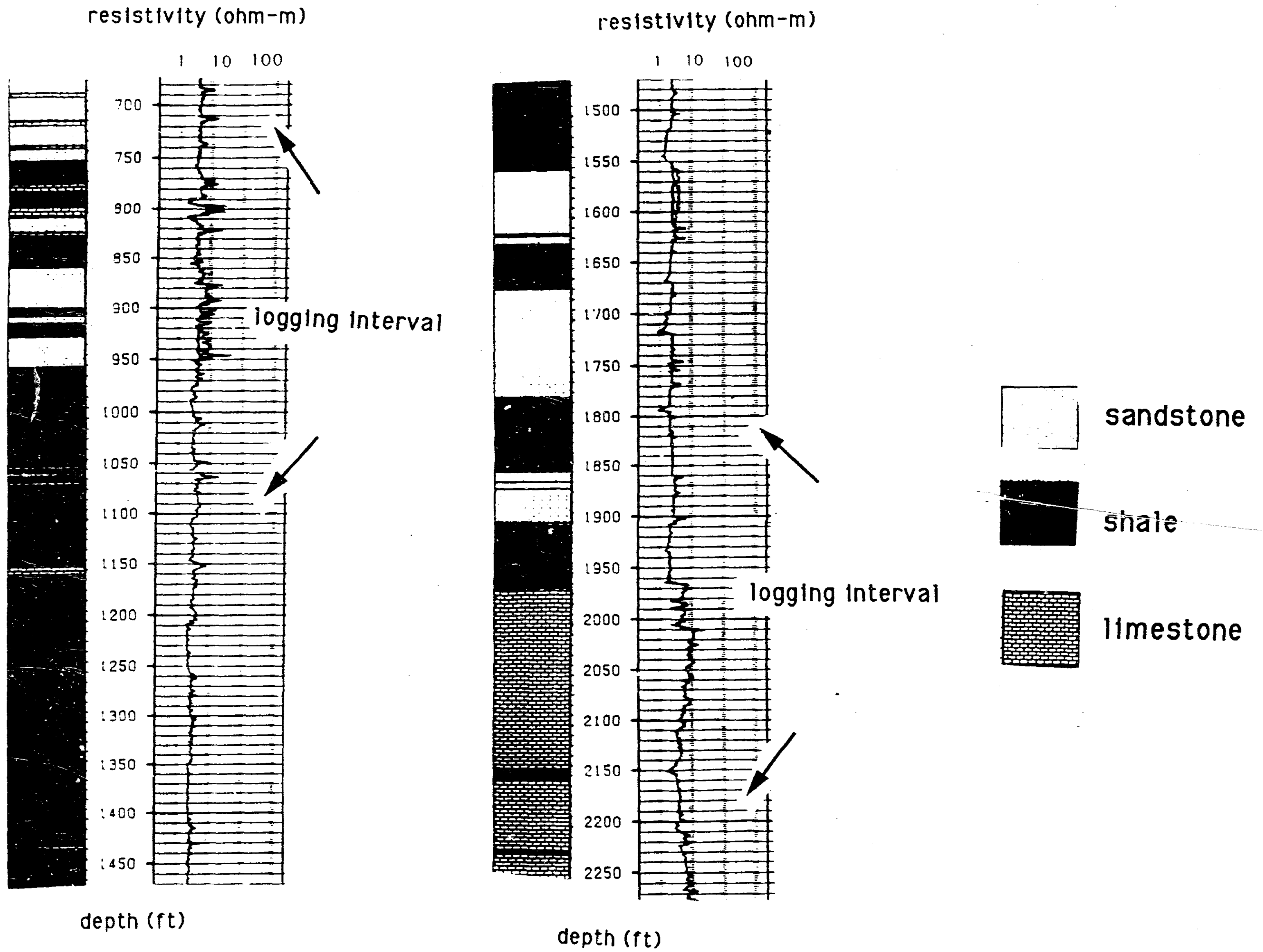


Figure 8 Geologic section and borehole induction log for the Devine test.

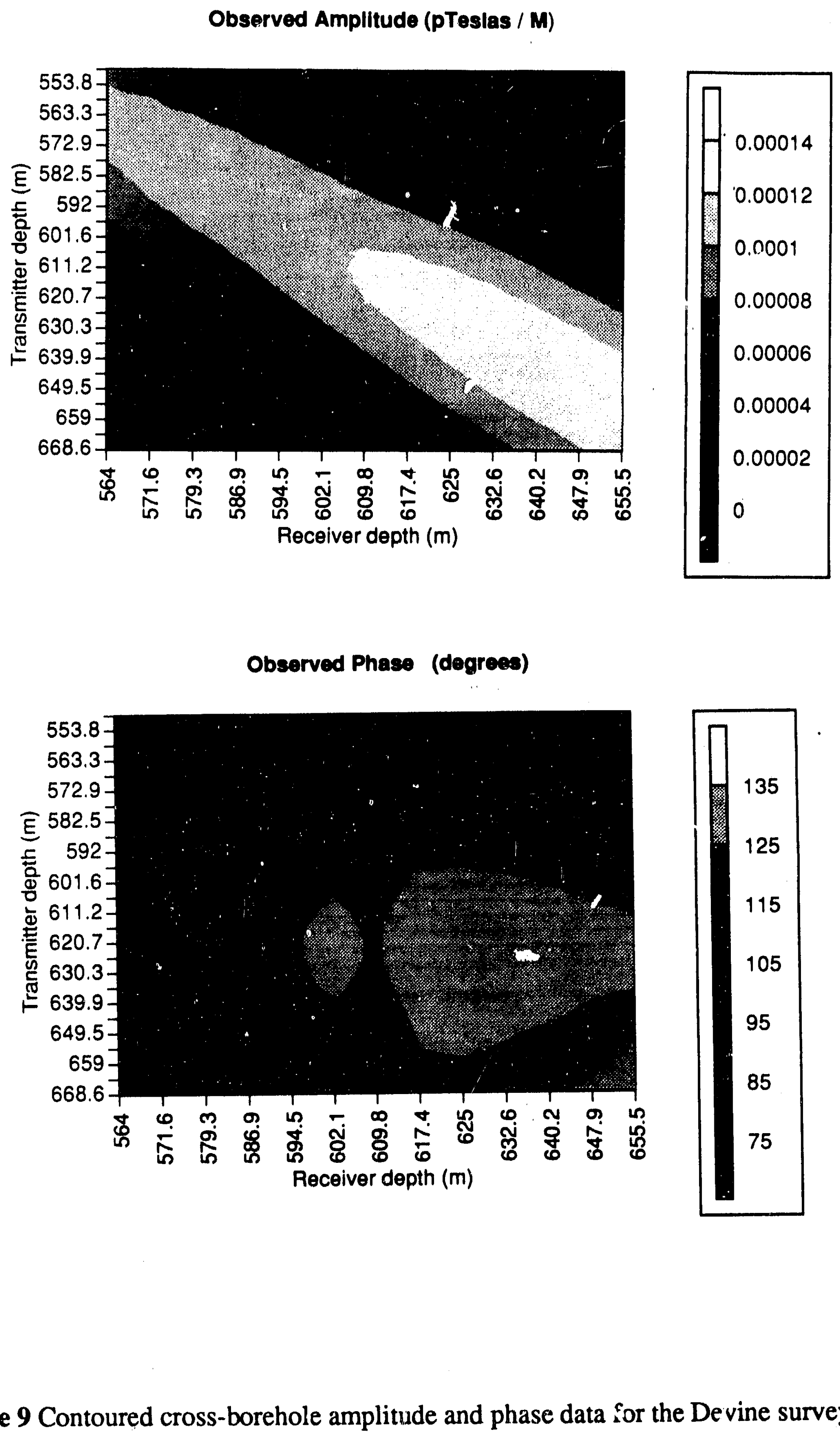


Figure 9 Contoured cross-borehole amplitude and phase data for the Devine survey.

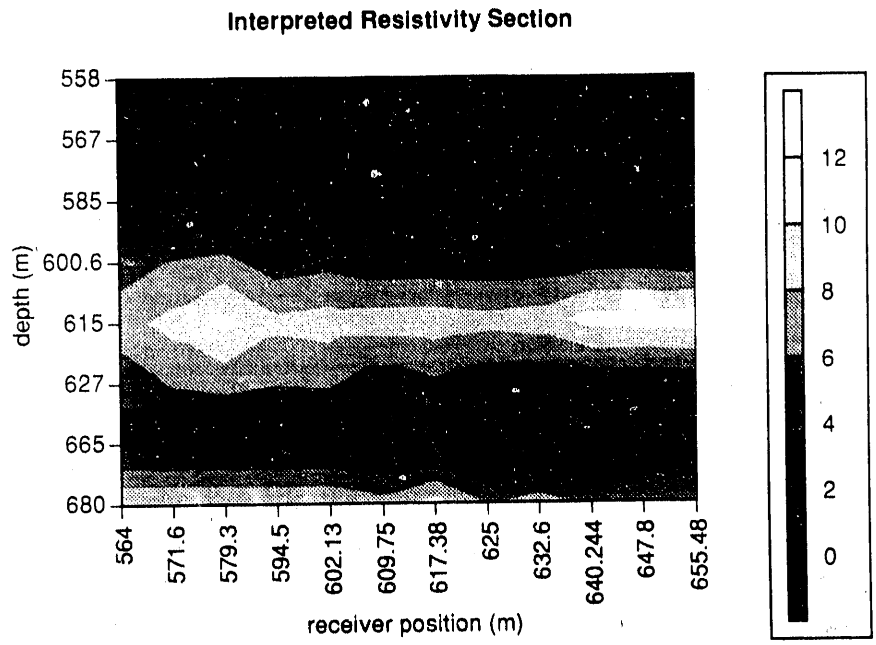
Field Test: British Petroleum Test Site Devine, Texas

The Devine test site, established and operated by British Petroleum is located some 30 miles southwest of San Antonio, Texas (Figure 7). The site was established to test geophysical methods and instrumentation. It is located in an isolated area, away from sources of cultural noise, but still within reasonable access to population centers. Three boreholes are available for experimental use; boreholes #2 and #4 are steel-cased to 160m and plastic lined below this to a depth of 900m; borehole #9 is steel-cased to a total depth of 900m. The two plastic lined holes are separated by 100m. The geology at the site consists of a sequence of sandstones, shales and limestones. Individual beds are continuous and flatlying across the entire site as is evident from an examination of the well logs. The borehole resistivity logs (Figure 8) show variations from 1 to 300 ohm-meters with the higher resistivity layers (limestones) concentrated towards the base of the section and the sandstone and shale layers ranging in resistivity from 1 to 10 ohm-m .

For the Devine test we chose to collect a set of cross-hole profiles spanning a change in resistivity from 2-3 ohm-meter sands and shales to 30 meter thick 10 ohm-m predominantly limestone strata and back to sands and shales (see Figure 8). For each profile the source moves between fixed depths 120m apart and the receiver remains fixed in the other borehole at a depth within these limits. Subsequent profiles are then made between the same source positions using different receiver locations. Each set of profiles corresponds to 13 receiver position covering a similar depth span as the source coil.

Surface-to-borehole data were collected with a 100m square loop situated over borehole#2 and the receiver lowered in this same borehole to stations spaced 15m apart. These data were collected within both the steel-cased (upper) and plastic-cased segments of the borehole to a maximum depth of 500m.

The cross-borehole amplitude and phase data for the above profiles using a frequency of 512 Hz are shown as contour plots in Figure 9. Each contour plot consists of a series of amplitude (or phase) profiles, such in Figure 3, stitched together to form a continuous plot. Each profile is for a separate receiver depth ranging from 550m to 670m, at 8 meter increments. The amplitude data dominantly reflect the relative positions of the source and receiver coils, peaking where the coils are in closest proximity. The peak amplitudes are larger at the lower parts of the section which corresponds to a zone of higher resistivity, (and lower field attenuation). In contrast, the phase data are rich in character



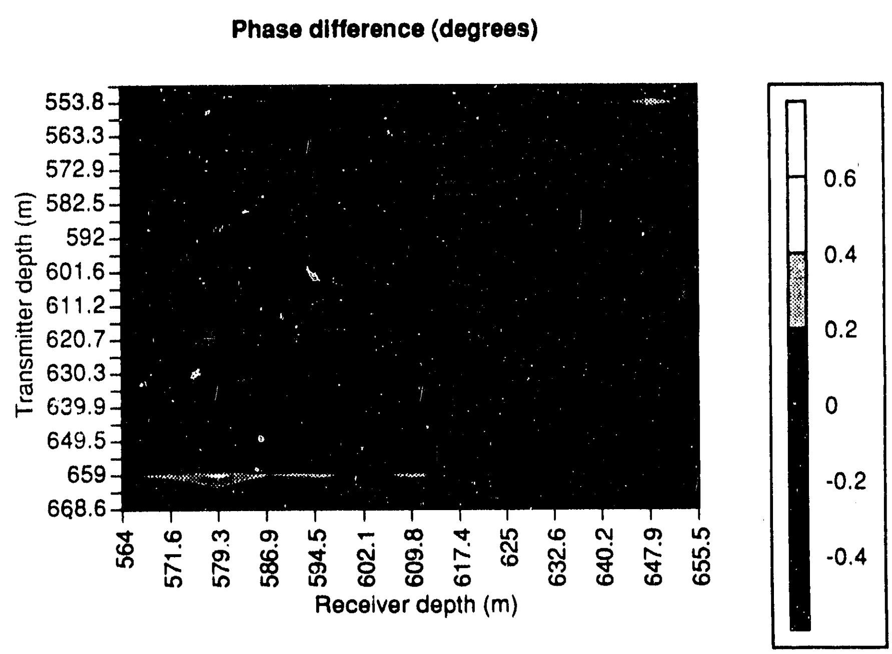


Figure 10 One-dimensional interpretation of the cross-borehole EM phase data and the data misfit.

showing a smooth, continuous variation of more than 60 degrees within the profile span. The maximum phase values generally correspond to the high resistivity limestone, the minimum phases correspond to the lower resistivity sands and shales. The contact between these layers, located at a depth of 600m, can be correlated with sharp gradients in the phase.

Interpretation:

At present, interpretation of cross-borehole and surface-to-borehole EM data is in a fairly primitive but rapidly evolving state. Automatic one-dimensional (layered model) inversion are presently available and some limited three dimensional forward and inverse modeling may be done (Newman and Hohmann, 1988), but a general two dimensional or three dimensional imaging platform is still under development.

Fortunately at the Devine site the resistivity logs indicate that the strata are continuous and flatlying and therefore this site should be well suited for a layered model interpretation. One test of our system is to match the field data to layered models. In areas where the rocks are flatlying a layered resistivity model should be electrically equivalent to the borehole induction log.

Layered Model Inversion

We selected the field profiles shown in Figure 9 and fit the observed phase data, profile by profile, using computer program **NLSEM1D** developed by Ms. M. Descz-Pan of the University of California and Dr. K. Lee of Lawrence Berkeley Laboratory. The program does a layered model inversion, of up to 20 distinct layers, using arbitrary cross-borehole or surface-to-borehole magnetic field data. Only every fifth point in the cross-borehole profile is used in an effort to save computer time. (Fitting all 128 points with a 20 parameter model would require 11.5 hours on a VAX 8650 computer). First-guess layer boundaries and resistivities were assigned to match within about 20 percent with the induction resistivity log. The program was then free to adjust resistivities and layer boundaries until a fit was achieved.

The results of the inversion are given in Figure 10 along with the misfit of the observed and calculated data. The plot gives a stitched-together cross-section of the layered models obtained by individually fitting the various profiles. For a one-dimensional section

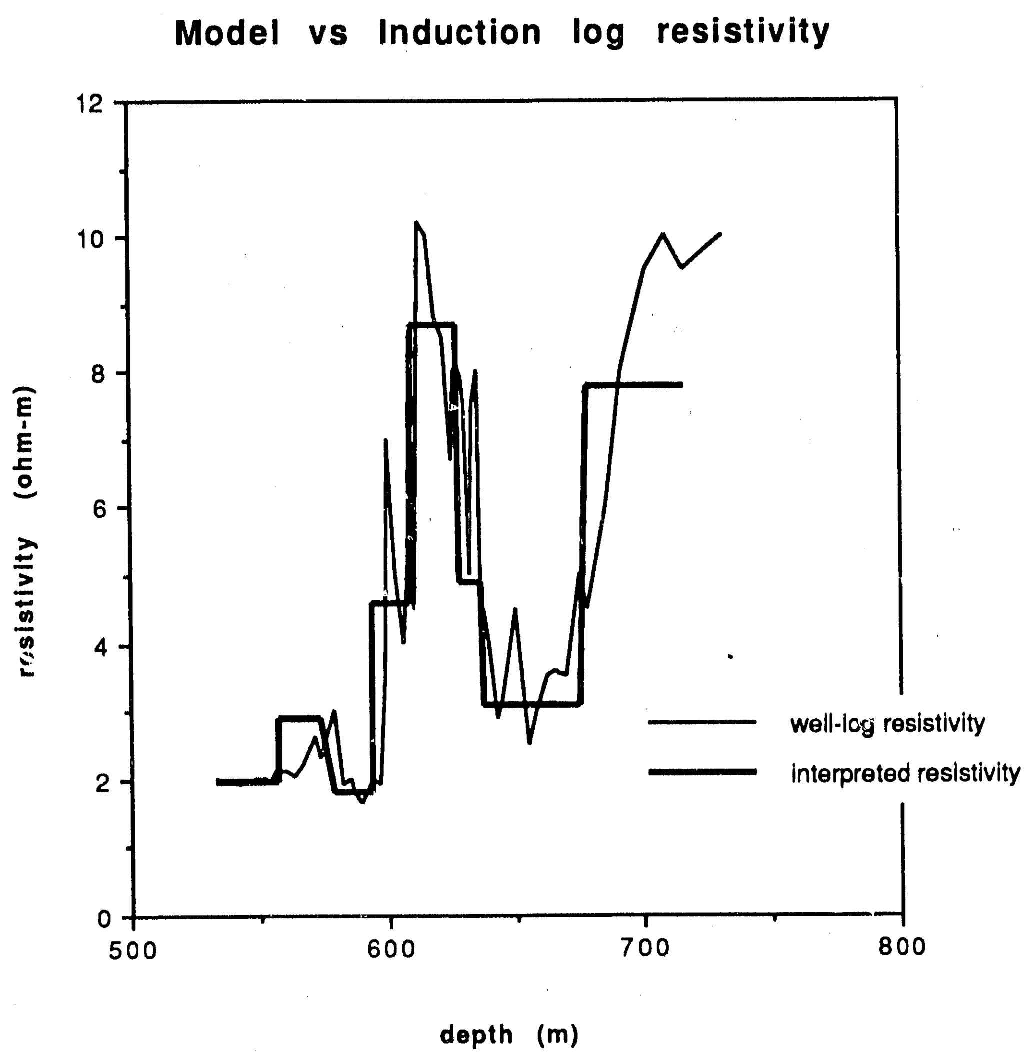


Figure 11 Comparison of the interpreted EM results and the borehole induction log in the same interval.

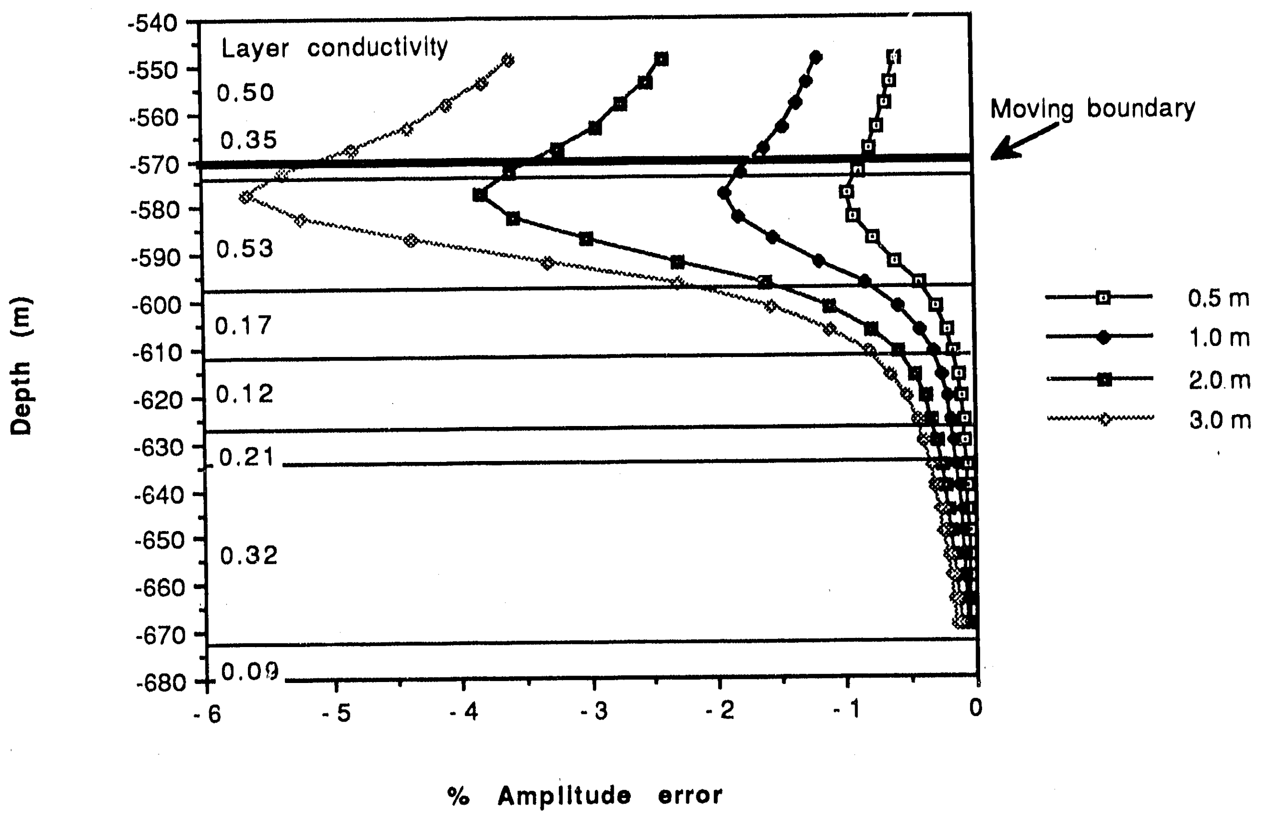


Figure 12 Sensitivity analysis for layered model inversions.

these plots should relatively little variation from profile to profile and the layered sections should closely match with the borehole induction log. Some variation is expected, however, since the EM data are most sensitive to the resistivity of the rock nearest to where the receiver probe is situated and least sensitive to the rock at the farther reaches of the profile. The results shown in Figure 10 indeed show a continuous and flatlying section. The dominant feature of the section is the relatively high resistivity (10 ohm-m) layer corresponding to a limestone between 600 and 625 meters in depth. Rocks above this horizon are predominantly 2-4 ohm-m sands and shales, below the limestone are more sands and shales, and at the lower reaches of the section more resistive limestone is encountered. The lower plot in Figure 9 shows that the individual profiles were fit to within 0.2 degrees, which is consistent with the repeatability errors shown in Figure 4.

In Figure 11 we show a comparison of the layered model inversion for the profile from receiver station 609.75 to the borehole induction log spanning the same depth interval. The correspondence between the inverted section and the induction log is remarkably close. Although there is considerably more detail in the induction log the figure suggests that the EM data can resolve layers as thin as 5 meters.

Next, we examine the sensitivity of the cross-borehole measurement to variations in the layered models. Beginning with a seven layer model that fits one of the the observed profiles we added a thin layer within the uppermost horizon that is slightly less conductive than the host. The resulting magnetic field differences due to this new model serve to indicate the sensitivity to the change in model parameters. In Figure 12 we examine this difference at a frequency of 2048 Hz for a thin layer of 25 percent reduced conductivity with a variable thickness. For a 3 m thick layer the results show a substantial data misfit over large portions of the profile with a maximum error of more than six percent. Since the precision of the measurement is approximately 0.5 percent, this layer this is an easily detectable feature. At 512 Hz we observed that the misfit was about 1.5 percent, so the sensitivity was reduced approximately inversely proportional with frequency.

Note that this level of sensitivity is far greater than the surface or surface-to-borehole EM surveys can achieve.

Measurements Through Steel Casing

Several experimental profiles were measured through steel-cased portions of the boreholes The profiles were made as preliminary tests on the sensitivity of the cross-borehole system to steel-casing. As these measurements were not the primary focus of the experiment we did not optimize the system for these experiments; these are meant only as a feasibility test..

We made profile measurements with one and/or both tools in the steel-casing. With both tools inside the steel-casing we did not measure a discernable magnetic field; attempts were made at 128 and 512 Hz. With the combined attenuation of both well-casings the field level is simply too small at these frequencies. At lower frequencies (ie 10 Hz) it is likely that signal could successfully be propagated through both casings, at these frequencies the resolution is very low however.

With only one tool within the steel casing the proposition is more tenable. In Figure 13 we show amplitude measurements at 32 Hz for the receiver situated at 198m and the transmitter moving between 175m and 130m (the base of the casing is 180.0 m). Repeat measurements of this profile showed that data could be reproduced at about the one percent level. Data collected at 128 Hz could be repeated at the five percent level.

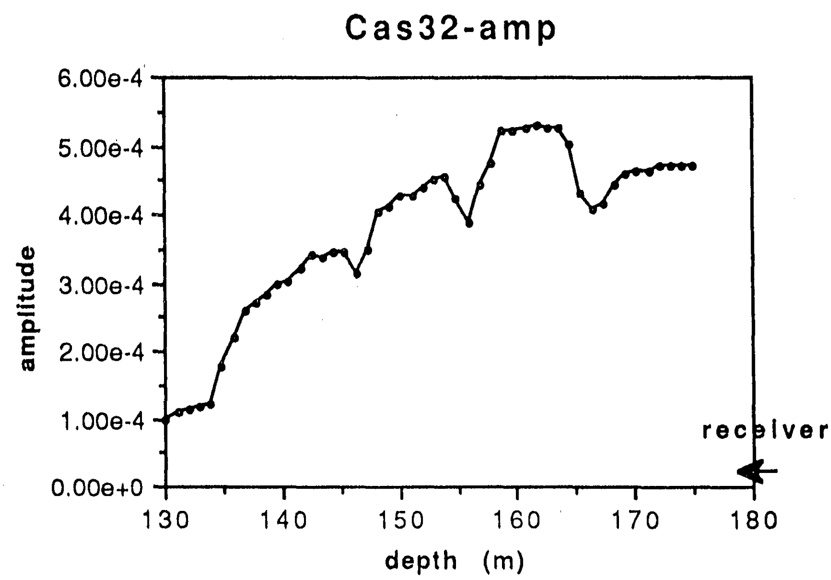


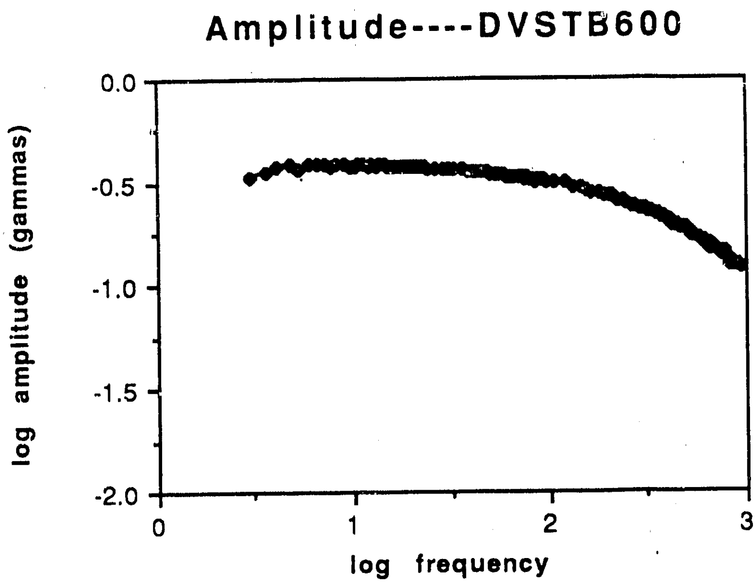
Figure 13 Cross-borehole electromagnetic profile through steel well casing.

The EM profile through the steel casing (Figure 13) shows much more abrupt structure than profiles through the non-conducting casing. Note, for example, that there are large perturbations at approximate 10 meter intervals; these are caused by casing joints. Other irregularities are possibly due to variations in the conductivity and magnetic susceptibility of the casing string and movement of the tool side-to-side in the well. The noise and irregularities of this profile suggests that interpretation through cased sections of the well might prove to be a difficult task. A smoother profile might have been obtained by positioning the receiver within the steel-cased borehole and moving the transmitter in the plastic hole.

The fact that we were able to collect repeatable data at 128 Hz without optimizing the system bodes well for future experiments. With simple adjustments such as increasing the amplifier gain at the coil and increasing the current in the source coil it is likely that data could be collected at the one percent level at frequencies up to several hundred hertz. Also note that although interpretation of raw data through casing may be difficult it is most likely that the effect of the casing is static. That is, for monitoring purposes the variations in field due to subsurface resistivity changes might be unaffected by the presence of the casing.

As stated previously surface-to-borehole data may be more easily collected through steel-cased boreholes than cross-borehole data because the surficial source is much more powerful than borehole transmitters. In Figure 14 we show two surface-to-borehole amplitude spectra one for the receiver at a depth of 170 meters (within the steel cased portion of the well) the second for the receiver at a depth of 182 m, which is within the plastic lined segment below the steel casing. The plots show that the attenuation due to the casing is several times larger than that due to the formation; at frequencies of one thousand hertz the signal has been attenuated to almost undetectable levels. Notice that while the amplitude for the shallower sounding begins at a higher level, the signal rapidly attenuates due to the steel casing.

Although Wilt and Ranganayaki, (1990) showed that the casing effect could be removed from surface-to-borehole soundings, Figure 14 suggests that the signal probably cannot be recovered at frequencies above 1000 Hz due to the high degree of attenuation caused by the steel casing.



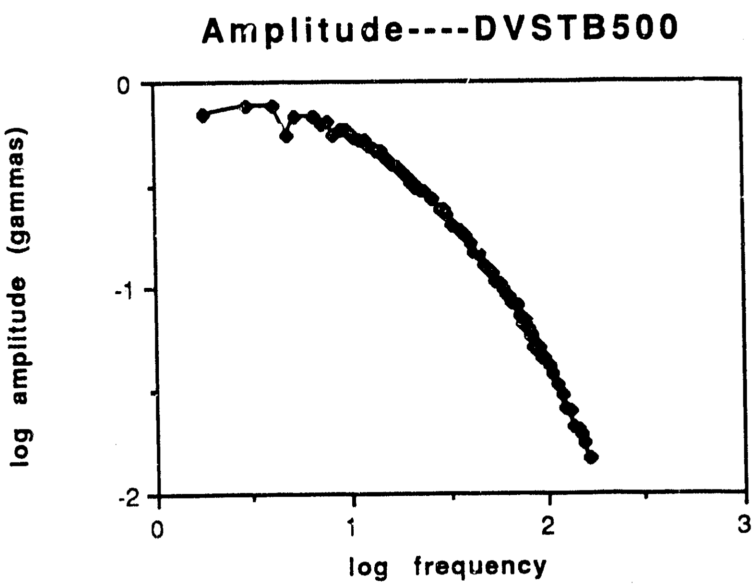


Figure 14 Sample surface -to-borehole sounding mad at depths of 182 meters (below the steel casing) and 170m (within the steel casing).

Conclusions and Future Work

This paper has focused primarily on the benefits of cross-borehole and surface-to-borehole EM and demonstrating the capabilities of a field system developed at LLNL/LBL. The primary application of this system is to characterize oil fields where a complex three dimensional resistivity distribution is expected, and to monitor the movement of injected agents for secondary and tertiary oil recovery. Although our system was adequate for the flatlying stratigraphy at Devine a more complex area would require additional boreholes and/or the measurement of horizontal field components in addition to the vertical. These additional measurements would be needed to more properly characterize the rocks or the process. We are presently developing a multicomponent borehole tool for such purposes at Lawrence Livermore and Lawrence Berkeley Laboratories.

The main stumbling block, at present, is the development of an effective software tool to apply to the field observations. This project is the first priority in our research effort but it is also the most difficult part of the research.

Acknowledgement

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