OIL RESERVOIR CHARACTERIZATION AND CO₂ INJECTION MONITORING IN THE PERMIAN BASIN WITH CROSSWELL ELECTROMAGNETIC IMAGING

Final Report

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ABSTRACT

Substantial petroleum reserves exist in US oil fields that cannot be produced economically, at current prices, unless improvements in technology are forthcoming. Recovery of these reserves is vital to US economic and security interests as it lessens our dependence on foreign sources and keeps our domestic petroleum industry vital.

Several new technologies have emerged that may improve the situation. The first is a series of new flooding techniques to re-pressurize reservoirs and improve the recovery. Of these the most promising is miscible CO$_2$ flooding, which has been used in several US petroleum basins. The second is the emergence of new monitoring technologies to track and help manage this injection. One of the major players in here is crosswell electromagnetics, which has a proven sensitivity to reservoir fluids.

In this project, we are applying the crosswell EM technology to a CO$_2$ flood in the Permian Basin oil fields of New Mexico. With our partner ChevronTexaco, we are testing the suitability of using EM for tracking the flow of injected CO$_2$ through the San Andreas reservoir in the Vacuum field in New Mexico.

The project consisted of three phases, the first of which was a preliminary field test at Vacuum, where a prototype system was tested in oil field conditions including widely spaced wells with steel casing. The results, although useful, demonstrated that the older technology was not suitable for practical deployment. In the second phase of the project, we developed a much more powerful and robust field system capable of collecting and interpreting field data through steel-cased wells.

The final phase of the project involved applying this system in field tests in the US and overseas. Results for tests in steam and water floods showed remarkable capability to image between steel wells and provided images that helped understand the geology and ongoing flood and helped better manage the field.

The future of this technology is indeed bright with development ongoing and a commercialization plan in place. We expect that this DOE sponsored technology will be a major technical and commercial success story in the coming years.
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1 Introduction

Substantial petroleum reserves exist in US oil fields that cannot be produced economically at current prices, unless improvements in technology are forthcoming. Recovery of these reserves is vital to US economic and security interests as it lessens our dependence on foreign sources and keeps our domestic petroleum industry vital.

One of the most promising oil recovery technologies to emerge in recent years is carbon dioxide (CO$_2$) injection with intermittent water injection, called WAG (water-alternating-gas). Dramatic increases in oil production in the Permian Basin have been reported for CO$_2$ injection programs (Moritis, 1993; Norman, 1994). The downside of CO$_2$ injection is the high cost of obtaining CO$_2$, building infrastructure, and separating the CO$_2$ from produced oil for re-injection. For the process to be economical, a reservoir must contain substantial reserves, the geology must be well understood, and the mobilized oil must be tracked and produced to recover the CO$_2$.

A second important development is the emergence of crosswell geophysical technologies for inter-well reservoir characterization and recovery monitoring. These techniques have proven invaluable for tracking subsurface fluid movements from injection and production. The crosswell technologies provide physical property images at a scale similar to that of reservoir simulation models, which is crucial for having a direct impact on production. The crosswell electromagnetic (EM) method, which was initially developed at several of the US National Laboratories, is particularly interesting because of its high sensitivity to reservoir fluids. The technique has been demonstrated in water and steam flood operations and become more widely used commercially in the past several years. The biggest challenge to the widespread use of this technology is its ability to propagate and measure EM signals through steel well casing. The crosswell EM technology, although successful in several California fields, is presently unsuitable for the majority of oil fields where the well separation is large and where wells are completed with steel well casing.

This project was designed to address these issues and to focus a solution that will be suitable for US based oil fields in the Permian Basin and California. The project consists of several field and engineering phases to develop a field system and software that is capable of effective operation in widely spaced steel cased wells.

In the first phase, we describe a preliminary field test at the Vacuum field in eastern New Mexico made with our prototype crosswell EM system, which has been successfully applied in California but was not entirely suitable for the large well spacing and steel-casing environment on the Permian Basin. These tests were important to provide a baseline data set prior to the CO$_2$ injection and to collect engineering and noise data to help in the design of the new field system.

Next, we provide an overview our newest field system, the X2C. This system is considerably more powerful and sensitive than its predecessor and is equipped with technology to operate in steel-cased boreholes spaced up to 300m apart. In this section, the system is described and results are provided for a series of bench and field tests.
Next, we provide several case studies where this system is applied to operating oil fields in California and China. These field exercises were designed to test the limits of the new system as well as to provide feedback on the operation of the technology to separate the steel casing and formation affects.

Finally, we describe the present and future plan for using this technology in a commercial setting and the remaining R and D to achieve the project goals of successful commercial development.

This report demonstrates that the project has succeeded beyond expectation in almost every area. The hardware and software developed as part of this project is in continually in use for R and D and the concepts and technology developed as part of this project was used to manufacture new field systems that is are presently is use in the US and worldwide.
2 Phase I: Preliminary Tests with the XBH2000 System

Our first step in designing a crosswell system for the Permian Basin conditions was to make preliminary field tests in Texaco’s Vacuum Oil Field with the existing prototype field system, the XBH2000. The system and crew had no experience in carbonate environments, so these tests in the target reservoir prior to finalizing design improvement specifications were designed to reduce the risks involved in designing the new tool. They allowed us to look for changes that could enhance imaging results in carbonates, or improve resolution through steel-cased wells. In short, these test surveys helped direct the design requirements for the hardware and software upgrades we undertook in Phase 2.

2.1 Background on Vacuum Field

The Vacuum Oil Field lies in the western part of the 200,000 square mile Permian Basin oil province located in west Texas and New Mexico (Figure 1). The Permian contains many oil and gas fields and it has produced more than 30 billion barrels of oil since its discovery, during water well drilling, in the early 1920’s. At its peak, the basin produced more than 2 million barrels of oil and 5 billion cubic feet of gas per day, from more than 100 individual fields.

Figure 1. Setting for the Permian Basin oil province
Oil and gas production in the Permian Basin has been declining since the early 1970’s. Presently, production is less than one million barrels per day due to declining pressure. Although most fields are on water flood to maintain pressure, a few of the larger fields are also injecting CO₂ gas to boost production.

Miscible CO₂ injection has been shown to be effective in a number of fields due to the nature of the CO₂ interaction with oil. CO₂ naturally forms a continuous phase with oil that lowers the viscosity and eases flow to producers. The gas also penetrates in many areas where water cannot access the oil, thereby accessing bypassed pockets (Mortis, 1993). In many fields, the CO₂ injection is alternated with water injection, a process known as Water Alternating Gas or WAG, to “push” the CO₂ towards the producing well.

The Vacuum Oil Field is situated near the small town of Buckeye in eastern New Mexico, about 30 miles west of the New Mexico-Texas border (see Figure 1). Vacuum is one of the larger fields in the basin that is still producing more than 50,000 barrels of oil per day, from several hundred wells. The field is operated in multiple leases by Conoco-Phillips, Exxon-Mobil and several other operators. ChevronTexaco, one of the major leaseholders and our partner in this project, produces about 12,500 barrels/day (Figure 2).

Figure 2. ChevronTexaco wells in the Vacuum Oil Field

Chevron’s experience with injecting CO₂ at Vacuum has mostly been positive. Oil production has been stabilized, and in several patterns dramatically increased, but there have
been difficulties with handling the gas, unexpected production of gas in wells outside of the pattern and damage to casing pipes and production tubing due to the generation of carbonic acid. They also found that a CO₂ flood is quite expensive to initiate and maintain and it must be properly managed to be cost-effective. The process required sophisticated gas handling facilities, continuous evaluation of injection and production wells and a continuous stream of CO₂ that must be purchased from outside suppliers.

The flow of the injected CO₂ is unpredictable, because its flow properties depend on whether there is oil, water or gas in its flow path as well as the location and orientation of fractures in the reservoir. For this reason, ChevronTexaco is interested in the EM technology to track the movement of the CO₂ in the reservoir.

2.2 EM Field Test at Vacuum

The first crosswell EM test at Vacuum involved our prototype field system developed in 1999, the XBH2000. This system was developed under a contract with the Shengli oil field in China and at the time it was the most powerful system of its kind. The system was not able to collect or interpret data in two steel-cased wells but could work if one of these wells were steel-cased and the wells were less than 1000 ft apart.

For the initial test, ChevronTexaco selected a triangular grouping of three vertical wells (Figure 3). Two of the wells are steel-cased and separated about 1,200 ft. The third well, which is uncased below 4,100 ft, is about 850 ft from the other two wells. These tests would allow us to collect crosswell EM data between two open-steel well pairs and one steel-steel. Although we were incapable of interpreting these data from the latter well pairs, the data were useful for establishing signal and noise levels. In addition, the well pairs would provide different angles to the theoretical flow stream directions of the previous waterflood pattern.

ChevronTexaco did substantial well preparation prior to the survey. They first pulled production tubing from production well VGSA57 and packers from injection wells VGSA150 and VGSA157. They then swabbed all wells to remove obstructions. The wells were then fitted with blowout preventers to eliminate the flow of fluids or gasses to the surface. All geophysical deployments were made using isolation lubricators and well packoffs. During the survey, however, the wells did not re-pressurize and we were able to log during relatively benign conditions.

Figure 3 is a map of a portion of the field used in the EM survey. Measurements were made between production well VGSA57, which is an uncased producer in the main reservoir (4000-4700 ft), and steel-cased injection wells 150 and 157 (orange arrows). The well separations were approximately 220m (~700 ft) for both well pairs. Figure 3 also shows the region where CO₂ is presently being injected (yellow wells) and the area where new injection will start in about 6 months (yellow stippled area).

In Figure 4, we display a borehole induction resistivity log from two of the wells used in the tomography. The logged section (4000-4600 ft) has an average resistivity of more than 50
ohm-m and several intervals that exceed 1000 ohm-m. The higher resistivities usually indicate impermeable limestone and dolomite sections, or regions of high oil saturation.

Figure 3. CO$_2$ injection area and tomography well

Figure 4. Induction logs from two of the three survey wells
The wells show a fair-to-poor degree of continuity and the resistivity values can change by more than 50 percent for correlatable intervals. This suggests substantial variation in formation properties, fracture density or fluid saturation.

The challenge for the crosswell EM data is to interpret data in an area where the formation resistivity is so high. The inductive formation signal is directly proportional to the frequency and inversely proportional to its resistivity. The steel well casing forces us to use lower frequency transmission thereby reducing formation response and the high resistivity reduces the response even further. We estimate that the formation response for these conditions is only about five percent of the total measured field. This compares to a response of more than fifty percent for many open hole surveys and it constitutes a significant obstacle for the generation of high-resolution images.

After some initial start-up problems, the surveys proceeded smoothly. Data quality for the survey was, in general, good. Considering that injection and production wells can often induce substantial tool noise as a result of fluid induced motion, the data collected in these wells were surprisingly quiet. We did full tomography for both well pairs in the interval from 3950 to 4600 ft.

The data also suggested a noise level for the system of about 10 microvolts for the vertical sensors and about 30 microvolts for the horizontal sensor. With these conditions, it should be possible to acquire useful crosswell data with the new system to well separations of 2,000 ft or more.

Figure 5. Sample field profile from Hobbs survey
Crosswell EM data were collected using our three-component sensor package. This tool measures the vertical and two horizontal components of the field originating at the transmitter. It is a high-resolution measurement of the field that can produce better quality images than the single component (vertical) receiver but it is much slower to deploy. We chose to deploy it in these wells because our objective is to measure downhole conditions and attempt to produce one or two high quality images.

A sample amplitude profile for one of the three component data sets is displayed in Figure 5. The plots indicate a good quality data set for the vertical sensor and noisier profiles from the horizontal sensors. This profile is typical of the data quality during the survey at 24 Hz.

Notice that when the transmitter enters the base of the casing string, above a depth of 4050ft, the fields dramatically decrease but the system is still able to recover them. This bodes well for future surveys to be made with the newer more powerful system.

2.3 Data Interpretation

The data processing consisted of first editing the files to remove spikes and outliers, then adjusting the data for the casing affect using the borehole logs and a single point in the profiles to make the adjustment (Wilt, 2002). The data are then combined into a single file for the data inversion. These data are interpreted by fitting the observed data to model derived data for a 2D model. In this process, we first derive a starting model from the logs and/or geology and adjust this model until the misfit is within a given tolerance, usually 2-3 percent. We note that in this case, well VGSA57 did not have a resistivity log available so the interwell section was constructed assuming that an interwell extrapolation of the resistivity log from well VGSA150 was a good first guess at the interwell resistivity.

After 15 iteration of the inverse code, the misfit was reduced from about 8 percent to about 3 percent. The misfit section for the inverse model between wells 57 and 150 is given in Figure 6. This section shows a very close fit to the real data component (in-phase with the transmitter) and a much worse fit to the much smaller imaginary field component (90 degrees out-of-phase with the transmitter). We note that most of the formation information, at these low frequencies, reside in the imaginary field component so the 10 percent data fit means that the image resolution is low to moderate.

In Figure 7, we show the resistivity cross-section between producing wells VGSA57 and VGSA150 at the Vacuum field, derived from an interpretation of the EM data. The section indicates that the formation resistivity ranges between 50 and 500 ohm-m which is very high for a typical oil field, but perhaps typical of a Permian Basin field. We note that at the right margin, the section agrees with the one log that we have available in well 150. This indicates that the oil-bearing zone has a relatively high resistivity, dips from well VGSA57 towards well VGSA150, which is in accord with the geological models.
Figure 6. Data misfit for Hobbs survey

Figure 7. Interwell resistivity image
Figure 8. Compare porosity logs (right) and interwell resistivity data

Figure 8 shows a plot of the porosity section, derived from the well logs (well 57 does have a resistivity log). We find that the resistivity and porosity sections agree in the dip and overall structure in this part of the field and the zones of highest porosity (red on plots) match with the higher resistivity (red-yellow) horizons in the resistivity section. The lower resistivity interval is typically 80-150 ohm-m sandy intervals that correspond to lower porosity formation. These depths are typically at the base of the section, within the producing upper San Andreas section.

Although the attached model is reasonable and fairly consistent with the geology, the resolution is fairly low and the match of calculated to the observed secondary field data is worse than 10 percent in several intervals. We feel that the residual noise in the secondary field component is prohibiting a closer data fit and therefore limiting the confidence of this final model.

Unfortunately, we feel that this is the limit of this technology with the older field system. One important result from this test was to establish the noise level of the system in this environment and, to our surprise and delight it is quite low. We were able to collect and fit field data at signal levels that approached the predicted sensor noise, about 50 picoteslas.

We feel that the results of this survey is a very encouraging sign for the future deployment of X2C. If the noise level of future surveys is similar to the present survey then the new instrumentation will allow us to collect better quality data at a higher frequency. In addition, it appears that our ambitious goal of crosswell EM in two steel cased wells separated by 500m is now possible.
2.4 Notes from the Tests at Vacuum Field

From these tests, the following information became clear:

- The transmitter power and/or receiver sensitivity of the XBH2000 system was inadequate. Data collection was made at low frequency (24 Hz) and this made high resolution imaging impossible due to the high background resistivity. A frequency of 100 Hz is the minimum acceptable which would require a signal to noise increase of approximately a factor of 5.

- The noise level of the deep measurements was surprisingly small, about 10 microvolts (or 50 picoteslas).

- Tool reliability was a major issue in this field, as the client often must remove the production tubing. The breakdowns frequency of the XBH2000 system was unacceptably high.
3  Phase II: Development of an Advanced Crosswell EM System

A primary goal of this project is to develop a new high power high sensitivity crosswell EM system designed for oil field conditions, where well spacings are moderate to large and most wells are steel-cased. More specifically, the system would be designed for CO$_2$ injection well field patterns in the Permian Basin. Design objectives for the system are 2,000 ft.

Below, we describe the operation of a crosswell EM system and how the data is evaluated. We then provide an overview of the X2C system, provide details on the system performance and show how this system is designed for a more practical oil field environment.

3.1 Overview of Crosswell EM

The crosswell EM method is designed to map the interwell resistivity distribution in a 2D (or 3D) sense. These data can be used to characterize reservoirs structurally and stratigraphically as well as to track ongoing processes where pore fluid is replaced or moved.

A crosswell EM field system consists of a transmitter tool deployed in one well and a receiver tool deployed in a second well located up to 3,000 ft from the source well (Figure 9). The tools are connected with surface wire telemetry and deployed with standard wireline equipment. By positioning both the transmitter and receiver tools over a vertical interval roughly equal to the well spacing we can achieve adequate coverage for tomographic imaging. The depths must include positions above, below, and within the zone of interest for an effective tomographic interpretation of the resistivity distribution between the wells (Figure 10). The tools are typically deployed at depth intervals of two to five percent of the well spacing, which is also roughly equal to the image resolution.

![Figure 9. Schematics of crosswell EM](image-url)
Our field instrumentation uses downhole electronics and computers for signal generation and data acquisition. The recent placement of source and receiver electronics downhole, instead of at the surface, has resulted in very accurate and efficient data collection using standard wireline equipment. We use small surface stations, at both the transmitter and receiver sites, for communication and power supply and a laptop computer to control the acquisition and log the data.

The transmitter antenna is a vertical-axis magnetically permeable core wrapped with several hundred turns of wire and driven to broadcast a continuous monochromatic sinusoidal signal at frequencies from 10 Hz to 2 kHz. The frequency selection depends upon the borehole environment (steel-casing or open hole), the well separation and the formation resistivity. Steel well-casing, larger well separation and low formation resistivity necessitates the use of lower frequencies.

The transmitter generates a magnetic field that is more than 100,000 times stronger than the source in a normal single well induction logging system. This is sufficient to broadcast between wells up to 2,000 ft apart in open holes, less if the wells are steel-cased (see below). The transmitter signal induces electrical currents to flow in the formation between the wells. These currents, in-turn, generate a secondary magnetic field related to the electrical resistivity of the rock where they flow (Figure 10). It is this secondary current that provides the information that we seek to interrogate the interwell resistivity.

At the receiver borehole, we use induction coil receivers to detect the magnetic field generated by the transmitter (primary field) as well as the magnetic field from the induced currents (secondary field, Figure 10). The detection coils are extremely sensitive devices consisting of many thousands of turns around high permeability magnetic cores; this allows us to accurately measure signals generated by our transmitter more than 2,000 ft away. To reduce the logging time, we normally deploy a string of receiver coils to simultaneously record the signals. The older XBH2000 system included a 4-level string of sensors but the new X2C system allows up to 16 sensors.
The system is typically deployed with the receiver sensors stationary in one well while the transmitter moves between the depths of interest in the second well, broadcasting signal continuously. Completed transmitter traverse, or profile, is made for each receiver position. To reduce the noise, the incoming signals, which are normally very weak, are averaged several hundred times before sampling. This reduces the noise dramatically but also slows data collection. The transmitter moves at a rate of 5 to 30 ft per minute depending on the amount of averaging and the frequency of operation. After a complete profile is measured the receivers are then re-positioned and the process is repeated until all desired receiver position are occupied. A typical crosswell deployment requires roughly 12-30 hours of field recording for a vertical section of 1000ft. Data are typically averaged until they can be repeated to within one or two percent.

The transmitter and receiver tools are linked together with a surface cable, which is used for phase synchronization, sending of commands and collection of digital data streams. The logging is done at the transmitter location because at this site, the tool is moving during the logging, as opposed to the receiver side where it is stationary. The logging operation is controlled through the logging surface station and the laptop computer. We note that the operation requires two wireline units and a mast or crane at each well.

All crosswell data are processed in the same manner. We first edit the profiles to remove any spurious points, apply calibration corrections and, if required, adjustments for steel casing and then re-sample the profiles using spline interpolation. The final edited data set is then displayed in contour form to examine for tears or misties. This difference section is crucial for data quality control as well as to accurately position the tools in 3D space. Errors in tool position are probably the largest single source of error in crosswell data.

The crosswell EM data are interpreted by computer inversion. The interwell formation is divided into two-dimensional square blocks whose sides are 2-5 percent of the well spacing. We apply a two dimensional inversion based on a finite difference forward code. Each block is assigned an electrical resistivity value, estimated from the borehole resistivity logs or known geology. The inversion code then modifies the resistivity of these blocks until the calculated and measured EM data agree to within a specified tolerance level. This is often related to measurement error, which is typically 1-3 percent. This process usually requires 12-30 hours per data set on a fast computer workstation (PC based) to produce a detailed image of the underground strata. The resolution of the images is roughly 2-5 percent of the well spacing.

We note that the images produced by this process are not unique. That is, we could define a different resistivity distribution that might fit the data as well. By constraining the inversions with the borehole logs and a good knowledge of the geology, we can reduce this uncertainty dramatically.

3.2 The Effect of Steel Well Casing
The system described above is adequate for interwell EM from wells spaced up to 2,000 ft apart, if neither well is steel cased. As shown below, the presence of steel casing dramatically attenuates the signal at frequencies above a few tens of Hertz.

In Figure 11 we show data collected with a magnetic field receiver situated in a steel-cased well using an external EM source. The 5” steel pipe is made of a soft iron similar to that used in oil field. It has a high magnetic susceptibility and electrical conductivity and a 3/8” wall thickness. Note that the data on the plot are normalized to the source strength, that is, the shape of the curve shown in Figure 11 would be flat if it were not for the casing.

The plot in Figure 11 shows little attenuation at low frequency but progressively greater as the frequency increases. Above 100 Hz the attenuation is roughly exponential, falling to below the sensor sensitivity above 1000 Hz. Our experience is that having one of the well pair cased with steel imposed no great restriction on data collection or interpretation. The 15-30 dB attenuation experience in these cases reduces the range somewhat and may reduce the frequency but the impact in field deployment and image resolution is fairly moderate.

In Figure 12 we show a plot for a borehole transmitter in a steel-cased well. Here, we plot the transmitter moment, or the strength of an equivalent transmitter in an open hole environment, as a function of frequency. The plot has a similar shape to Figure 11 but the attenuation begins at lower frequencies and it has roughly a constant slope above 50 Hz. We note that there are significant transmitter casing affects at frequencies as low as one Hertz.

These curves suggest that for a field survey made in standard 1/4-3/8” steel casing, the attenuation is roughly 40-60 dB at 50 Hz, whereas at 100 Hz, it becomes more than 60-80 dB. Above this frequency, crosswell through two casings is simply not possible as the
attenuation becomes exponential in each well. We note, however, that for a remarkably large number of well spacings and background resistivities, 10-100 Hz is an appropriate frequency for the crosswell data, and the crosswell EM system can be effective.

A second issue is that the attenuation and phase delay due to a casing pipe varies according to the magnetic and electrical properties of the pipe, in addition to its thickness and diameter. The net effect is that the crosswell data collected will reflect variations in the casing string much more than the formation resistivity. Fortunately, this affect is localized so we can employ a local sensor to strip this from the data.

In Figure 12 we show several sample field profiles collected in steel-cased wells at the Kern River field in southern California. As opposed to the open-casing profiles (see Figure 7 for example), these data are much rougher, reflecting the properties of the individual casing joints as well as the connecting collars. Notice, however, that the amplitude plots for the 4 individual receivers are remarkably similar to each and also similar to the basal plot, which was made from a casing monitor, placed in the transmitter tool.

Our strategy for compensating for the steel casing is to use this monitor signal in addition to the signal from a second coil and some software to adjust the crosswell data for the effects of the steel well casing. We note that the casing compensation scheme requires two separate operations, one to adjust the data for the transmitter casing effect and one to adjust the data for the receiver pipe.

We show an example of this type of compensation in Figure 14. Here we have selected one of the field profiles shown in Figure 13 and applied both a transmitter and receiver casing
adjustment and then compared the result to a 1D model solution. The close fit suggests that the scheme is effective, but the residual noise suggest that is not perfect.

Figure 13. Crosswell amplitude in 2 steel-cased wells
3.3 Design of the X2C Field System

The X2C field system was designed to provide maximum power and sensitivity in a steel well-casing environment. X2C is an acronym for crosswell (X) EM through 2 steel casings (2C). The system was also designed for high reliability and straightforward deployment and make up, with full compatibility with other standard wireline tools.

Our philosophy was to use the existing XBH2000 technology as a base and strive to make improvements in every aspect of tool performance and reliability. In particular, we made major efforts to maximize the source power in a steel-cased well, improve the receiver sensitivity in a steel casing and improve system dynamic range and data collection software. In addition, we have also incorporated technology to compensate collected data for steel well casing thereby allowing data collection and interpretation in steel-cased wells.

The system described below is a pre-commercial prototype that has been used in more than 30 surveys since its initial testing in 2002. At the present time, five field systems of the X2C are being readied for commercial operations in the US and worldwide market.

Below, we provide an overview of the new system, describe some of the new technology that we applied to enhance performance and provide some results from bench and local field tests that compare the system to its predecessor, the XBH2000.

3.4 System Description
A schematic diagram of the system configuration is provided in Figure 15 and a block diagram is shown in Figure 16. Below, we describe how these are connected together and what each module does.

The borehole tools are all modular and mechanically compatible with Schlumberger wireline equipment. The tools employ standard Schlumberger parts such as joints, connectors, tool heads, and electronics packaging. They are composed of 10-20 ft segments which are assembled at the wellhead. The transmitter tool, when fully assembled, is 27 ft long and 3 3/8” in diameter. The 4-level receiver tool is more than 59 ft long and also 3 3/8” in diameter.

The transmitter tool consists of an electronics cartridge and a sonde. The electronics cartridge has three main units: the wireline interface, which is directly connected to the logging cable; the transmitter power driver, which supplies signal to the antenna, and the TxDAS for digitizing the monitor and housekeeping signals. This cartridge mechanically connects to the transmitter sonde (antenna) using a standard screw joint. The transmitter sonde uses an oil pressure compensation module for operation at depths up to 12,000 ft.

The transmitter tool connects to the wireline via a standard 31 pin Schlumberger cable head. We also utilize a centralizer module at the top and rubber stand-offs on the tool body to keep the tool centered in the well during logging.
The receiver tool string is comprised of a series of four receiver modules. Each module consists of an electronics cartridge (containing analog electronics and receiver data acquisition system) and a receiver sonde. The receiver data acquisition system is similar to the transmitter data acquisition system with almost interchangeable components and firmware. The top tool also has telemetry and communication circuitry for relaying commands and sending the data stream. Again, the receiver tool is centered with an upper centralizer and a series of rubber stand offs located on the tool body.

The surface computer (SC, typically a laptop) fully controls the system. It sets the acquisition parameters and receives/stores acquisition data. The SC is connected directly to the transmitter surface station (TSS) through the computer’s serial data ports. The receiver
and transmitter surface stations are connected together via a surface cable. In each logging apparatus, the depth encoder is connected to a port on the surface station, and each tool depth is read continuously during logging.

Key components of this design are more fully described in the next subsections.

Figure 16. Block diagram of the X2C

3.4.1 Transmitter Antenna and Driver

The transmitter output is the product of the cross-sectional area of the inductive source, the number of windings on the core, the current flowing through the windings, and the
magnetic permeability of the mu-metal core. The source output is typically limited by the internal field level that saturates the magnetic core. To increase the power of the transmitter, we did substantial development work on the antennas, tuning circuits and source drivers to compensate for the effects of steel casing.

Optimizing an inductive transmitter antenna in a steel-cased well was a challenging undertaking. The process is highly non linear. The transmitter actually interacts with the casing pipe and the field strengths are large enough to fully saturate the pipe and produce non-linear responses. These, unfortunately, are very difficult to model with currently available codes and therefore quite difficult to predict. In the development of the system, we manufactured several prototype transmitter antennas and driver systems.

In Figure 17, we show a photo of the new transmitter coil in a cut-away view. The antenna is more than 15 ft long and 4” in diameter and consists of a fiberglass enclosure loaded with a magnetic core and wrapped with several hundred to more than one thousand turns of wire in specific winding patterns. The entire package is housed in a fiberglass case that is pressure compensated.

![Figure 17. Photograph of the X2C transmitter (BB)](image)

We experimented with various core materials, several winding strategies and several driver circuits in order to achieve maximum output through steel-well casing. We actually did most of the optimization using trial and error bench testing. During the testing of prototypes, we found the following useful principles:

- Because of inductive coupling between the transmitter and the casing, there is a detuning effect. That is, the antenna cannot be effectively tuned with capacitors when it lies in the steel casing. The casing tends to remove the inductive component of the impedance and replace it with a strong resistive component. The final designs therefore use bare or untuned source coils.
As shown above, the EM source field is attenuated logarithmically with frequency in steel casing. Our goal is to optimize the performance in the frequency range of 1-100 Hz, which provides an acceptable balance between casing attenuation and geologic resolution.

After a series of tests, we found that the transmitter optimum core material has a large saturation limit but only a moderate magnetic permeability. The optimum moment is a unique combination of the core volume, the driver current and the number of turns.

As part of this project, we manufactured 2 transmitter antennas, one specifically designed to maximize performance in steel casing, the second is designed to operate more efficiently in an open hole environment. The steel-casing tool is 4” diameter tool and more than 20 ft long. It has a moment of more than 20,000 A-m$^2$ in air (our record) and several hundred in steel.

In Figure 18, we plot the performance of both of the antennas against the XBH2000 source in an open hole environment. In Figure 19, we plot the transmitter performance in a steel-cased well.

![Figure 18. Transmitter moment in air of the X2C as compared to the XBH2000](image)

In an open hole, the X2C system is 20-40 times stronger than the XBH2000. This marked improvement was made by increasing the transmitter volume, increasing the voltage limit on the power supply and optimizing the number of turns to ensure that the casing core was fully saturated. This remarkable improvement was actually fairly straightforward to engineer based on our previous experience with the XBH2000.
As shown in Figure 18, the power improvement supplied by the new transmitter in the open hole did not completely pass through into a cased hole environment. In steel-casing, the X2C system is approximately 3 times stronger than the XBH2000. Although smaller than anticipated, it will still provide a major improvement over the old system.

The reasons for the much smaller improvement relates to the interaction between the transmitter windings and core and the steel casing. Our transmitter actually induces currents to flow in the casing pipe that cancel its own field. This effect varies with the casing properties, tool diameter, the current in the windings and the properties of the core. The final design for the X2C transmitter was optimized from a series of tests through steel casing.

![Graph showing transmitter moment in steel casing of the X2C (BB and MB) as compared to the XBH2000](image)

Figure 19. Transmitter moment in steel casing of the X2C (BB and MB) as compared to the XBH2000

3.4.2 Receiver Antenna and Amplifier

The receiver system consists of a sonde section, which contains the antenna and amplifier, a digital electronics section consisting of a data acquisition module and a borehole computer, and a telemetry and communication section where commands are processed and data is sent to and from the surface computer. A photo of the sonde is given in Figure 20.

Schlumberger/EMI has been a pioneer in magnetic sensor design for more than 20 years. Our induction coils have used innovative design and have excellent reliability in a wide variety of custom and commercial applications. The XBH2000 system uses a modified form of the commercial BF6 sensors for the receiver sondes. These coils have shown good sensitivity and reliability in an open hole environment, but the performance in the steel casing has been different than predicted by computer models.
The goal of this project is to improve the sensitivity of the coils, fully understand the effect of the casing and downhole noise and to achieve a robust mechanical design that will survive hostile downhole conditions.

We designed three coils for operation in casing and 4 separate field amplifiers. The sensors featured two different cores and three different core windings. In a quiet environment, the new coils have up to a factor of 10 improvement in sensitivity over the receiver coils in XBH2000 system.

After testing these coils on the bench and in open and steel cased wells during field tests, we found several surprising things.

- The coil sensitivity function depends somewhat on the casing. That is, the casing becomes part of the electronic circuit and the sensitivity is a function of the casing magnetic and electrical properties.

- At depths above 4,000 ft, the signal-to-noise ratio of the sensors mostly depends on the background noise. The coil sensitivity is a much less important function. Below these depths, the boreholes are normally quieter and the coil sensitivity is more important.

- The background noise in the borehole primarily consists of mechanical or vibration noise, and electrical noise from sources propagating down the casing or through the formation.

In Figure 21, we show a noise spectrum for three prototype sensors measured at an operating southern California oil field. In the same plot we show the theoretical BF6 magnetic sensor noise and the expected system noise. The plot shows a significant variation of sensor noise with the coil design although in all cases the measured noise was much in excess of the sensitivity of the BF6 coil. We also note that the noise in a cased hole is considerably higher than in an open or in a fiberglass-cased well in the field at the same depth.
After considerable research in this area, we discovered that in applications shallower than 5,000 ft, the sensor used in the XBH2000 system was adequate; design improvements made with the X2C were mainly to improve thermal characteristics, manufacturing simplicity and tool reliability. For deeper applications, the sensitivity achieved with the new system is worthwhile.

These findings have changed our data acquisition strategy. It seems the main constraint on the receiver side is the level of background noise. We will therefore design our system to mitigate this noise. For this, we are testing three strategies.

- Smart-stacking software - If the time series data had impulse noise spikes related to shock or EM pulses, then the data will be contaminated. These spikes can often be recognized by software and deleted from the time series prior to data averaging and this will greatly reduce the error.

- Sensor string - If the noise distribution is random (Gaussian), then the only noise reduction possible is by averaging. We can optimize our data collection by simply adding more receivers to the string, improving our electronic filters and optimizing tool operation.

- Auxiliary sensors - It is also possible that much of the noise is acoustic and may be removed with an acoustic sensor. Here, we are testing the coherence of the EM noise to the signal from an acoustic sensor (accelerometer).
Each of these strategies requires further work but we expect conservatively that some combination will improve the signal-to-noise ratio by 2 to 3.

3.4.3 Data Acquisition System and Software

In addition to the re-design of antenna and tool hardware, we also did an extensive re-design of the data acquisition system and the software. Are chief goal here is to employ a 24 Bit acquisition technology to improve system dynamic range to take full advantage of the sensor range. We also wish to improve the signal averaging routines and reduce data overhead, so that more time is spent collecting data and less time in sending commands and data transmission. A second goal is to improve the reliability of electronic components, especially under conditions of high heat and vibration.

Operating software for this system is a critical component not only for smooth data collection but also for optimizing the system performance. The software component consists of a firmware, or software resident in the tool, and a surface software that communicates to the borehole tool and to the other surface systems.

A block diagram of the software workings is provided in Figure 22. The software is written in C and various assembly languages for operation on a PC based platform. Computers in the tool and at the surface all program in compatible languages and in fact firmware resident in the tool can be loaded from the surface PC.

![Figure 22. Block diagram of the X2C software](image-url)
The firmware and software are in continual development as signal to noise gains can be achieved via smart stacking algorithms, better statistics and improved digital filters. We are also continuously working on algorithms for data display and storage.

3.4.4 Final Design Configuration

The above provides an overview to the present working experimental prototype tool. This system has been used in more than 30 surveys worldwide, and has been effective in collecting data in a variety of field conditions and well casings. We have, in fact, collected and interpreted data in dual steel cased wells spaced up to 1,000 ft apart. We expect that the optimization process to continue for several more years by which time we hope to expand the well spacing range to 2000 ft and improve the image resolution.

Below, we give the final design configuration of the X2C crosswell system.

<table>
<thead>
<tr>
<th>Table 1. X2C final design configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Transmitter Moment (Air) A-m²</strong></td>
</tr>
<tr>
<td>4” (Cased-Cased)</td>
</tr>
<tr>
<td>3 3/8” (Open-Cased)</td>
</tr>
<tr>
<td><strong>Transmitter Moment (Casing)</strong></td>
</tr>
<tr>
<td>50-500</td>
</tr>
<tr>
<td><strong>Receiver sensitivity (microG)</strong></td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td><strong>Effective sensitivity (micro G)</strong></td>
</tr>
<tr>
<td>5-50</td>
</tr>
<tr>
<td><strong>Effective Range (Open)</strong></td>
</tr>
<tr>
<td>1 km</td>
</tr>
<tr>
<td>(Open-Steel)</td>
</tr>
<tr>
<td>(Dual Steel)</td>
</tr>
<tr>
<td><strong>Frequency Range</strong></td>
</tr>
<tr>
<td>1-200 Hz</td>
</tr>
<tr>
<td><strong>Pressure Rating</strong></td>
</tr>
<tr>
<td>10,000 ft</td>
</tr>
<tr>
<td><strong>Temperature Rating</strong></td>
</tr>
<tr>
<td>125 °C (250 C ft)</td>
</tr>
</tbody>
</table>
4 Phase III: Field Tests with the X2C System

In this section, we describe the results of two field tests made with the X2C system in 2003 and 2004. The tests were both made in operating oil fields and include measurements made in steel cased wells as well as data collected in steel-open hole combinations.

The field exercises were designed to test the capabilities of the X2C system for data collection and imaging and to determine the utility of the method for management of operating oil fields under water and steam flood.

4.1 Steam Flood Monitoring at the Kern River Oil Field, Southern California

The first set of tests were made at the Kern River oil field near Bakersfield in southern, California (Figure 23). The tests were made for the joint purpose of establishing the tool performance in a high temperature steam flood environment, as well as to provide insight on the flow of steam in this mature field.

The Kern River oil field has been a major California producer for more than 50 years. At present, it is about 90 percent owned by ChevronTexaco. More than 1.5 billion barrels of oil have been produced from a stack of roughly horizontally layered oil sands at depths from 500-1500 ft. The oil has mainly been produced under steam drive, using many closely spaced production and injection wells. At present, more than 100,000 barrels of oil a day are produced from more than 4,000 production wells using more than 2,000 steam injection wells. There are also approximately 600 observation wells for monitoring downhole temperatures and fluid saturations.

An aggressive steam and heat management program was initiated in the early 90’s as a means to lower the cost of production. They found that by regulating the downhole
temperature within specific limits, they were able to reduce the production costs by as much as 50 percent while maintaining production. ChevronTexaco used temperatures and saturations measured in their observation wells to infer downhole conditions field wide and targeted steam injection to only those intervals that needed the adjustment to stay within a specified downhole temperature range. Of course, using only the borehole logging measurements and software to interpolate between holes is only roughly accurate especially in geologically complex regions. For example, ChevronTexaco has recently found several unsuspected “coldspots” within the field, and in other areas they suspect significant bypassed oil due to geological complexity (i.e. faulting) or nonuniform pattern sweep. For this reason, ChevronTexaco expressed an interest in testing the crosswell EM technology as a field management tool in their field.

For the present study, the primary geological targets were small faults suspected from the borehole logs and geologic cross-sections that may be re-directing the steam flow. A secondary goal was to use inferred resistivity variations to map zones where the temperature and fluid saturation levels are changing due to the steam flooding and fluid production.

The EM tests were run episodically over a one-year period, in 2002 to 2003, using several of the temperature observation wells for tool deployment. The testing began soon after the release of the first prototype system in late summer 2002. In addition to the engineering tests, we selected a small group of wells to image interwell geologic targets.

4.2 Field Work

The field activity started in the fall of 2002 with tests at the Reed Crude leases in the older, central part of the field. During this first phase of tests, which lasted several weeks, we completed 4 crosswell surveys. Several times, the surveys were interrupted to repair and upgrade tools. The tests were in fact quite useful in hardening instrumentation against temperature.

All data were collected in steel-cased observation wells. The wells used in the tomography were separated from 350 ft to more than 800 ft. We typically logged the interval from 400 ft to 1200 ft, which covers the five primary pay zones in this part of the reservoir. Borehole temperatures ranged from ambient to more than 260°F in the steam-flooded zones.

Crosswell logging proceeded slowly due to the noisy downhole conditions and the frequent tool breakdowns in this stage of tool development in these hot holes. With no breakdowns, a typical crosswell survey would require more than 30 hours for the logging because of the high background noise. At the shallow 400-1200 ft reservoir depths, the ambient noise in the boreholes was very high. This is likely due to the high level of surface activity in this very busy oilfield.

For two of the well pairs measured (RCA1-RCA2 and RCA1-RCA5), the data were of very good quality, the other data is of lesser quality primarily due to tool breakdowns (see Table
2). These latter profiles were acquired in several pieces. We suspected that this discontinuous collection process resulted in calibration mistakes and depth control errors.

Table 2. Crosswell EM survey details at Reed Crude

<table>
<thead>
<tr>
<th>Well pairs</th>
<th>Well Separation (ft)</th>
<th>Frequency</th>
<th>Data Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCA1-RCA2</td>
<td>672</td>
<td>31 Hz</td>
<td>Good-continuous</td>
</tr>
<tr>
<td>RCA1-RCA5</td>
<td>836</td>
<td>31 Hz</td>
<td>Good-continuous</td>
</tr>
<tr>
<td>RCA2-RCA8</td>
<td>590</td>
<td>31 Hz</td>
<td>Fair-discontinuous</td>
</tr>
<tr>
<td>RCA5-RCA7</td>
<td>468</td>
<td>31 Hz</td>
<td>Fair-discontinuous</td>
</tr>
</tbody>
</table>

In the next section, we present selected interwell resistivity distributions and compare the image to the color-coded induction logs at the margin of the plots. In addition, for the best quality data, we also calculated a “pseudo time lapse image”. This latter image is an estimate of the resistivity differences in the interwell region in the time period from the measurements of the resistivity logs in the observation wells used to the present time.

We obtain this difference image by keeping track of resistivity model adjustments made by the inverse code as it strives to match the observed data. If the initial model is a good representation of the interwell resistivity at the time that the wells were first logged, the model changes should reflect resistivity changes over time. For this case, we base the initial model on an interpolation of the borehole logs in the wells used in the tomography. In an area of fairly simple geology, such as Kern River, this interpolation is a reasonable estimate of the interwell resistivity.

At Kern River, where there has been significant local heating and large areas of desaturation, this difference display is invaluable as a guide to reservoir changes. Since there have been no baseline surveys made, it is our only means of measuring changing reservoir conditions.

In fact, we expect that much of the ongoing reservoir processes at Kern River to be visible with crosswell EM. From laboratory measurements, resistivity decreases of 40-60 percent due to local heating are expected as the temperature changes from 80°F to more than 260°F in steam-flooded regions (Keller, 1988). Similarly, production-induced saturation effects will likely increase the resistivity, as fluid withdrawn is not completely replaced by injected fluid. A 40-80 percent increase would be expected for this latter process.

4.3 Data Processing

In Figure 24, we show a plot of the raw field data in the steel-cased wells and the data corrected for the effect of the casing using our sensors and software. The difference between the cross-sections illustrates the profound effect the steel casing has on the crosswell EM data. The adjusted data are both much less jittery and different in shape and magnitude from the raw data.
In Figure 25, we show the plot the casing adjusted data and the calculated data from the crosswell inversion. After 15 iterations, the inversion has reduced the misfit from approximately 14 percent to an average of 2-4 percent, which is typical of good crosswell data and roughly equal to the measurement error. This distribution of this data misfit is shown on the basal plot.
In Figures 26, we show the interwell resistivity section for well pair RCA1-RCA2. The inverted image indicates a smooth resistivity distribution that is consistent with the logs shown at the margin of the plots. The letter designation on the log at the right margin indicates marker horizons, as selected by ChevronTexaco geologists. The higher resistivity sands, indicated in greens and red colors, are continuous in the basal layers but less continuous in the upper layers. Upper sections are lower in resistivity and roughly continuous, but there are hints of faulting based on offsets of the K1 horizon.

The resistivity section shown above is consistent with the geology and the logs but it is difficult to use these sections to isolate interwell regions where changes are occurring due to the ongoing steam flood. Here the difference section, shown in Figure 27, is most useful. The difference image indicates several interwell areas where changes are occurring. For example, the image indicates a broad arcuate area, shallow near well RCA1 and deeper near well RCA2, where the resistivity has decreased by up to 50 percent form the starting model. This level of change is consistent with a temperature increase caused by steam injection and it suggests that recent steam flooding is progressing to shallow depths near well RCA1.

In Figure 28, we show the temperature log from observation well RCA1. This log indicates that the well has been heating up at depths from 400-600 ft in recent years. Note that the position of the low resistivity anomaly almost exactly matches the zone of increasing temperature measured at the observation well. The 50 percent decrease is somewhat smaller than what we would expect from a temperature effect alone. We suspect that oil and water is also being withdrawn from these depths, which would tend to change the resistivity in the other direction and therefore dampen the resistivity decrease.
Figure 27. Resistivity and difference sections for well pair RCA1-RCA2

Figure 28. Temperature logs well RCA1
The arcuate shape of the low resistivity zone that stretches from deep to shallow in the interwell space suggests that faulting may influence the steam flow. We would guess that a fault cross somewhere near 400 ft from well RCA2 may be helping to channel steam upwards into the shallow section near well RCA1.

Notice that at greater depths in Figure 29, the cross-section indicates that the resistivity is increasing. The repeated temperatures log shown in Figure 28 indicates that the temperature at these depths is stable, so we suspect that the resistivity increase is a saturation effect. The resistivity versus saturation function suggests that the observed resistivity increase of 30-50 percent could be explained by a decrease in water saturation of 6-10 percent. This suggests that the deeper portions of the section are desaturating due to production. That is, there is a net withdrawal of fluid (both water and oil) from these depths that is resulting in a higher formation resistivity.

Assuming that this assertion is valid, then we should see consistent resistivity increases at depths where oil (and water) extraction is ongoing but smaller increases where the extraction is complete. We note, however, that if the temperature falls, the resistivity will also increase, so it is difficult to distinguish between these alternatives without the temperature data.

![Figure 29. Crosswell and log-based resistivity sections and an overlay image of the two](image)
4.4 Comparing the Crosswell EM Section to the Geological Data base

We note that the well density at Kern River is very high; in fact there are 5 wells between the temperature observation wells used for the tomography. In Figure 29, we display a resistivity cross-section derived from the seven logs along with the crosswell EM cross-section and finally and overlay of the two.

In general, the resistivity section derived from the crosswell EM data replicates the log-based resistivity but at a lower resolution. We notice significant differences between the section in the overlay cross-section (Figure 29). Some of the difference may be due to dropped detail but most of difference between these sections is due to formation resistivity changes that have occurred after the wells were drilled. That is, this part of the field is being actively produced and steamed so the resistivity is constantly changing, and these changes will not be reflected in the older logs.

In Figure 30, we superimpose the log based resistivity and the cross well resistivity difference sections. This figure may help explain the nature of the arcuate shaped zone of decreasing resistivity that was observed in the difference plot of Figure 27. Figure 30 shows that the low resistivity anomaly actually crosses several significant flatlying producing layers and this suggests that the upward steam flow may be helped by small-offset faults in several of these layers. ChevronTexaco geologist James Eacmen has actually projected faults of this type into this interwell section using a log-based geologic model (Wilt, et al., 2004).
Although not easily mapped with from the logging data, these faults likely serve as steam conduits that conduct the steam from the deeper to the shallower layers. If they were common in other parts of the field, it would be valuable to know where they are and how they are affecting the steam flood.

4.5 Overall Evaluation of the Technology/ Potential Impact at Kern River

After some initial startup problems, the crosswell system ultimately performed well at Kern River. Crosswell data could be collected in approximately 2 days and the processing was typically completed in several days. The crosswell EM data could be accurately collected between two steel-cased wells spaced more than 800 ft apart. The inversion provided interwell images consistent with the logs and the field data. These images could be used to identify interwell structure and also to determine interwell temporal resistivity changes associated with the steam injection. The data are particularly useful for identifying intervals that are heating, or desaturating and for identifying faults that serve as active transporters or blockers of subsurface steam flow.

In general, we feel the prognosis is excellent. We feel that these data provided information that could be of significant use in developing the edges of the field and in finding new imaging targets within the field.

We also believe that the resistivity interpretation is clearly enhanced by the good working knowledge of the geology and steam flow characteristics in this field by the ChevronTexaco geologists and engineers. This knowledge allows us to better focus geologic controls on the steam flow.
5 Field Test in Shengli, China, March 2004

Below, we describe the first international field test of the X2C tool. The test site was chosen for the application to a water flood environment where only steel wells were available. We note that a nearby site was used in an earlier test of the XBH2000 system in 2000.

5.1 Background

The crosswell survey was made in mid March 2004 at the Gudao oil field in the Shandong province in China (Figure 31). Gudao is an anticlinal trap located along the Yellow River delta along the eastern coast in central China (Figure 32). The field consists of channel and deltaic sands deposited in an ancient flood plain. Large parts of the field are characterized by continuous deltaic sands and other parts by distinct channels but generally both channel and flood sands are present in each area. The configuration of the sands and the controlling structure is crucial in understanding the ongoing waterflood and in optimizing the oil production strategy. At present, it is estimated that 25 percent of the reserves in this field have been recovered but also that another 15 percent are recoverable with improved reservoir knowledge. Improvement of this knowledge is one of the key goals to the present crosswell EM project.

![Figure 31. Plan view of Gudao oil field](image)

Gudao is a large mature field with many production and injection wells; the production is roughly 50,000 barrels of oil per day. A typical well in this field produces 20-30 barrels of oil per day and more than 500 barrels of water. With the water cut rising each year, it is critical to find the bypassed reserves and locate and shut off the fast-path water channels.
The project consisted of 4 separate surveys using 3 well pairs (Figure 33). The goals of the project were: 1) to test and establish performance data for the new system in the Chinese environment; 2) to provide interwell resistivity data within this chosen well pattern to help better understand the waterflood dynamics and locate bypassed reserves.

These wells are located in a mature part of this waterflood. Flooding started in this part of the field in 1985 and has progressed continually since then. In Figure 33, we show a plan view of the wells in this part of the field. Wells 29-412 and 30-26 are producers, well 29-413 is a water injector and well 31-523 is a newly drilled producer that was used in the tomography.
In Figure 34, we show several resistivity logs from wells in this pattern. The earlier log (1984) indicates that the oil sands have an initial resistivity of 15-25 ohm-m and the background silts and clay have a resistivity of 2-4 ohm-m. The flooding and production are centered in three principal zones. Zones 3 and 4 are well-defined continuous deltaic sands that range in thickness from 4 to 12 meters; these have been continually flooded since 1985. Zone 5 is a less continuous zone with heavier oil that has had less success in waterflooding operations. At present, a cyclic steaming strategy is being used in this layer with some success.

Figure 34 also indicates that after years of waterflooding, the resistivity of the oil sands in zones 3 and 4 has decreased to 8-10 ohm-m from 15-25 ohm-m. This is mainly the result of saturation changes as the injected water replaces the oil. Obtaining the present saturation level is difficult because it is necessary to know the salinity of the formation water. In this field, this quantity is poorly known because the source of the injected fluid has changed a number of times during the waterflooding.

5.2 Crosswell EM Survey

The crosswell measurements were made with the newly developed X2C-GM system. This field system is a hardened version of the prototype X2C tool made and tested in California during the previous year.
In general, crosswell EM is used to provide formation resistivity between wells. This interwell resistivity is used for reservoir characterization, structural mapping and most importantly for tracking processes such as water and steam floods where the formation fluid (oil, gas and water) is exchanged with injected fluid (water). This fluid exchange typically results in a large resistivity change due to the saturation change, and thus the process is traceable via the interwell resistivity and resistivity variation.

After some initial startup problems, mainly due to communication difficulties on a long surface cable, the system was deployed on March 14, 2004. The objectives of the Gudao crosswell EM project were threefold.

- Provide an initial field test of the X2C-GM field system. This was necessary to provide operational data, training for local engineers and to test the system reliability.

- Determine the signal and noise limits of this system in the Chinese environment and thereby establish resolution and range guidelines for future surveys.

- Provide an improved reservoir definition in this part of the Gudao field.

The data collection plan called for the use of open hole 31-523 (523) to collect open-steel data sets using wells 30-413 (413) and 29-412 (412) for the receiver tools. The final survey was made between steel-cased wells 413 and 412.

The tomography covered the depth interval between 1150m and 1350m. The system operates with a stationary 4 level receiver string and a moving transmitter. The transmitter moves from the bottom to the top of the interval at a rate of 3-6 m/minute; data is collected every 1-2 meters depending on the amount of signal averaging and the logging rate. After each transmitter profile, the receivers are repositioned and the process is repeated until the entire depth interval was covered.

For these surveys, receivers were spaced 5m apart and the transmitters covered the same interval at 1 m measurement spacing. The tomography required 20-35 hours for completion for each crosswell survey. The longer time periods were for the dual casing surveys.

We initially deployed the transmitter in well 523 and the receiver in well 413 and collected complete open-to-casing data at two frequencies, 32 Hz and 104 Hz. These data were used to compare the image resolution with frequency. Next, data was collected in well pair 523-412, and steel-cased well pair 413-412 was measured.

<table>
<thead>
<tr>
<th>Well Pair</th>
<th>Separation</th>
<th>Frequency</th>
<th>Quality</th>
<th>Casing</th>
</tr>
</thead>
<tbody>
<tr>
<td>31-523 30-413</td>
<td>260m</td>
<td>104Hz</td>
<td>Excellent</td>
<td>Open-steel</td>
</tr>
<tr>
<td>31-523 30-413</td>
<td>260m</td>
<td>32 Hz</td>
<td>Excellent</td>
<td>Open-steel</td>
</tr>
<tr>
<td>31-523 29-412</td>
<td>310m</td>
<td>32 Hz</td>
<td>Excellent</td>
<td>Open-steel</td>
</tr>
<tr>
<td>29-412 30-413</td>
<td>300m</td>
<td>32 Hz</td>
<td>Excellent</td>
<td>Steel-steel</td>
</tr>
</tbody>
</table>

Table 3. Crosswell survey details at Gudao
In general, the system performed very well throughout the survey. The system was straightforward to deploy and operate. There was less than 2 percent downtime experienced due to equipment problems.

5.3 Results

Sample raw data plots for the open-to-steel data and the steel-steel data are shown in Figures 35 and 36. The raw data shown in Figure 35 is smooth and continuous. The maximum measured field level of 1,200 microvolts is easily measurable. We see that for the open-steel surveys the amplitude curves are bell-shaped, reflecting the relative source-receiver position of the profiles. The variation in maximum field levels for each profile mainly reflects the different properties of the steel casing pipes in the receiver well.

![Figure 35. Raw crosswell data at 32 Hz](image)

The dual steel data (Figure 36) is far more jittery in nature, and the curves are less bell-like. This is due primarily to the steel-casing that imparts a different attenuation as the transmitter moves through each pipe. Note however the excellent correlation of the high frequency jitter in the receiver profiles. This coherency is what allows us to separate the formation and casing signal from these data. Notice that the field level of these data is more than 20 times smaller than the open-steel data even though the well separation is roughly the same. This suggests that the attenuation due to the steel casing on the transmitter is a factor of 20, which is in accord with Figure 12.
Repeated data profiles in the open-steel surveys suggest a system noise level of approximately 2-4 microvolts, or about 6-12 microgammas. This is slightly better than posted specifications and suggests that at these depths in this oilfield, the background is electromagnetically quiet, and at least from a data collection viewpoint, a very good spot for crosswell EM. This is a very positive result as it established that our system bias is below the measured noise level of roughly 6-12 microgammas. It also means that we can tolerate an even lower signal level in future surveys by increasing the amount of signal averaging.

We note that for each doubling of the well spacing, the field level drops by a factor of 8. The open-casing data in Figure 35 suggest that the well separation could be doubled and the data would still be easily measurable with our system, assuming a noise level of 2 microvolts.

5.3.1 Tomographic Results: Data Processing

We first reduced the data for the open-steel surveys, applied calibration corrections and interpreted the results using a 2D computer based inverse code. The code fits the collected data to a 2D model with an initial or starting model based on available geology and logs. The code essentially takes our best guess and the collected data and adjusts the model until the data is fit within the data measurement error, 1-3 percent in this case.

For the dual casing data, the casing correction is more complex and requires longer to implement. The data clearly have a casing imprint, which is removed by using a separate procedure described above. Note that for these data, we achieve a similar formation sensitivity to the open-steel data by using the same frequency. We maintained this in spite of
the lower signal levels (more than 20 times) and we compensated it by averaging the signals longer, thereby lengthening the data acquisition time from 22 hours to about 35 hours.

One of the chief indications that the inversion process is successful is to examine the misfit section, or the difference between the observed and calculated data, after the data has been fit by the inversion. This misfit section should fit within the error tolerance, and have a roughly random structure. A high degree of structure in the misfit section suggests error due to calibration, well separation and tool position or initial formation model.

The data misfit section for two of the cross-sections is provided in Figure 37 and Figure 38. These indicate a very close data fit and very little misfit structure indicating a well defined geometry and a good tool characterization. The misfit for well pair 523 to 413 displays and average fit within 1-2 percent. The dual casing data (412-413) show an average misfit of roughly 2-3 percent.

The final product of the data collection and processing are the interwell resistivity images; these are given for the three well pairs in Figures 39-41. In each plot we provide the interwell resistivity distribution in a color format with the color-coded induction resistivity logs shown at the margin of the images.

**Figure 37. Data fit for 523-413 (open-steel, 32 Hz)**
5.3.2 Interpretation of Tomography Results

The interwell resistivity image between well pair 523 and 413 is a smooth section consistent with a flatlying multilayered section and concordant the well logs at the margins. The low resistivity upper section represents clays and silts; within this section there are thin discontinuous higher resistivity sands (oil bearing?); note, for example, the layer at a depth of 1150ft. The oil-bearing zones 3, 4 and 5 are associated with continuous high resistivity layers. Layer three is higher in resistivity near well 523 and grades gradually lower towards well 413. The layer thickness stays relatively constant. Layer 4 stays roughly constant in resistivity but seems to thicken gradually from well 523 to well 413. The most interesting part of the image is near location 80 meters where the 4-layer basal unit 5 grades at well 523 into a 2-3 layer section. The section also indicates slight stratigraphic thinning in layers 3 and 4 and some variation in the overburden silts and muds at this same lateral position.

Variations in layer resistivity may be associated with saturation and/or water salinity. Clearly, the resistivity has fallen from the initial 20-25 ohm-m to the present day 8-10 ohm-m due to replacement of oil by injected water. As the oil desaturation continues, this trend will continue but it can be offset by variations in injected water salinity. We know that the injected water supply for this field has changed a number of times in this field, but we are uncertain as to the salinity. This therefore adds an uncertainty to our ability to associate higher oil saturated intervals with a higher resistivity.
The section for well pair 523-413, shown in Figure 40, is quite similar to the first section. The layers are also continuous except for a thinning near 120 in both units 4 and 5. In unit 5, this image indicates a clear convergence of the 4-layer section to a two-layer section shown on the log in well 412. This is important as it indicates that the 4-layer section visible in 523 is likely connected to the 2-layer section in well 412. We also note that this convergence occurs at about 120m and it is associated with a thinning of unit 5.
The dual casing cross-section shown in Figure 41 is similar in appearance to the other sections. It conforms well to the logs and looks very reasonable as compared to the other sections. A cursory scan of the section shows it to be of similar resolution to the other two although it is perhaps slightly lower as indicated by a scan of the upper section where the higher resistivity sands are less continuous. This section seems to indicate a thickening and increase in formation resistivity in all three layers near the middle of the section from 100-150m. We compared this to the observed thinning in the 523-413 section.

We suspect that these layers vary in thickness continuously throughout this part of the field due to the depositional conditions. This thickness variation probably also affects the water flood sweep efficiency and as such it is a worthwhile property to map. The layers also vary in resistivity, and this is likely due to the water saturation and salinity. It is unknown whether there exist significant bypassed reserves in the higher resistivity section, but this is clearly important knowledge for future drilling.

![32 Hz Tomography (Dual steel casing)](image)

**Figure 41. 32 Hz tomography for well pair 413-412**

5.3.3 Using CHFR\(^1\) Data to Improve Image Resolution

We note that the data processing in well pairs involving steel-cased wells relies somewhat on the induction resistivity logs. These logs are used to provide an initial model for the inversion and even play a role in the casing correction technology.

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\(^1\) CHFR stands for cased hole formation resistivity. It is a recently developed technology that is used for measuring the near-well formation resistivity within a steel-cased well.
In the Gudao case, there is some uncertainty on the resistivity in the oil sands at the time the crosswell section was measured. We know that in the earlier period of the waterflood, the injected water was largely saline formation water and the resistivity declined from 20-25 to 8-10 ohm meters. More recently, it is suspected that fresher water was injected that might have included polymers. The resistivity of this water is unknown as was the injection history but we suspect that it was higher than the initial injectate.

Clearly the nature of the injected water will have an impact on the crosswell EM section. Fortunately, a borehole tool is available to measure the resistivity at the well bore through the steel-casing. Data from this tool can help establish the present day resistivity at the well and better define the crosswell section.

5.3.4 Model Adjustments using the New Logs

In late May, CHFR logs were measured in wells 413 and 412. The CHFR logs for the two wells are shown in Figure 43, along with the open hole logs in the same wells. In well 413, the cased hole logs follow the original open hole logs very well except for the shallowest depths in the interval. These data suggest that in the reservoir layers (units 3 and 4 in particular) the resistivity has increased during the past several years, presumably due to the introduction of polymers and fresher injection water. In the deeper low resistivity silts no resistivity change was observed but in the shallower silty layers, an increase was also measured. We did not expect a change in these shallow silty layers and experienced CHFR interpreters suggests that this change may be due to near well effects, (i.e. due to injected water leaking up the annulus) but probably does not indicate a true formation change and we did not include it in our starting model.

![Figure 42](image-url)
The change from 8 ohm-m to more than 15 ohm-m in reservoir layers 3 and 4 is substantial and was included in the crosswell EM interpretation as shown below. We note that no changes were observed in reservoir layer 5. This is consistent with observed injectivity problems in this horizon.

![Figure 43. CHFR and earlier induction logs in well 412](image)

The log data were then used to adjust the starting models for the crosswell EM, and the inversion was repeated. The main adjustment was to increase the resistivity in layers 3 and 4.
from 8 to 18 ohm-m, but we made no adjustment on any other part of the starting model. We then repeated inversion from well pairs 523-413 and 413-412. The results are displayed by themselves and compared to the original inversions in Figures 42 and 44.

We note that the interwell EM would have difficulty resolving the type of formation resistivity change observed in CHFR independently because it involves a resistivity increase that may be localized. This type of structure is difficult to map with an inductive system as it has a relatively small influence on the data. Knowing such information independently (from CHFR for example) allows the inversion code to begin at a more accurate starting model and thereby provides a better resolution of this subtle feature.

In Figure 44, we display the results from the re-processed well pair 523-412, and the comparison of this section to the earlier section. The main difference is observed in reservoir layers 3 and 4 where we observe the higher resistivity which was inserted at well 413 in the starting model, has extended to approximately 2/3 of the way across the section. Note that the color image appears slightly different from the earlier plots as a result of a scale change.
6 Follow-up Vacuum Survey

The final deliverable for this project is a return trip to the Vacuum field to track the progress of the CO$_2$ flood. In early 2004, ChevronTexaco informed us that the flood was underway and that they were interested in doing the experiment and in seeing the results of the test.

Upon arranging for the new deployment, we faced a number of obstacles. First, due to the ongoing CO$_2$ injection, the wells were all now pressurized at between 100 and 1000 lbs of wellhead pressure. To log these wells requires either that the pressure be reduced (blow the wells down) or that the tools be isolated using lubricators and grease fittings.

The first option is preferable and this was tried by ChevronTexaco who stopped injection on two wells and monitored the pressure. After 2 weeks, however, the pressure had come down very little. At the rate it was declining, it would not reduce to background for 4-6 months at least.

The second option was to isolate the tools using lubricators and pack-off with grease fittings. This too was a problem as only monocable fittings were available for this purpose. That is, the only jobs of this type done are using very slim 3/16” cable with a single conductor. It was feared that using existing fittings for a 3/8”, 7 conductor cable (that we use) would leak and the contractor would not guarantee its safety.

The final issue was the cost. The cost of two grease crews (one at each well), two full time cranes with operators and two wireline crews was approximately $35,000/day. A 5-day operation would cost more than $175,000 which was far in excess of the budgeted amount.

Although the cost was a factor, the main issue that prevented the completion of this last field exercise was the safety risk. We note that this may continue to be an issue using the technology in pressurized wells (especially pressurized with gas). The solution could come with a system modification to allow for monocable operation.
7 References


Norman, C., CO₂ for EOR is plentiful but tied to oil price. Oil & Gas Journal: v. 92, n. 6, 1994.

OGJ Special, EOR oil production up slightly. Oil & Gas Journal, 1998.
