

WILLOWSTICK TECHNOLOGIES LLC.:

ELECTROMAGNETIC GROUNDWATER SURVEY:

A demonstration of an Electromagnetic Groundwater Survey to Identify
Flowpaths of Injected Water in the Shannon Sandstone, Naval Petroleum Reserve
No. 3, Teapot Dome Field, Wyoming

Final Report for the Period of July 26 – November 1, 2005

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ABSTRACT

Willowstick Technologies, LLC and the Rocky Mountain Oilfield Testing Center jointly conducted a test using patented AquaTrack technology to map and delineate the concentration and preferential flowpaths of water injected into the Shannon Sandstone during a small-scale waterflood. AquaTrack technology uses Controlled Source-Frequency Domain Magnetics to map a magnetic field created by inducing a current through the subsurface. The AquaTrack survey identified three hydrologic boundaries within the targeted project area, creating four separate hydrologic zones. These three major boundaries strike in a north-south orientation. The data gathered from the investigation suggests that the survey layout, including antenna/electrode configurations and data grid spacing, were appropriately designed, and that the findings of the study are reliable. Cultural and electrode influences such as pipelines and powerlines were successfully identified and filtered out of the final results as necessary. Analysis of historical production data along with reservoir studies of the Shannon Sandstone, confirm that the hydrologic boundaries detected by the AquaTrack likely exist. These boundaries or zones are probably due to lithologic, diagenetic, and facies changes across the formation affecting formation permeability. There is a known north-south permeability trend in the Shannon that correlates with the maps from the AquaTrack survey. The information obtained from this survey can facilitate the understanding of how water flood practices are likely to influence oil production within the area of investigation. The results of the investigation can also be used to provide insight as to how the reservoir may be managed to improve oil production.

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EXECUTIVE SUMMARY

This report presents the findings of a demonstration project to map and delineate formation water concentrations and flow paths created by water flooding activities in the Teapot Dome oil field, also known as the Naval Petroleum and Oil Shale Reserve #3 (NPR-3), located near Casper, Wyoming.

This demonstration project was funded in part by a Department of Energy Cooperative Research and Development Agreement (CRADA #2005-060) and by Willowstick Technologies, LLC. The project was performed by Willowstick Technologies, LLCTM using its proprietary groundwater mapping technology known as AquaTrackTM. The purpose of this project was to demonstrate how the AquaTrack geophysical subsurface water mapping technology can be applied to subsurface oil reservoirs to map relative water concentrations and preferential flow paths naturally occurring or created from water flood and/or steam injection activities.

The fieldwork and data processing were performed with minimal knowledge of the geologic site or reservoir conditions with the exception of the targeted formation depth and some maps showing well locations, pipelines, formation structure, etc. The targeted zone in the Shannon Sandstone is roughly 300-400 feet in depth. There are no known aquifers between the Shannon Sandstone and the surface.

As part of the CRADA, RMOTC reviewed the AquaTrack survey findings and compared its results with existing water flood and geologic information available for the study area. The review was to evaluate and determine the applicability and effectiveness of the AquaTrack technology in helping to manage and optimize water and/or steam injection operations. Having an accurate, cost-effective understanding of the effects of water flood and steam injection practices can reduce costs of managing and directing the injected fluids used to mobilize heavy oil reserves and ultimately increase industry revenues.

Results of the AquaTrack Survey Investigation

The AquaTrack geophysical investigative results identified electrically conductive subsurface zones, probable hydrologic flow paths, and hydrologic boundaries. These boundaries influence water flood operations as it moves through the targeted formation.

The final interpretation of the AquaTrack investigation can be summarized in four very important findings of the survey. These findings are as follows:

1. Two antenna/electrode configurations were utilized to focus energy in the targeted Shannon Sandstone. These two configurations consisted of an east and west survey and were carried out independently. The magnetic fields from both configurations were measured on a 30 meter by 30 meter grid pattern established on the surface of the ground. The two surveys were overlapped for comparison purposes, and the 10-acre overlapping portions of the data sets match very closely, having the same conductive highs and lows as well as hydrologic structural control defined within the overlapped area. This complementary information between the two data sets generates a high level of confidence with the antenna/electrode configurations, the resulting measured and recorded data, and the final interpretation.
2. The data suggests that within the study area of the Shannon Sandstone, three major hydrologic boundaries exist in a north-south orientation that separate and define four hydrologic-related zones.
3. The four hydrologic zones appear to represent different lithologic or diagenetic facies within the formation that influence the way water migrates when injected into the formation. On the east side of the survey, a distinct hydrologic barrier or aquitard largely blocks current flow to the east; thus, the low conductivity to the east of the boundary suggests that little if any water saturation exists in this area.

Observations and Information Supportive of AquaTrack Results

The information gathered through the AquaTrack investigation suggests that that the survey layout, including antenna/electrode configurations and data grid spacing, were appropriately designed and that the findings of the study are reliable. This confidence is based on the following observations and evidence:

- The magnetic contour maps, generated from the AquaTrack geophysical survey readings, showed a very strong contrast between areas of high electrical conductance (current concentration or flow) and areas of low electrical conductance. The areas of high electrical conductance are interpreted as areas where water likely concentrated in the subsurface formation. It is anticipated that the observed hydrologic boundaries directed water flow very much like they directed the electrical current.

- In the majority of the study area, the signal strength, repeatability, and signal to noise ratios were very high, indicating excellent data sets.
- Numerous and various measurements (horizontal and vertical 400-Hz magnetic field data, 60 Hz noise, spheric noise, signal repeatability, signal to noise ratios) provided clean, consistent and reliable information from which the interpretation was based. All measured and recorded data support, complement, and confirm the final results.
- The results of the survey correlate well with results from other geological and reservoir studies of the targeted formation.

Conclusion and Recommendations

The AquaTrack survey investigation has provided significant information about the oil reservoir beneath the study area. This information can facilitate the understanding of how water flood practices are likely to influence oil production within the area of investigation. In addition to the groundwater characterization map or model of preferential flow paths and controlling structure within the formation, the investigation has also provided insight as to how the reservoir may be managed to improve optimization of oil production. The results of this demonstration project strongly support the need for further investigation, development and application of the AquaTrack technology with the oil industry.

INTRODUCTION

Willowstick Technologies, LLC, a Utah-based company that provides subsurface water mapping services, contracted with Rocky Mountain Oilfield Testing Center (RMOTC) to conduct an electromagnetic groundwater survey of the Shannon Formation. The survey was conducted as a demonstration project to map and delineate relative formation water concentrations and flow paths associated with water injection activities in the Teapot Dome Oilfield at the Naval Petroleum Reserve No. 3 (NPR-3).

This demonstration project was performed using proprietary groundwater mapping technology known as AquaTrack™. The AquaTrack technology has proven effective in delineating and characterizing subsurface aqueous systems in complex hydrogeologic settings for a number of Willowstick clients and a variety of applications. Theoretical studies and field tests have suggested that the AquaTrack survey methodology can work in water flood and/or steam injection oil reservoirs, in both shallow and moderately deep environments (down to approximately 4500 feet below surface).

The purpose of this project is to demonstrate how the AquaTrack geophysical subsurface water mapping technology can be applied to subsurface oil reservoirs to accurately and efficiently map water concentrations and preferential flow paths naturally occurring or created from water flood and/or steam injection activities.

The overall approach used in this study included using a five spot well pattern for applying DC electrical current into the targeted lower Shannon Sandstone member of the Steele Shale formation. The central well was used to drive electrical current from the central area of the survey out to the return electrodes located in the surrounding four wells. The electrical current in the subsurface created a magnetic field that was recorded and mapped. Mapped areas of high concentration in the magnetic field show where water saturations were the highest in the targeted formation.

The data presented in this report were collected from field work beginning on July 26, 2005 through August 10, 2005. An additional 3 weeks of in-shop data processing and interpretation was necessary in order to generate the results of the test. A report showing the final interpretation and results of the survey was presented to RMOTC on November 1, 2005 by Willowstick Technologies. Those results are presented in this report.

The information obtained from this demonstration project could provide the oil industry with a tested management tool to optimize water flooding efforts and other enhanced recovery operations by delineating relative water concentrations in an oil reservoir. Having an accurate, cost-effective means in which to better understand the dynamics of water flooding could help the oil industry to significantly reduce costs and increase revenue by optimizing production.

BACKGROUND INFORMATION

This test was performed at the Rocky Mountain Oilfield Testing Center (RMOTC) field site within the Naval Petroleum Reserve No. 3 (NPR-3), located approximately 35 miles to the north of Casper, Wyoming (figure 1). NPR-3 is situated on the Teapot Dome Anticline in the Powder River Basin, Wyoming. Teapot Dome is the southern extension of the much larger Salt Creek Anticline. The Teapot Dome oilfield has a rich history dating back to the early twentieth century (Curry, 1977). During that time over 1300 wells have been drilled into the structure which consists of a doubly plunging anticline cored by a basement high-angle reverse fault. Today at NPR-3, there are approximately 700 active wells producing oil and gas from several different geologic formations.

The most prolific production has come from the Shannon Sandstone. The Shannon originally had a reserve estimate of 144 million barrels (MMBO) of original oil in place (Olsen et al., 1993). Of that, 11.4 MMBO has been produced. Several enhanced oil recovery (EOR) and improved oil recovery (IOR) processes have been used in the past at NPR-3 within the Shannon Sandstone to try and improve the recovery rates. These include huff n' puff operations (where gas is injected into a well to build pressure and then the well is returned to production), water flooding, and steam flooding.

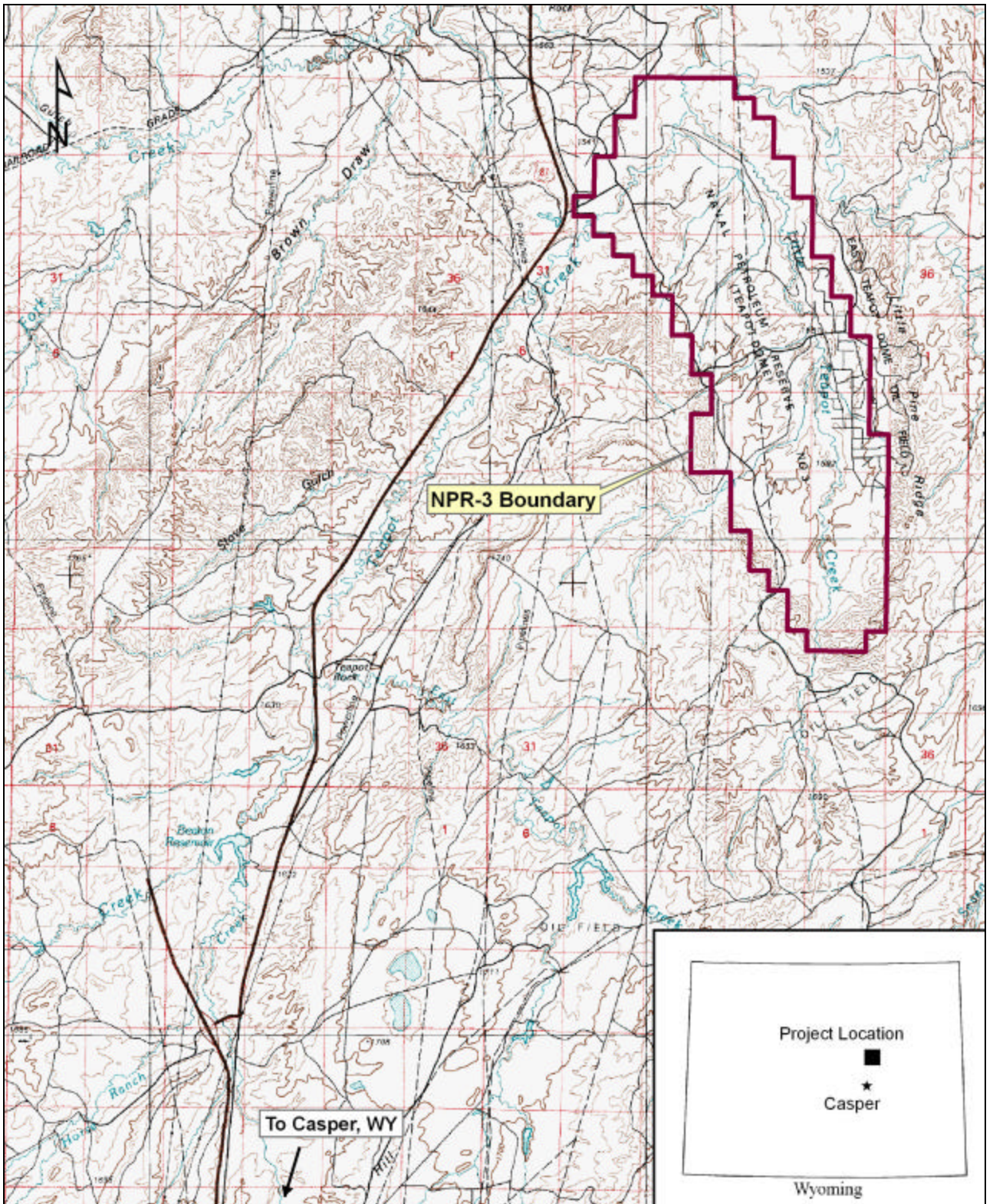


Figure 1. Map showing location of Teapot Dome on the Naval Petroleum Reserve No. 3 in East Central Wyoming, USA.

Within the study area (figure 2), a fireflood, or in-situ combustion operation, was attempted to mobilize the oil in the early 1980's. In this process, part of the formation was ignited using injected air and natural gas to fuel the combustion. Despite difficulty in sustaining the combustion, the project exhibited a positive production response (Sarathi et al., 1994). The fireflood concept was eventually abandoned in favor of a steamflood due to mechanical problems with wells combined with the high costs associated with operating the combustion.

Steamflood operations began in 1985 and run through the mid 1990's. The steam flood was initially successful at increasing Shannon production (Doll et al., 1995), but problems with premature breakthrough of steam and the high costs to generate high-quality steam eventually forced that project to be shut down.

Current IOR activities within the Shannon, include water flooding and air huff n' puff operations. These recovery processes have been successful on a limited scale. Within the study area, a small-scale water flood was initiated in late fall of 2004, and ran intermittently through July of 2005. In this water flood, produced water from the Tensleep Sandstone was dumped down the backside of the 55-66-SX-3 well. Initial results showed a small but positive response in production to the nine wells surrounding the injector well. Due to the recent influx of water into this well, the surrounding area was deemed as a suitable candidate for testing Willowstick's AquaTrack technology.

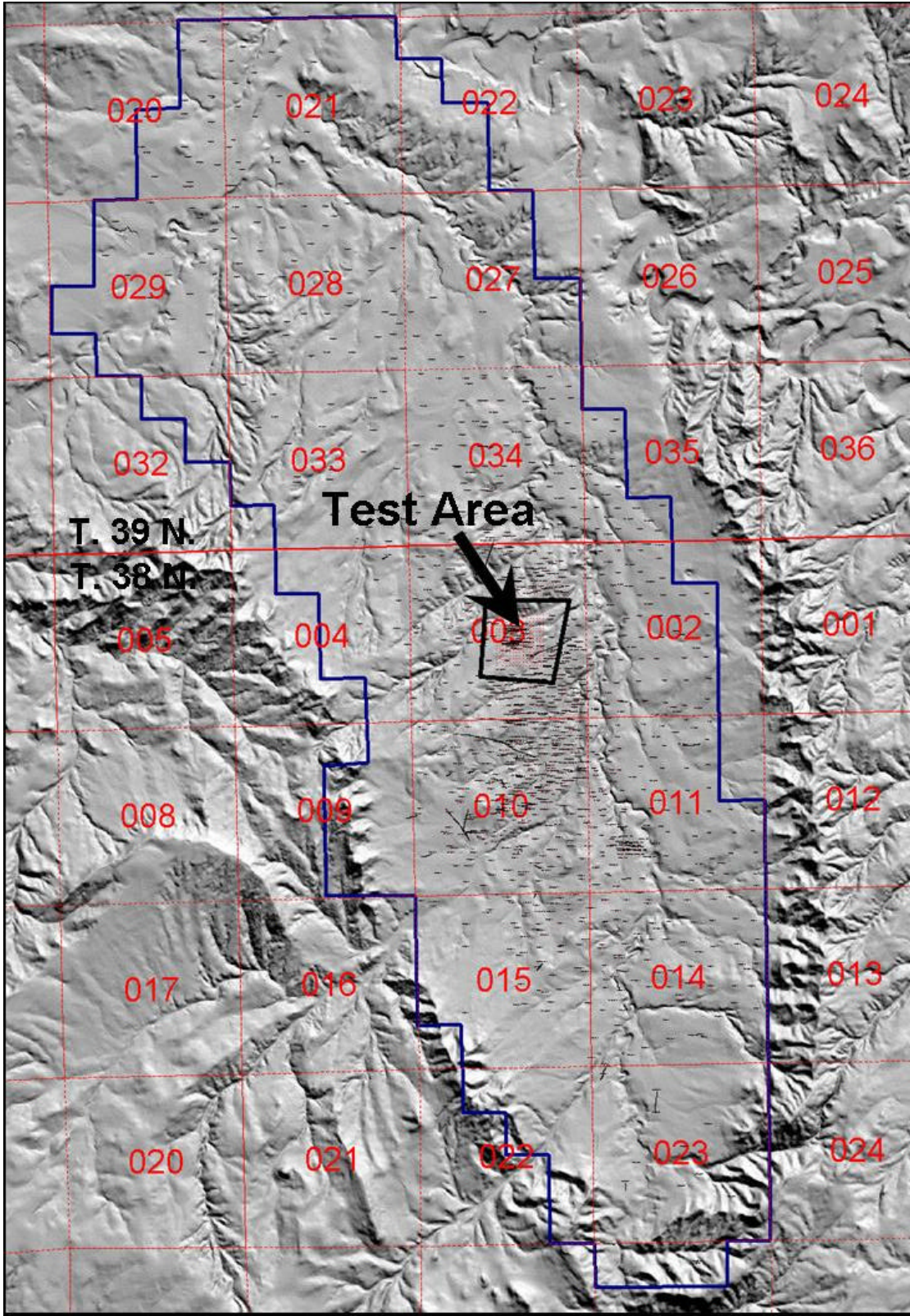


Figure 2. Map showing location of test area within the Teapot Dome Oilfield at the Naval Petroleum Reserve No. 3 (NPR-3).

Geologic Description

This project was conducted in the Upper Cretaceous Shannon Sandstone member of the Steele Shale Formation (figure 3). The Shannon Sandstone represents one of several pulses of offshore shelf sand deposition that occurred during the Late Cretaceous period (Obernyer, 1986). The Shannon Sandstone is typically interpreted to have been deposited in a shallow marine environment. The formation is thought to represent shelf-ridge (bar) complexes that were deposited at middle to inner shelf depths by south to southwest flowing currents in the Cretaceous Western Interior Seaway. The ridges trend in a north-south direction, which is slightly oblique to the paleo-current flow (Tillman and Martinsen, 1984).

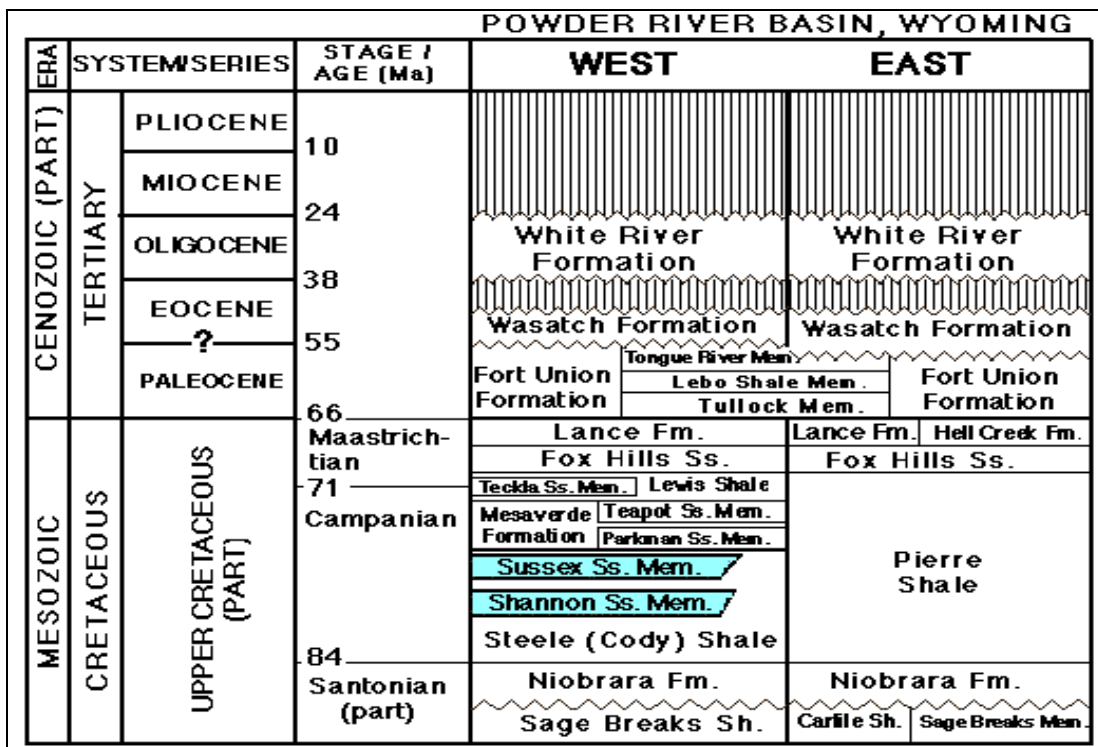


Figure 3. Stratigraphic column and regional correlations of Upper Cretaceous and Tertiary formations in the Powder River Basin (USGS DDS-33).

In the Salt Creek anticline area, including Teapot Dome, the Shannon Sandstone is comprised of two vertically stacked shelf-ridge complexes, the Upper Shannon and the Lower Shannon. Figure 4 shows the Shannon interval with the two stacked upward-coarsening units. According to Tillman and Martinsen (1984), the Lower Shannon is correlative with productive Shannon intervals in many areas of the Powder River Basin. The Upper Shannon seen at Teapot Dome appears to be locally constrained to the Salt Creek/Teapot anticline area. The Shannon Sandstone at Teapot Dome can be classified as a tight, highly fractured reservoir. Lateral and vertical facies changes, or changes in the lithologic character of the rock, are abrupt (Obernyer, 1986). In the oil-producing interval of the Shannon, average permeability is 63 millidarcies (md) and average porosity is 18 percent. Both productive (reservoir-quality) Shannon intervals average 30 to 40 feet of net pay. A high permeability trend runs north-south in the Shannon, just to the east of the structural crest of the Anticline (Doll et al., 1995).

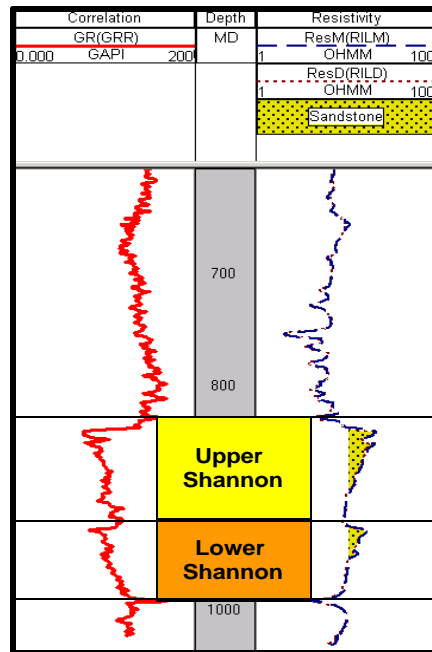


Figure 4. Typical gamma-ray and resistivity logs showing the Upper and Lower Shannon sandstone intervals at Teapot Dome.

A geologic structural map of the Shannon, surrounding the project area, shows that there is faulting to the north as well as to the south (figure 5). One fault crosses the lower part of the survey. This fault is expected to act as a partial barrier to fluid flow across that area. Most of the faulting in the Shannon appears to be trans-tensional normal faults that cross the main structure obliquely in an east-northeast direction. Fault trench studies conducted in the field show that there is typically a small component of strike-slip movement along the fault planes. Fracture orientations of the Upper Cretaceous stratigraphic units along the boundaries of the field are typically oriented perpendicular or parallel to the hinge-line of the anticline. There are some fractures that strike obliquely to the structure in both northeast and southeast directions (Cooper et al., 2001).

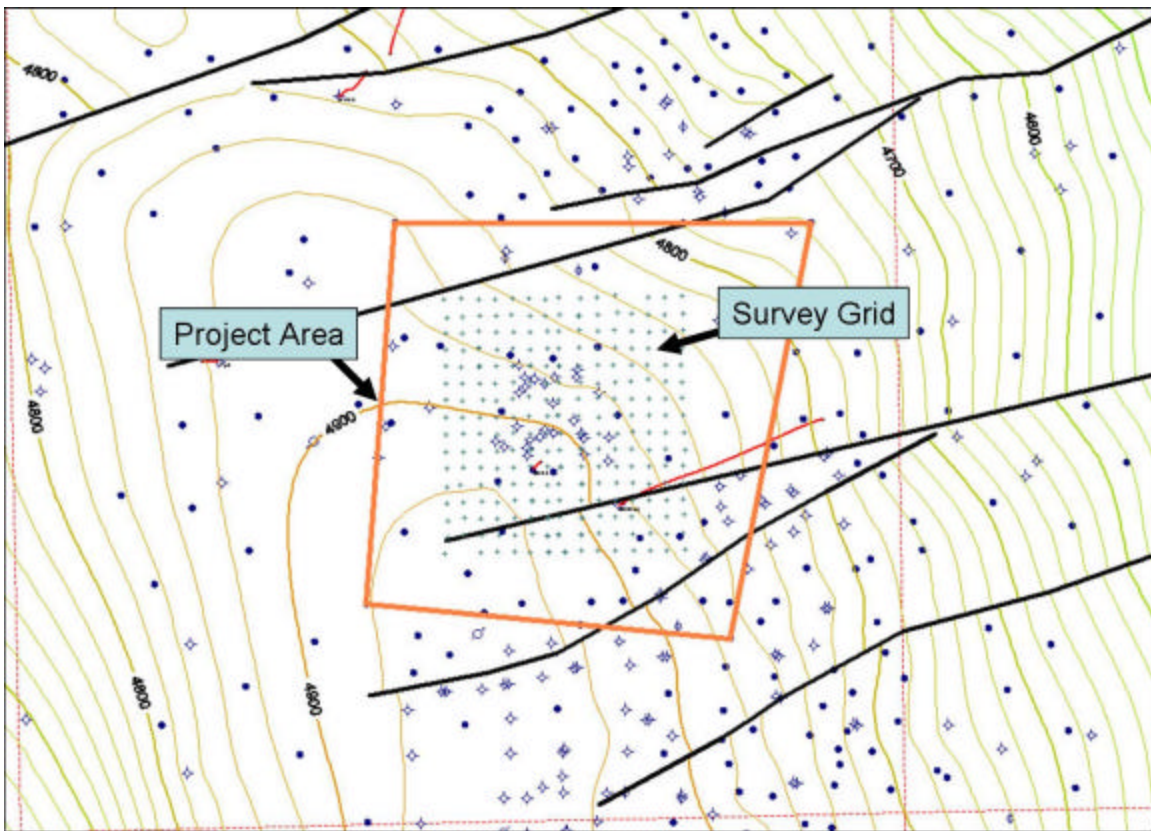


Figure 5. Map showing the geologic structure on the top of the Upper Shannon reservoir on the Teapot Dome Anticline surrounding the project area. The area within the survey grid is relatively unfaulted.

Within the project area, the combined upper and lower Shannon sandstone interval is approximately 160-feet thick (figure 6). Although the thickness is relatively constant throughout the field, there is a slight thinning of the Shannon on the crest of the anticline. The Upper Shannon is around 87-feet thick within the project area (figure 7). Of that, only about 30 to 40 feet of sand are considered reservoir rock. The upper Shannon thickens gradually to the east. The lower Shannon is approximately 75-feet thick within the project area (figure 8) and similarly, only the upper 30 to 40 feet are of reservoir quality. The thickness of the Lower Shannon remains fairly uniform within the project area. The overall trend of the Lower Shannon shows that the unit gradually thins towards the east of the field.



Figure 6. Isochore map showing the combined thickness of the upper and lower Shannon Sandstone members of the Steele Shale formation.

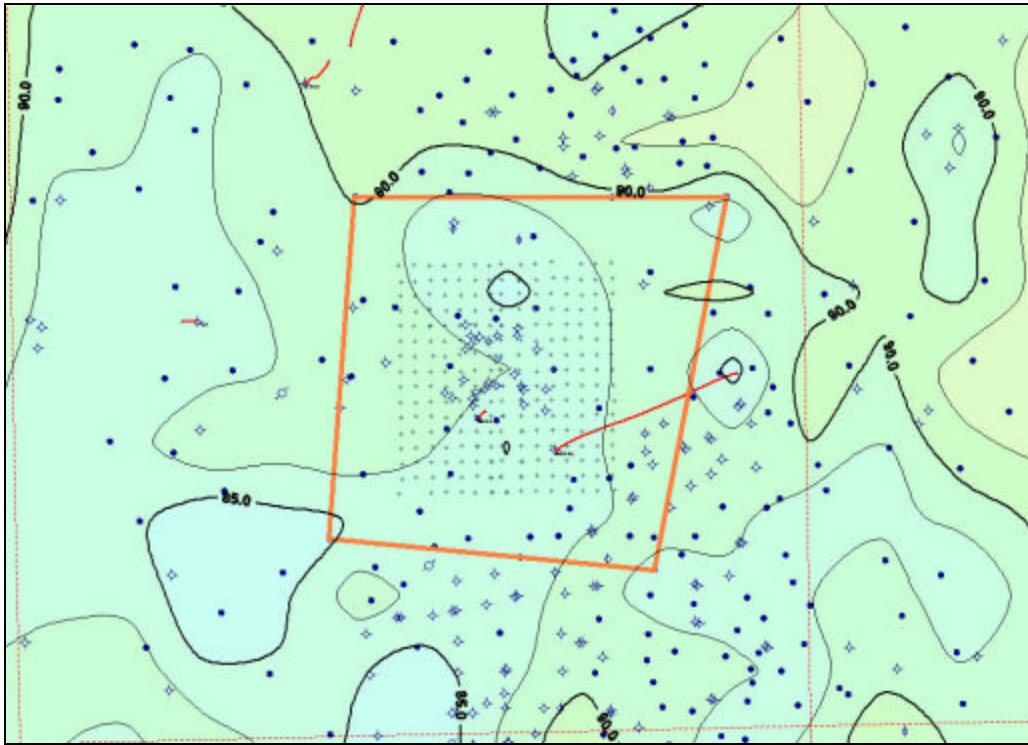


Figure 7. Isochore map showing the thickness of the Upper Shannon Sandstone.

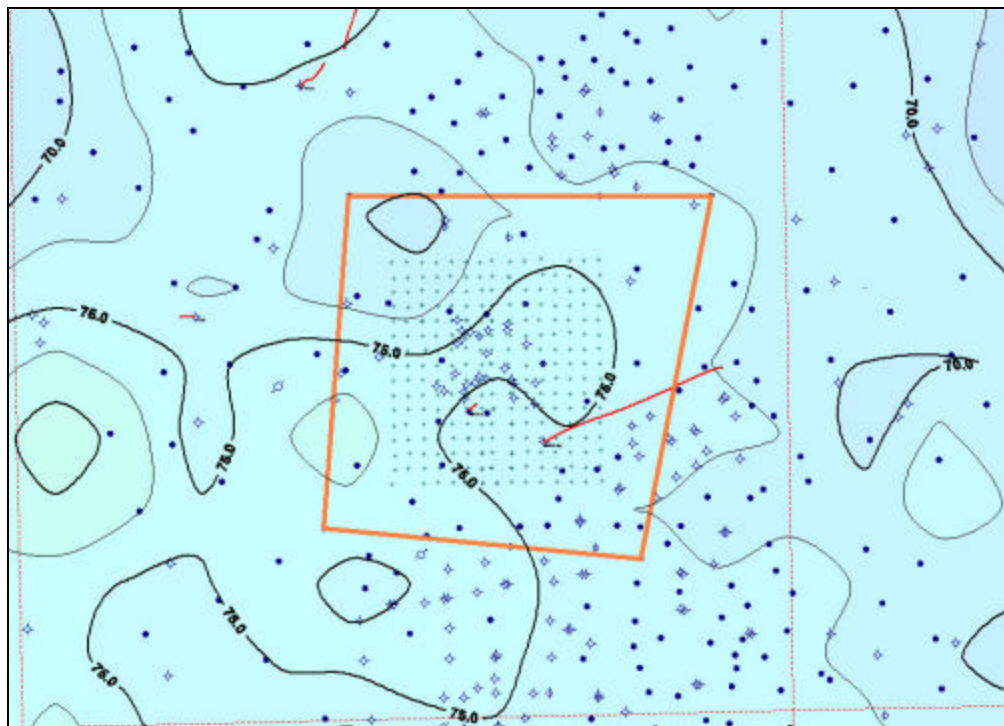


Figure 8. Isochore map showing the thickness of the Lower Shannon Sandstone. The Lower Shannon is thicker within the project area than it is off the eastern flank of the anticline.

INTRODUCTION TO AQUATRACK AND METHODOLOGY

The objective of this project was to demonstrate the capability of Willowstick, LLC, to map and delineate relative water saturation in an oil producing formation using their patented AquaTrack geophysical technology. This technology uses Controlled Source - Frequency Domain Magnetics (CS-FDM). AquaTrack utilizes a low voltage, low amperage audio frequency electrical current to energize the formation water of interest. Electrodes are placed in strategic locations to facilitate contact with the formation water. The induced electrical current follows the best available conductor through the subsurface and gets concentrated in highly water-saturated zones. The electrical current concentrates to a greater extent within a given porosity or level of saturation, in areas of higher total dissolved solids (TDS) or higher ion content between the energizing electrodes. As the electrical current takes various paths through the area of investigation, it creates a magnetic field (Biot-Savart law) characteristic of the injected electrical current. This unique magnetic field is identified and surveyed from the surface using highly sensitive equipment. The locations of field measurement stations are identified using a Global Positioning System (GPS) unit and then recorded in a data logger along with the magnetic field readings. The measured magnetic field data are then processed, contoured, and interpreted in conjunction with other hydrogeologic data, resulting in enhanced definition of the extent of subsurface water saturation in the vicinity of the study area.

Equipment

The equipment used to measure the magnetic field induced by electrical current flowing through the groundwater includes: three magnetic sensors oriented in the orthogonal directions (x, y, and z); a Campbell Scientific CR1000 data logger used to collect, filter and process the sensor data; a Global Positioning System (GPS) instrument used to spatially define the field measurements; and a Windows-based, Allegro CE handheld computer to couple and store the GPS data with the magnetic field data. This equipment is mounted on a surveyor's pole and hand carried to each measuring station (Figure 9).



Figure 9. Taking measurements of the magnetic fields generated by current induced into the subsurface Shannon formation.

Data Collection

The AquaTrack instrument measures induced voltage across the three sensors corresponding to the strength of the magnetic field at each measurement station. For quality control, a base station is established within the survey area, and base station measurements are taken at the beginning, midpoint and end of each field day. The base data are used to identify any changes in the background magnetic field and/or diurnal drift. The magnetic field measurements collected during the survey are then normalized to compensate for these factors.

To ensure data quality at each measurement station, the Campbell Scientific CR1000 calculates the 400-Hertz magnetic field strength (after Fast Fourier Transform, statistical

analysis, and stacking of sixteen separate readings) and compares the signal to the background or ambient magnetic field strength at numerous frequencies. These data are compared to pre-determined signal quality criteria and signal to noise ratio criteria to establish data quality and repeatability.

Prior to initiating the fieldwork, the antenna array(s), electrode placement, and grid measurement stations and intervals are all determined and submitted to the client. The antenna/electrode configurations and measurement grid are established to optimize the data collected and to define the areas of high water saturation and/or elevated TDS groundwater throughout the survey area.

The antenna arrays are wires and electrodes used to complete the transmitter circuit. Depending upon the given site conditions, one or more sets of antenna configurations may be used. In all cases where possible, antenna wires were routed around the survey area and far enough away to have little effect on the readings. Electrode placement was based on optimizing contact with the targeted formation water as well as the total area to be surveyed. Measurement stations and density of measurement stations were based on specific site requirements.

Data Reduction and Interpretation

The field data are processed and corrected to account for distance from the source electrode, to reduce the effects of antenna interference and to remove the effects caused by ambient and shallow subsurface sources, if necessary. The processed and corrected data (reduced data) are used to generate contour maps of the induced magnetic field. Relative changes in the magnitude and/or gradient of the horizontal and vertical fields, rather than the absolute magnitude of the induced field, are used for making interpretations. The results are presented in map view to show areas of highest formation water concentration (assuming approximately homogeneous ion content within the groundwater being mapped), or areas of elevated formation water TDS (assuming homogeneous water content and lower background TDS).

The magnetic field observed at the surface, due to subsurface electrical current flow in groundwater, is dominated by a horizontal component; therefore, interpretations of subsurface saturation are based primarily on the horizontal magnetic field readings. Vertical magnetic field gradients can supplement the groundwater characterization by helping to identify structural edges that influence the hydrology. However, the vertical data also reflects near-surface features more strongly than the horizontal component (including the influence from the antenna and electrodes), so in most cases the vertical data is used less in the final interpretation than the horizontal field data.

The AquaTrack data are correlated with known geologic and hydrologic information to provide the best possible insight to groundwater location.

Procedures

Once the field data has been reduced, natural and manmade interferences must then be accounted for. It is preferred that manmade interferences are known prior to the survey. If unknown, these interferences can often be recognized by their specific signature signals in the data, especially by analyzing the vertical field data in conjunction with the horizontal data. Once recognized, these features can be accounted for, corrected, and/or removed from the final reduced data set. Some of these interferences include:

- Ground noise from 60 Hz signal (from nearby electrical generating equipment, overhead or buried power lines, any subsurface cathodic protection of pipes, etc.)
- Cultural features (buried pipes, steel cased wells, etc.)
- Atmospheric noise (diurnal magnetic variations, electrical storms, solar activity and related magnetosphere activity, etc.)

These various features specific to an individual site need to be identified, reported and portrayed.

Presentation

The reduced data, as well as known magnetic interferences, are then presented on contour maps or in profile plots. Any identified cultural features relative to the survey are also shown to aid in interpretation. Finally, any additional geological and hydrogeological information pertinent to the study is also integrated, resulting in a complete and comprehensive interpretation of the groundwater system being investigated.

SCOPE OF SURVEY

The AquaTrack demonstration project was focused in an area of recent water flooding activities in the Shannon Sandstone (300-400 feet deep). This area contains a very dense array of wells, many of which were used during steamflood and fireflood operations in the late 1980's and have since been plugged, abandoned, and the surface area reclaimed (figure 10). The area of investigation covers a relatively small area in comparison to other AquaTrack geophysical investigations performed by Willowstick. The total study area included an overall area of about 1380 feet by 1500 feet, or 48 acres.

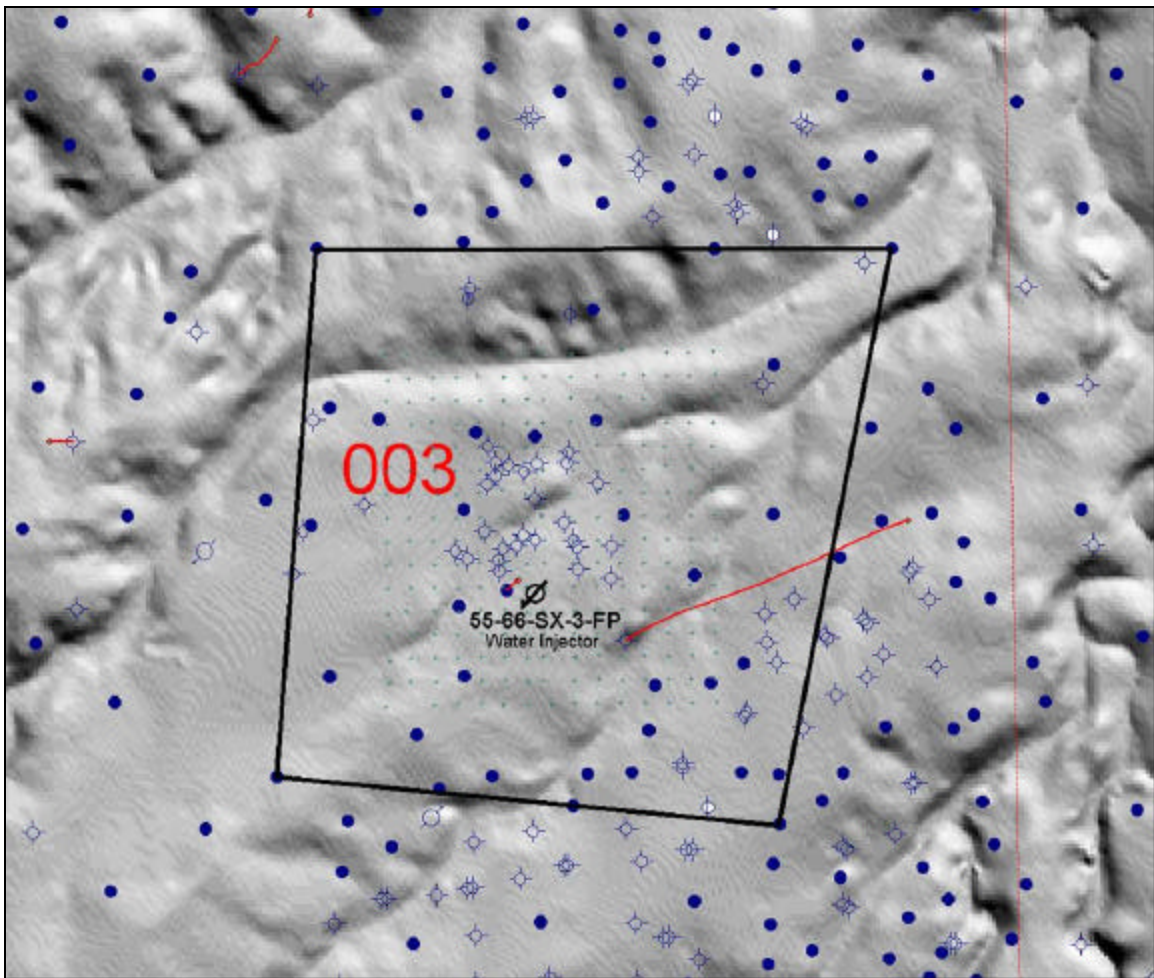


Figure 10. Map showing wells within the AquaTrack survey area (the outlined area). The 55-66-SX-3 well has been recently used as an injector well in a small-scale waterflood in the Teapot Dome field.

Survey Layout

Two horizontal dipole antenna/electrode configurations were employed to energize the subsurface study area for the purpose of conducting the AquaTrack geophysical investigation (Figures 11 and 12). Figure 11 portrays the west antenna/electrode configuration and utilized the same injection well (well 55-66-SX-3) and production wells 43-SX-3 and 47-12-SX-3. Figure 12 portrays the east antenna/electrode configuration which utilized injection well 55-66-SX-3 and production wells 83-SX-3 and 77-SX-3. These two antenna/electrode configurations were selected to energize the targeted formation in order to investigate how water, injected into the formation at the injection well, flowed radially out through the oil laden formation and eventually toward the production wells in which the return electrodes were placed. The east and west surveys included an overlap in the two investigations for comparison purposes and for matching or joining the two surveys together.

Table 1 shows the depths of emplacement of the electrodes in each well. The injector well 55-66-SX-3 had two source electrodes emplaced at different depths, one in the Upper Shannon, and one in the Lower Shannon. The receiver electrodes were emplaced in, or as near as possible to, Lower Shannon depths in the four corner wells. The fluid level in each of the corner wells at the time of emplacement was below the perforations in the Upper Shannon zone, but above the Lower Shannon. Therefore current induced into the formation would have mostly focused into the Lower Shannon reservoir. This was verified by inducing a current into the Upper Shannon at the injector and collecting measurements of the magnetic field. The process was repeated injecting current into the Lower Shannon and taking measurements. The results of the two fields were compared with near identical results. This suggested that current was taking the path of least resistance through the Lower Shannon reservoir. The current induced into the upper electrode followed the steel casing into the Lower Shannon and on to the receiving electrodes.

Well #	Depth of Electrode (feet)	Upper Shannon Perforation Depth Intervals	Lower Shannon Perforation Depth Intervals	Top of U. Shannon (ft from GL)	Top of L. Shannon (ft from GL)
55-66-SX-3 (injector)	281-293 (upper) 348-360 (lower)	279-282,286-287,291,294-301, 305-307,312-315,320-323	355-370, 373-388, 336-355(out of zone)	269	351
43-SX-3	381-393	287-291,297-303,330	371-383, 389, 391	287	369
47-12-SX-3	388-400	308-360	386-417	296	375
83-SX-3	399-411	369-373,377-389,397	451-459,463-475	364	466
77-S-3	368-380	306-356	387-417	304	387

Table 1. Table showing wells used in study along with depth of electrode emplacement, perforation intervals, and formation top depths.

It should be noted that the four production wells utilized in the investigation for energizing electrodes are located outside the survey grid. It is important that the electrodes establish groundwater contact outside the study area wherever possible. Note also that the antenna wire connecting the injection well electrode with the production well electrodes (Figures 11 and 12) is routed out and around the survey area. The reason for this is because very near the antenna and energized electrodes, the magnetic field is so strong that no other discernable information can normally be obtained. A physical example of this effect would be like looking at the sun. The sun is too bright and domineering to see any distinguishable features in or immediately around it. However, as one looks away from the sun, things become very clear and distinguishable. This is the concept behind the antenna and electrode placement. Given the area of investigation, the antenna/electrode configurations utilized in this investigation were designed to utilize the most advantageous locations available at the site in order to optimize current flow through the targeted area and obtain quality data.

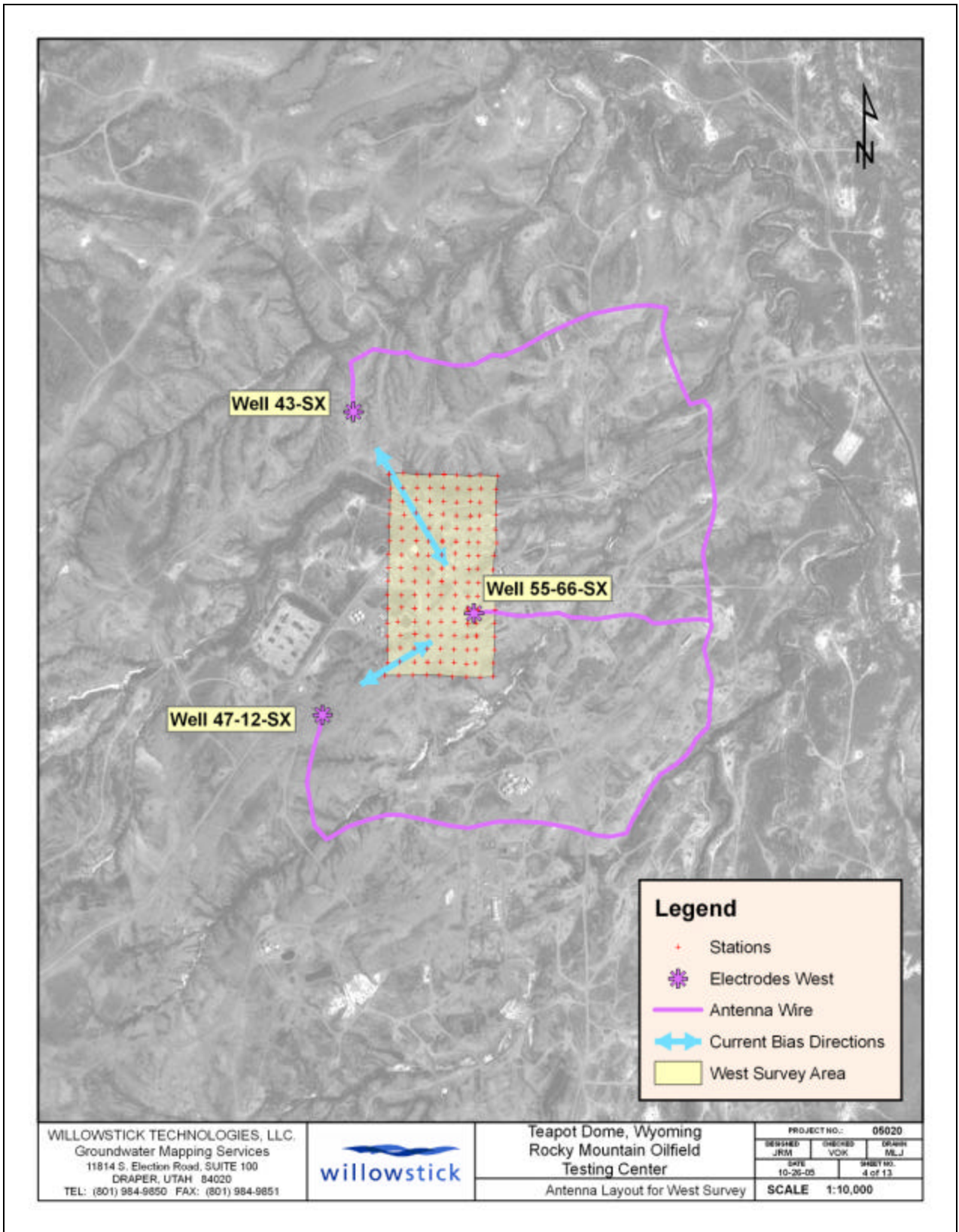


Figure 11. Antenna layout for west survey.

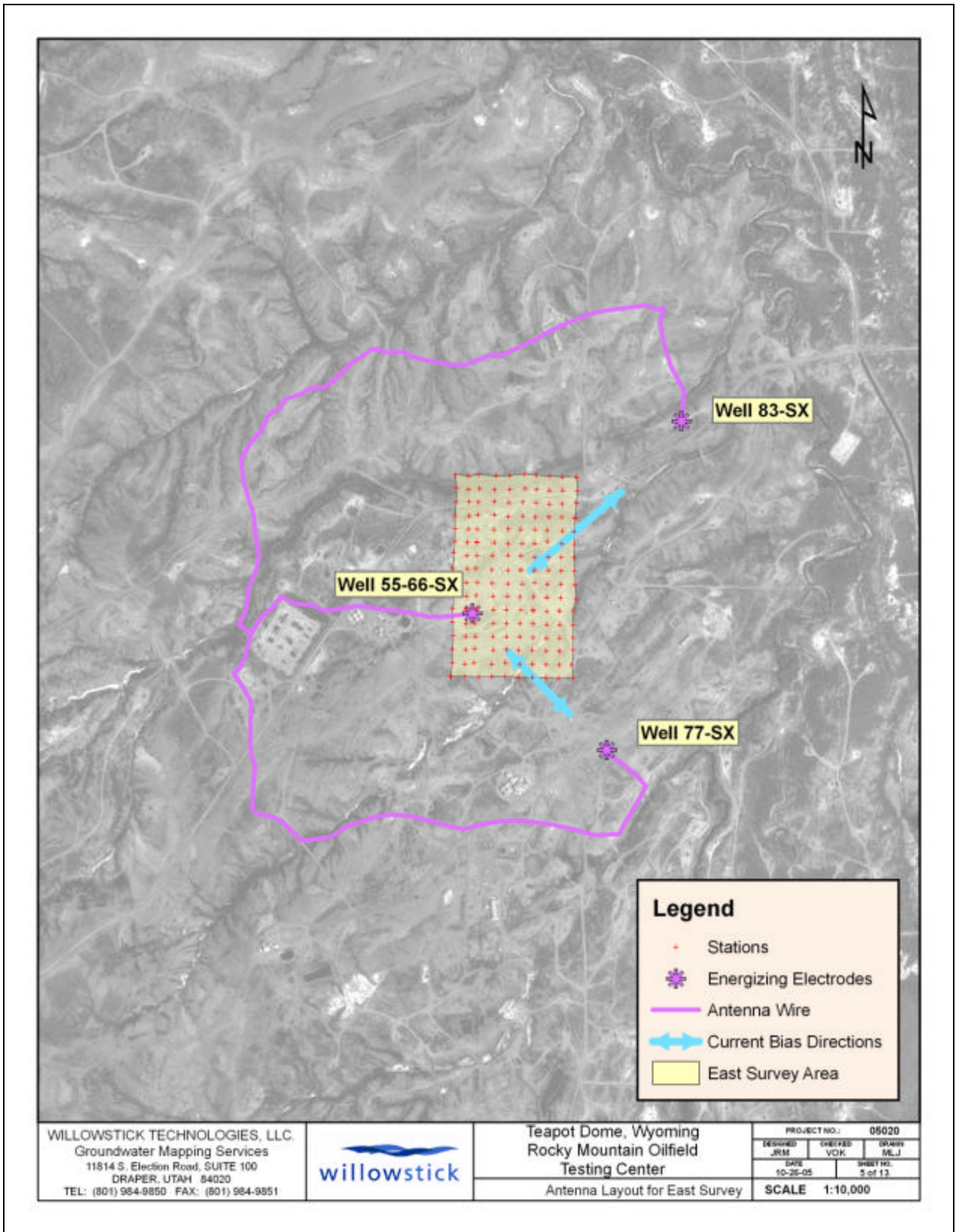


Figure 12. Antenna layout for east survey.

The overall approach to the fieldwork included inducing an electrical current out from the injection well toward the return electrodes located in the production wells to determine where electrical current flows and concentrates in the subsurface. A 2-amp, 110-volt, AC current with a specific signature frequency (400 Hz) was applied to the electrodes located in the paired wells. The resulting alternating current, flowing between the paired electrodes, followed the preferential flow paths through the ground. As the electrical current flowed through the subsurface, it generated a recognizable magnetic field that was measured from the surface of the ground.

Approximately 160 magnetic field measurements were recorded for each antenna/electrode configuration over the study area, yielding just over 320 field measurements for the two survey configurations. The station locations are denoted as small “+” signs or crosses on the figures and maps included with this report. These measurement stations were established on lines spaced 30 meters apart with measurements taken on each line at 30 meter intervals, resulting in a 30 meter by 30 meter spaced grid covering the entire 48-acre study site. The X, Y, and Z coordinates of each measurement station were recorded as part of the field work. These station locations are critical to data processing and interpretation. Moreover, in the area that overlapped between the two surveys, these exact locations or measurement stations were occupied twice, once for each survey.

The measurement pattern or grid configuration proposed for this demonstration project was proposed and accepted to provide sufficient detail and resolution for the depth of the formation while at the same time optimizing funds and time available for the investigation and to adequately cover the study area. It should be noted that the stratigraphic section between the surface and the targeted oil-laden formation consists of relatively dry sedimentary deposits which conduct very little electrical current. It was originally postulated that the path of least electrical resistance between the strategically placed electrodes in the injection well and production wells was likely the targeted oil-laden Shannon Formation. This will be discussed in more detail in the following section of this report.

The processed and contoured data measured and recorded from the AquaTrack geophysical investigative fieldwork showed significant changes and trends in the magnetic field created from the signature current flowing through the ground. The AquaTrack technology very effectively identified the areas of highest electrical conductance and concentration through the study area.

RESULTS

Field Data Reduction and Normalization

The analysis of the AquaTrack geophysical investigation entailed reduction of field data to a processed and corrected (reduced) data set ready for interpretation. The data quality was confirmed by examining the signal repeatability and the signal to noise ratios. The data were also subject to a number of comparisons and corrections for atmospheric noise (diurnal magnetic variations, magnetosphere activity, etc.) and ground noises (60 hertz power grid) as well as the effects induced by the electrodes and antenna (Appendix A).

Horizontal Magnetic Field Maps

The horizontal field maps or footprint maps of the conductive highs and lows are provided in Figures 13 and 14 (west and east surveys, respectively). The dark blue shading indicates conductive highs and the light blue shading indicates conductive lows beneath the study area. In the most general interpretation, these highs and lows can be viewed as areas of high or low groundwater saturation.

The data suggests that within the study area of the Shannon Sandstone, three major hydrologic boundaries (labeled 1, 2, and 3) exist in a north-south orientation that separate and define four hydrologic-related zones. Boundaries 1 and 2 are labeled in Figure 13; the same Boundary 2 is identified in Figure 14, as well as a third boundary.

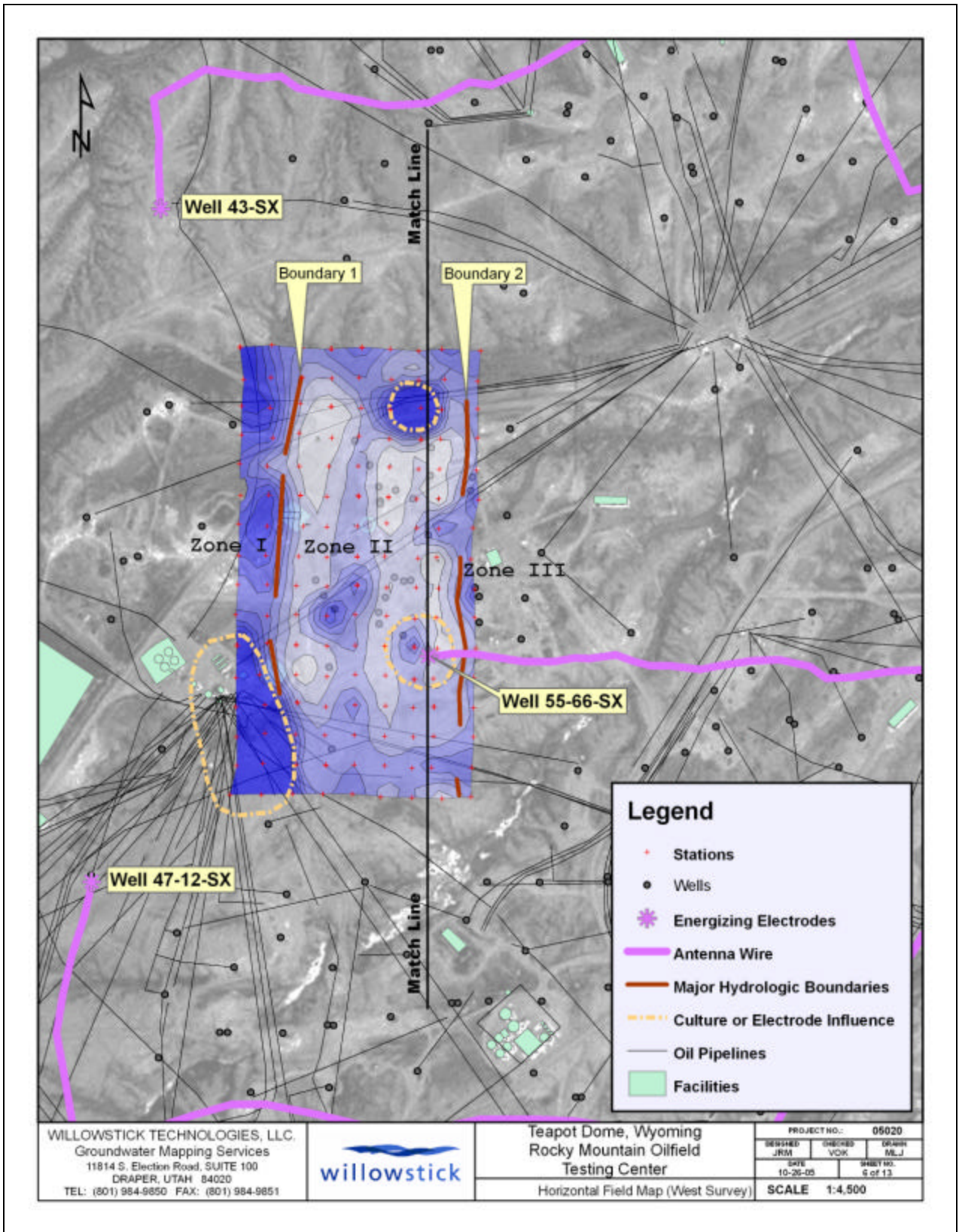


Figure 13. Horizontal field map for the western survey.

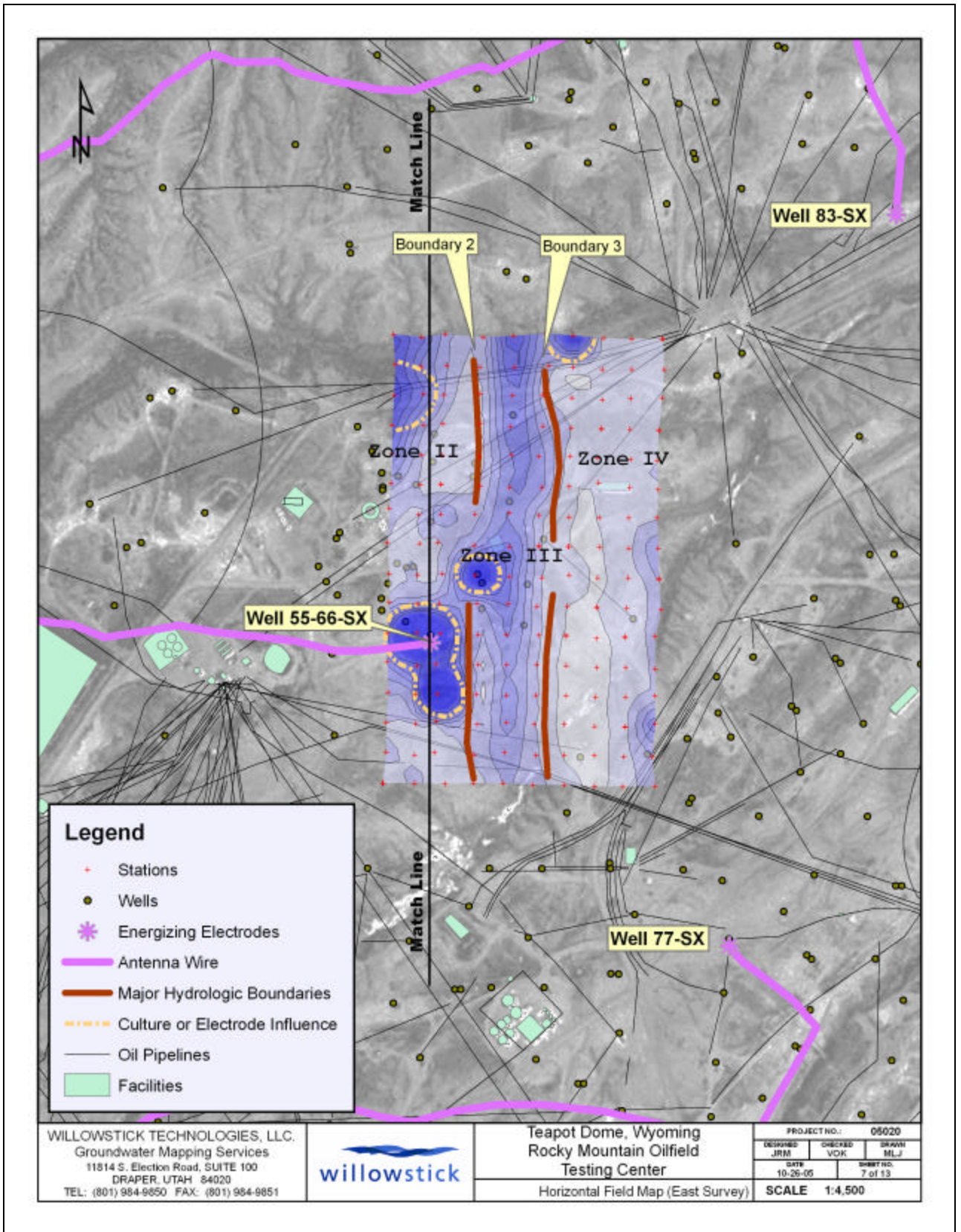


Figure 14. Horizontal field map for the eastern survey.

The four hydrologic zones appear to represent different depositional environments within the formation that influence the way water migrates when it is injected into the formation. Zones I and III are the strongest zones of saturation where most of the electrical current concentrates. Zone II comprises a mix of high and low conductive areas or probable groundwater saturation in a pattern similar to a braided channel. On the east side of Zone III, a hydrologic barrier or aquitard (Boundary 3) largely blocks current flow to the east; and in Zone IV to the east, the low conductivity suggests that little if any water saturation exists in this zone. The western extent of conductive Zone II and the eastern extent of non-conductive Zone IV both lie outside the survey area and are therefore not defined.

Aside from the isolated anomalies caused by electrode and/or cultural effects, the central overlapping portion of the east and west surveys show almost identical results with very similar conductive highs and lows. They both identify a boundary separating Zones II and III (labeled as Boundary 2). The correlations can be seen in Figure 15 where the two survey maps are joined together. The match lines shown in Figures 13 and 14 indicate where the maps were brought together. They run directly over the central energizing electrode in Well 55-66-SX-3.

From the merged picture in Figure 15, it is apparent that the central overlapping part of the survey matches up very closely with nearly the same conductive highs and lows. This complementary information between the two data sets generates a high level of confidence with the antenna/electrode configurations and the measured data.

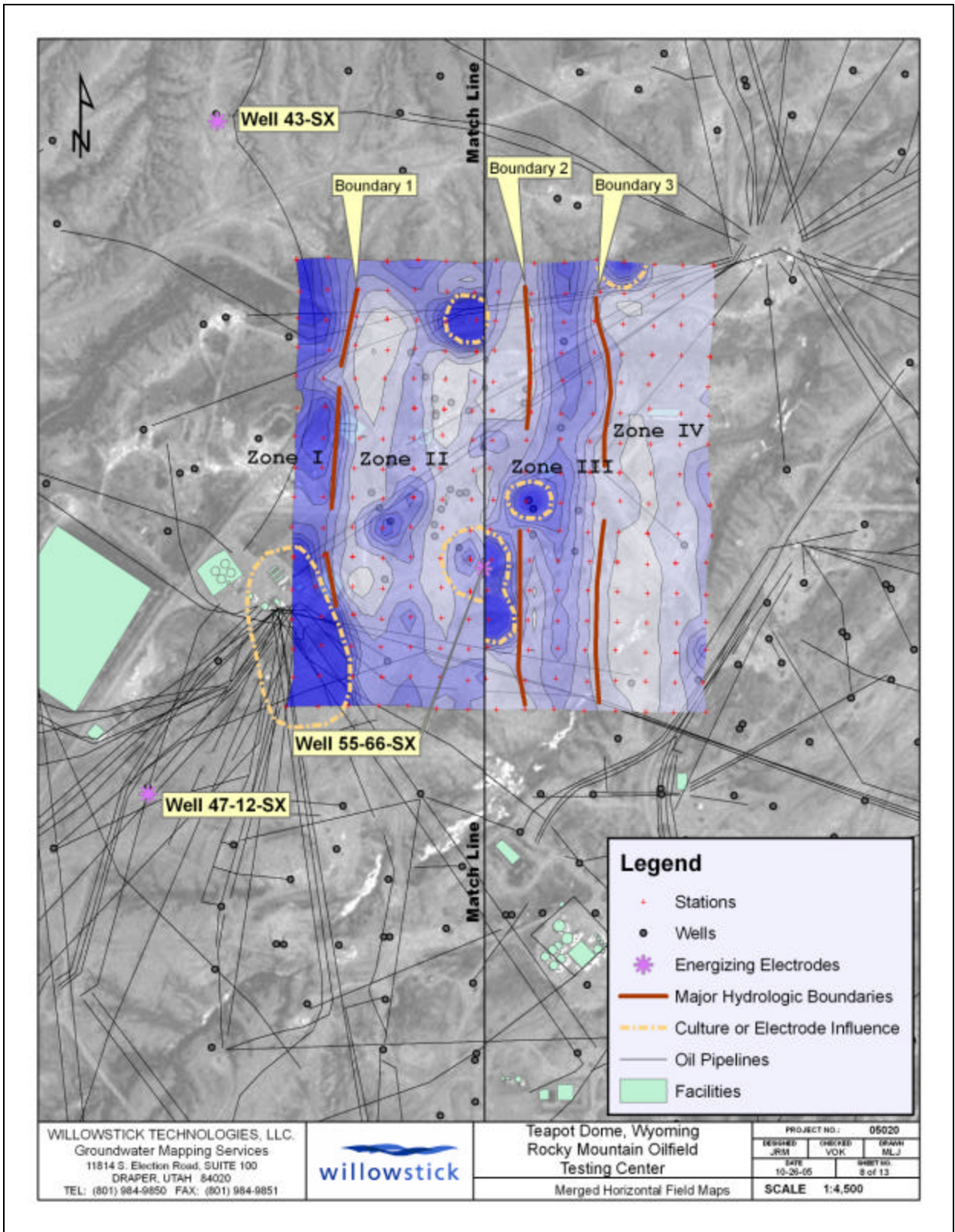


Figure 15. Merged horizontal field maps (the match line shows where figures 13 and 14 were merged together).

A number of anomalies are noted in Figures 13, 14, and 15 as being related to cultural or electrode influence. These are isolated anomalies that are considered separately and that do not affect the overall interpretation of subsurface water saturation. Some of these cultural influences may be caused by steel-cased wells that happened to intersect the subsurface zones of highest electrical current saturation in the formation.

The cultural influence noted in the southwest corner of the survey is clearly caused by the numerous pipelines and adjacent facilities in this area. The north central bulls-eye anomaly in Zone II shows a classic magnetic signature (see vertical magnetic field data as well) indicating that it is caused by some man-made (cultural) object located near the surface. The anomaly located in Zone III to the northeast of well 55-66-SX-3 is most likely caused by a significant amount of electrical current finding access into the steel cased well located at this spot. Another cultural anomaly is located on the northern edge in Zone IV. These anomalies in general reflect near-surface features and should be considered separately. Also, interpretations of each of these are supported by the anomalous signatures observed in the vertical data. Appendix A contains a discussion and maps identifying the cultural influence within the survey.

The particular anomaly around well 55-66-SX-3 is due to the energizing electrode. Note that the electrode influence around this well is much more pronounced in the east survey than in west survey. This is because removal of the electrode influence in the east survey did not improve the interpretation, and since its influence is very isolated it was left in the data without causing a problem.

DISCUSSION OF RESULTS

The merged horizontal magnetic field maps (figure 15) show that there is a distinct north-south trend of water saturation within the lower Shannon Sandstone. In order to confirm the results of the AquaTrack survey, production data was analyzed from wells within the survey area. Figure 16 shows water production at NPR-3 from October 2004 through October 2005. It is interesting to note that the map shows a general north-south trend for higher water production rates within the AquaTrack survey area. This general trend correlates well with the results of the AquaTrack survey. This trend also correlates with a known permeability trend at Teapot Dome. There are some discrepancies between the

maps, but it is believed that most of the discrepancies are due to the lack of accurate production monitoring and reporting of production data. RMOTC currently does not monitor individual well production in many of the Shannon wells. Instead, fluids produced from these wells flow into centralized collection systems where production output is monitored. The reported numbers for each well are estimates based on periodic testing of each well and the monthly output of each overall system. The hydrologic boundaries detected by AquaTrack do not show up in figure 16 due to the nature of the scattered data points. There is just not enough data from the wells to identify those boundaries. After careful examination of the map and the production trends however, there is a real possibility that the hydrologic boundaries do exist as demonstrated by the AquaTrack survey.

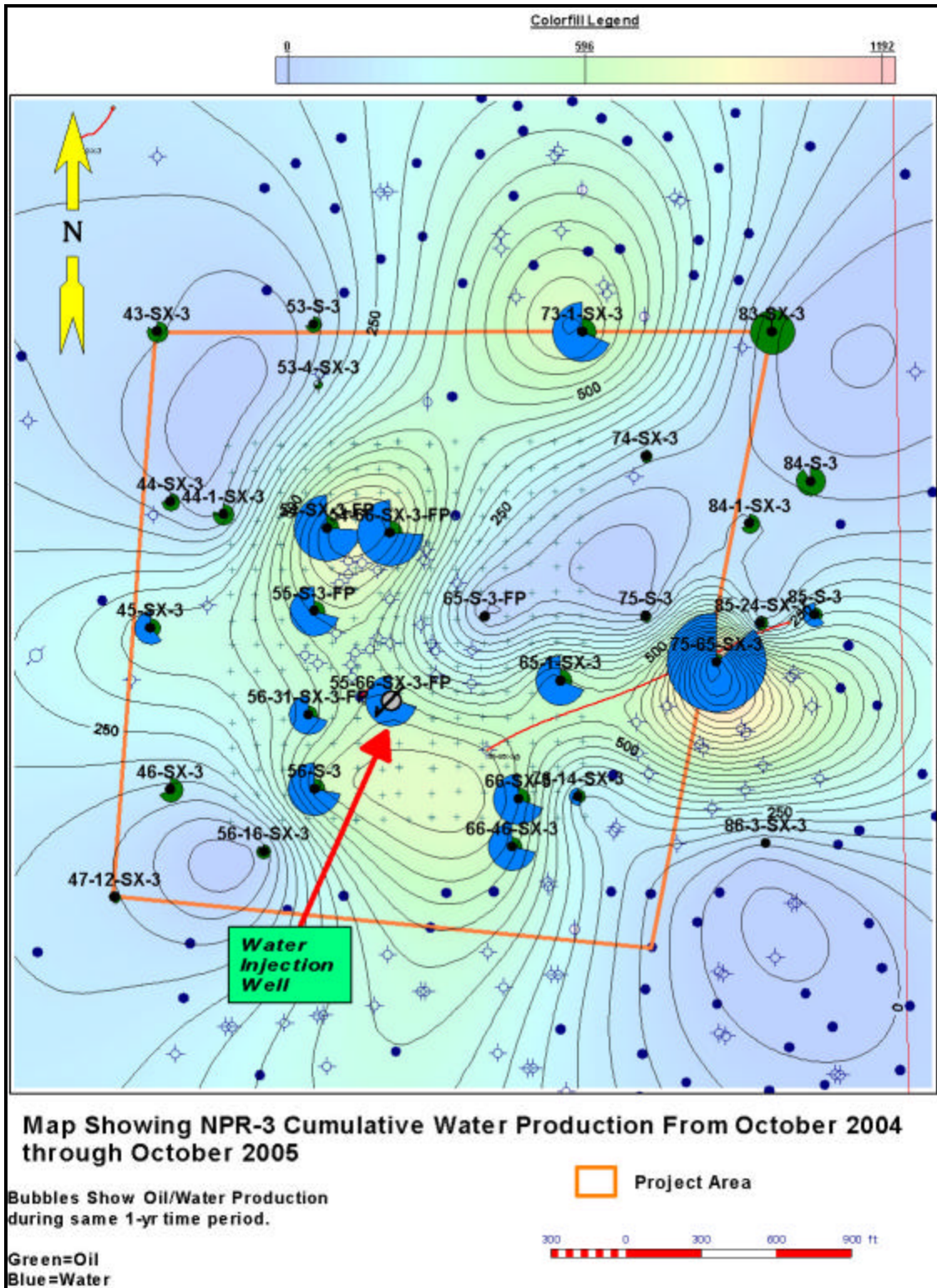


Figure 16. Map showing recent production data within the outlined project area. Water production trends indicate that the water is moving away from the injector well 55-66-SX-3 in mostly a north-south direction. This trend correlates well with the data presented from the AquaTrack survey conducted by Willowstick Technologies.

The explanation of the results of the survey may be due to geologic factors. Figure 17 shows the thickness of the Lower Shannon unit overlain by structural contours of the top of the Shannon Sandstone. Within the survey area, the Lower Shannon is somewhat thicker than the surrounding areas. The structure of the Shannon within the center of the survey, is dipping almost due north. Formation pressures are extremely low in the Shannon reservoir at NPR-3 ranging from 25 to 70 psi. This allows the water that is injected into the 55-66-SX-3 well to flow towards the north-northeast due to gravity. The water will follow the path of least resistance and highest permeability. Therefore, there must be a permeability trend that tracks north-south. This coincides with the depositional framework of the Shannon Sandstone.

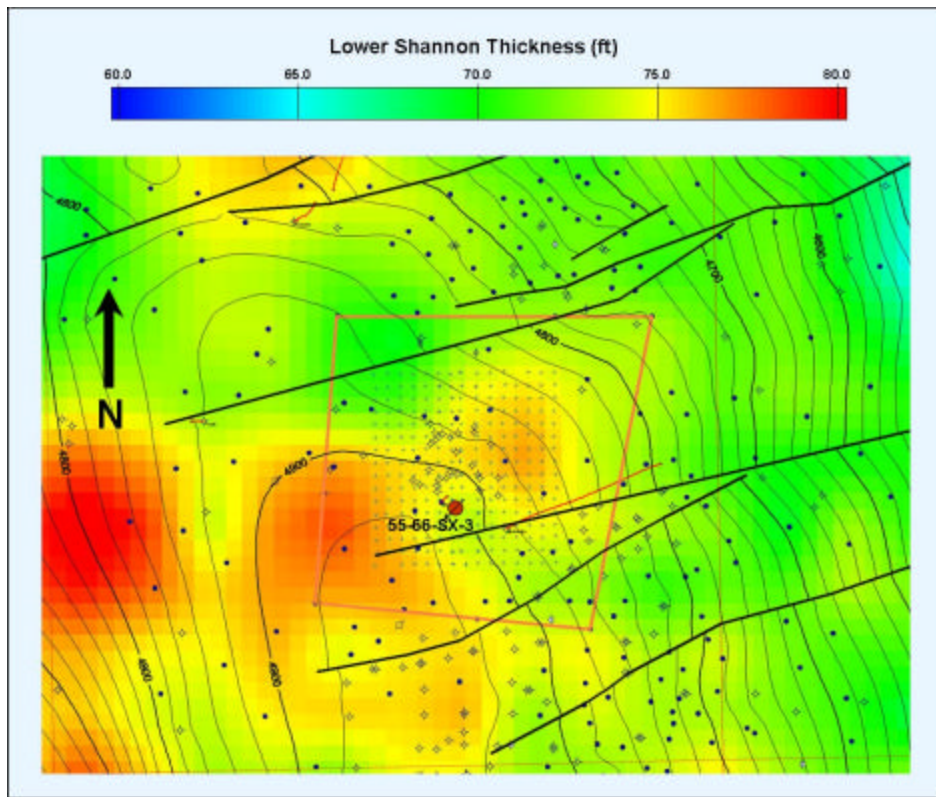


Figure 17. Color filled isochore map showing thickness of Lower Shannon overlain by the geologic structural map of the top of the Shannon Sandstone. Note that the eastern part of the survey area overlies a thicker interval of Lower Shannon.

CONCLUSIONS AND RECOMMENDATIONS

Willowstick, LLC has demonstrated that it can use AquaTrack technology to generate accurate and timely formation water characterization maps of an oil field from which informative decisions about future water flood and/or steam injection practices can be made to improve oil production. The data gathered during this demonstration project is consistent and reliable, and it can provide a valuable baseline map or model of the subsurface formation so that known data regarding the formation can be carefully studied and compared with the final AquaTrack results.

The horizontal magnetic field maps support and complement each other by providing sharp horizontal resolution that defines edges of saturation and vertical hydrologic boundaries or structure in the oil-laden Shannon Sandstone. The vertical magnetic field information supports the conceptual model of stray electrical current flow by identifying the anomalies where the current follows steel-cased wells or other strong conductors. The strong signal to noise ratios and low spheric background noise (Appendix A) further substantiate and confirm the high quality of the data.

The AquaTrack tool has proven its effectiveness in many groundwater applications, and this new investigation tool can provide critical insight as to how other reservoirs may be managed to improve and optimize oil production. The results of this demonstration project support the use of this relatively new technology to real world reservoir management projects. It is believed that the AquaTrack technology can provide information that will help better characterize water or steam flooding operations by better defining subsurface barriers, conductive zones, and overall hydrologic structure of the formation that influences water and/or steam flow condensate migration.

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APPENDIX A
ADDITIONAL MAPS AND COMMENTS

Vertical Magnetic Field Maps

Figures A1 and A2 show the vertical magnetic field data for the west and east surveys, respectively. Although interpretations of subsurface water saturation are primarily based on the horizontal magnetic field (which reflects horizontal current flow at depth), the vertical field data supports the interpretation in many ways. The vertical field information generally reflects electrical currents near the surface more than the horizontal field does, and each of the noted cultural anomalies are strongly present in the vertical field data. Also, electrode and antenna effects always produce a stronger signature in the vertical field data, and these can be seen most clearly in the east survey data (Figure A2) where these effects were not removed.

Signal to Noise Maps

Based on the signal to noise ratios (Figure A3), the quality of the data collected during the AquaTrack investigation was high in the majority of the survey area. The signal to noise is computed for each measurement as the ratio of the 400-Hertz signal to the mean ambient field noise, which is determined from a sampling of several other frequencies in the spectrum.

The areas of very poor signal are mostly confined to the far eastern edge of the survey in Zone IV where it was noted that that very little electrical current was able to flow (see Figure 14).

60 Hertz Signal Map

In some cases, the AquaTrack data can be influenced by noise generated by the regional power grid operating at 60 Hertz (i.e. overhead power lines, underground power lines, generators, motors, substations, etc.). Fortunately, the effects of this noise can be monitored and filtered out if necessary.

Figure A4 highlights the areas with a strong 60 Hertz signal—basically confined to the powerlines running through the survey area. The high 60 Hertz signals do not necessarily influence the AquaTrack signal as noise; in fact, only very minor influences are observed because the AquaTrack signal is tightly controlled at 400-Hertz and the nearest 60-Hertz

harmonic (possible noise source) in the electromagnetic spectrum is at 420 Hertz. This and other harmonics of 60 Hertz are monitored so that patterns of influence can be established and removed if needed.

Spheric Noise Map

The Spheric Noise Map, shown in Figure A5, demonstrates and delineates areas in the shallow subsurface that are influenced by ambient and surface sources of noise (i.e., electric storms, ionosphere activity, etc.). It can also be influenced by local cultural features. Values of the measured and monitored spheric noise were generally low and indicate that there was not significant interference from ambient magnetic fields, atmospheric fluctuations or other natural sources.

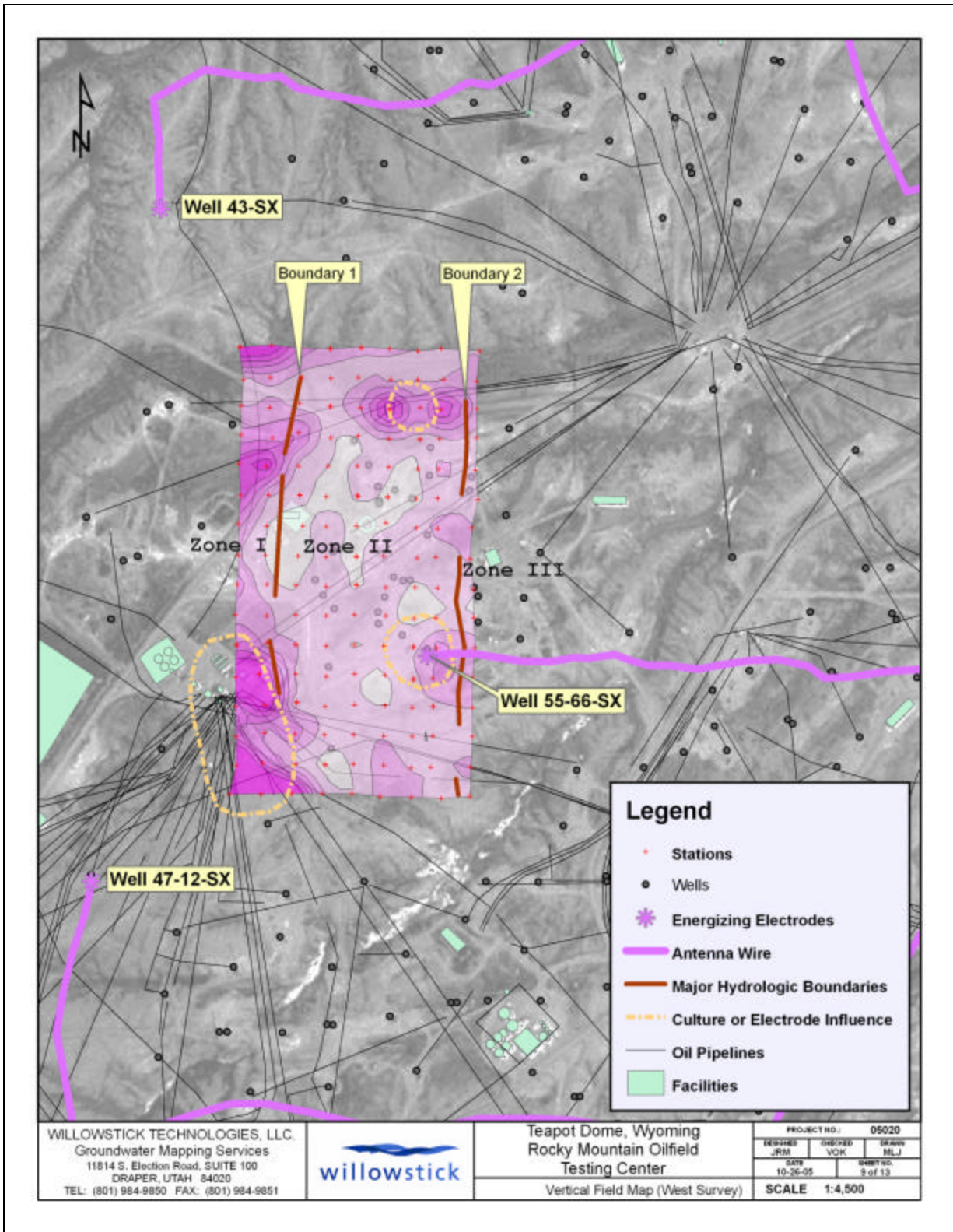


Figure A1. Map showing the vertical magnetic field from the western survey.

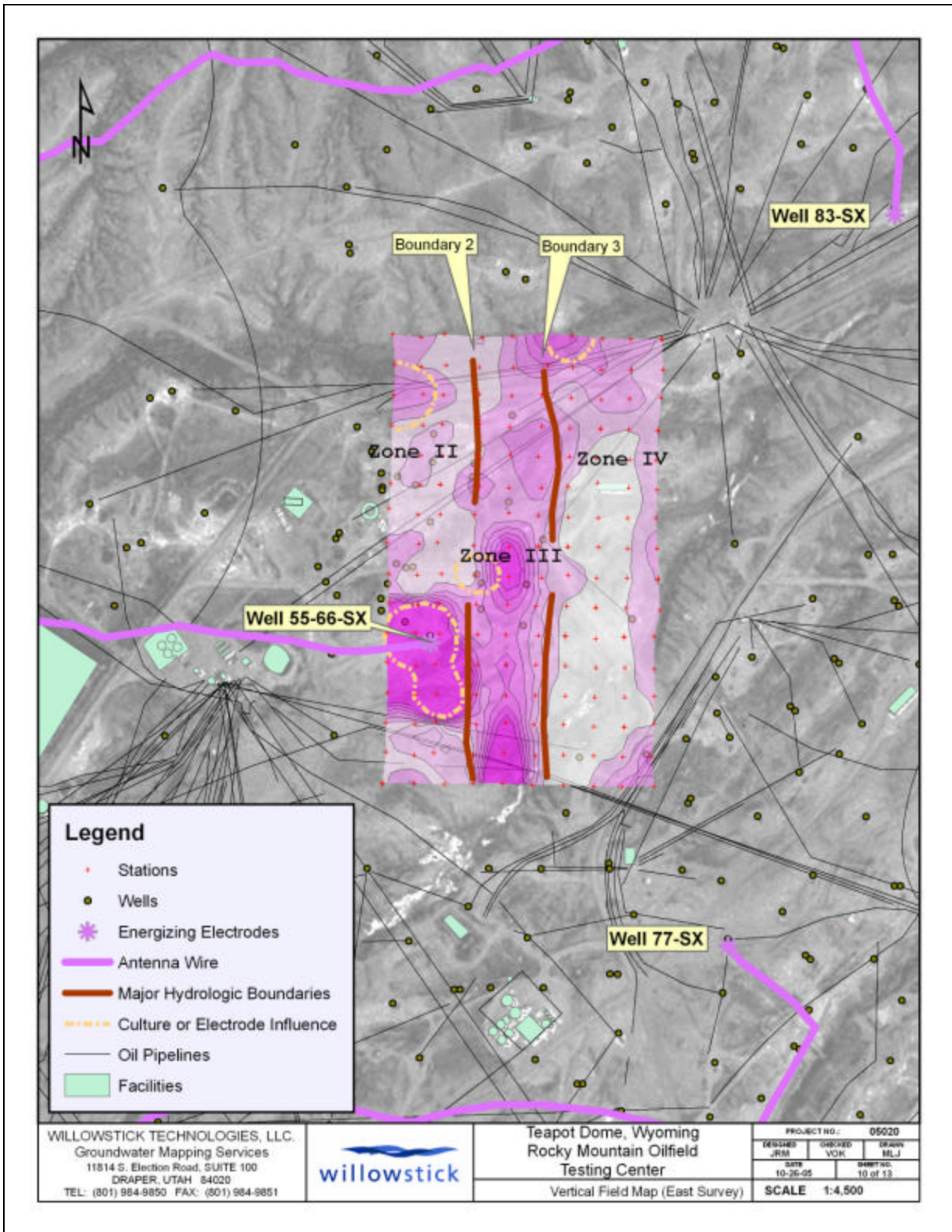


Figure A2. Map showing the vertical magnetic field from the eastern survey.

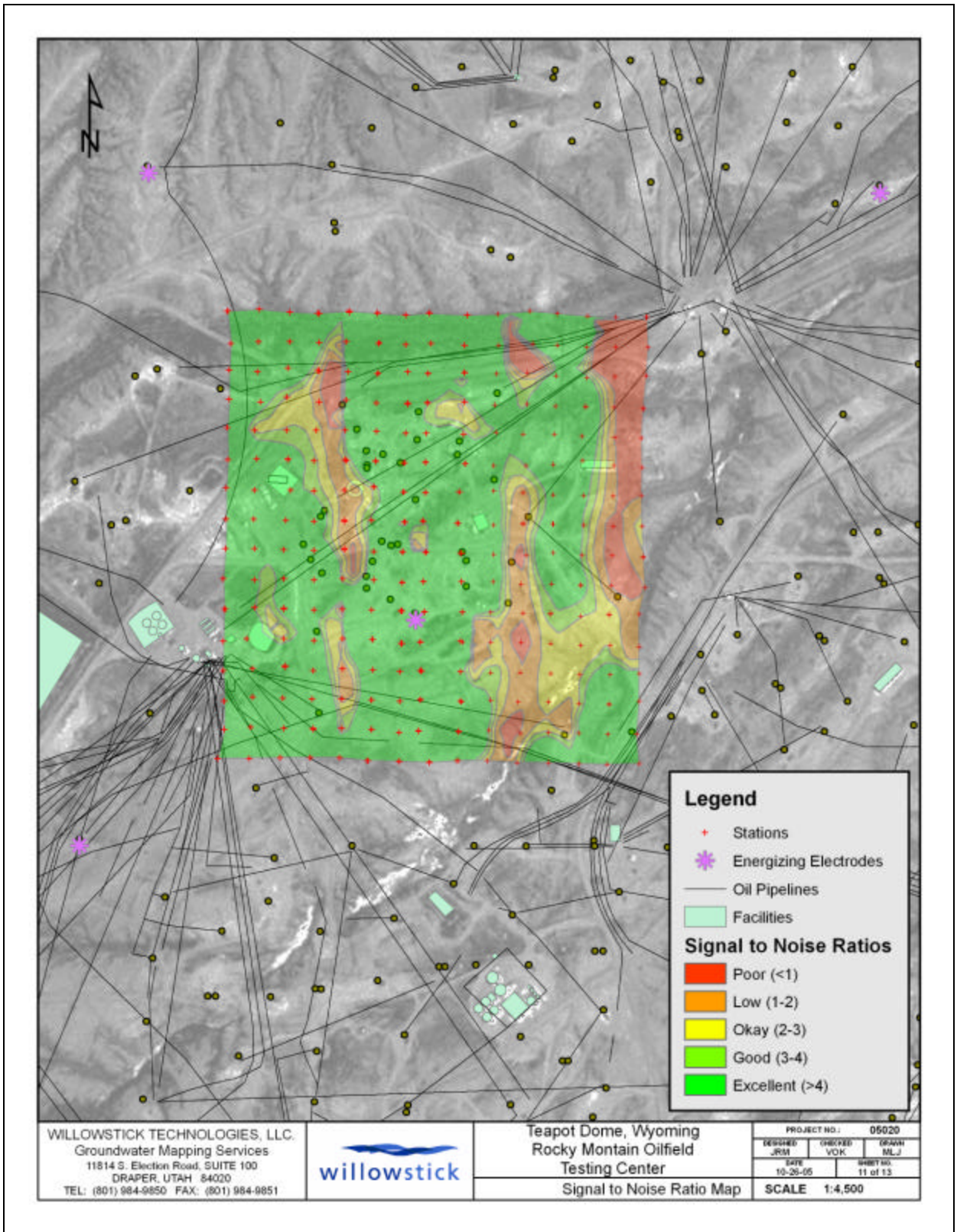


Figure A3. Map showing the signal to noise ratio.

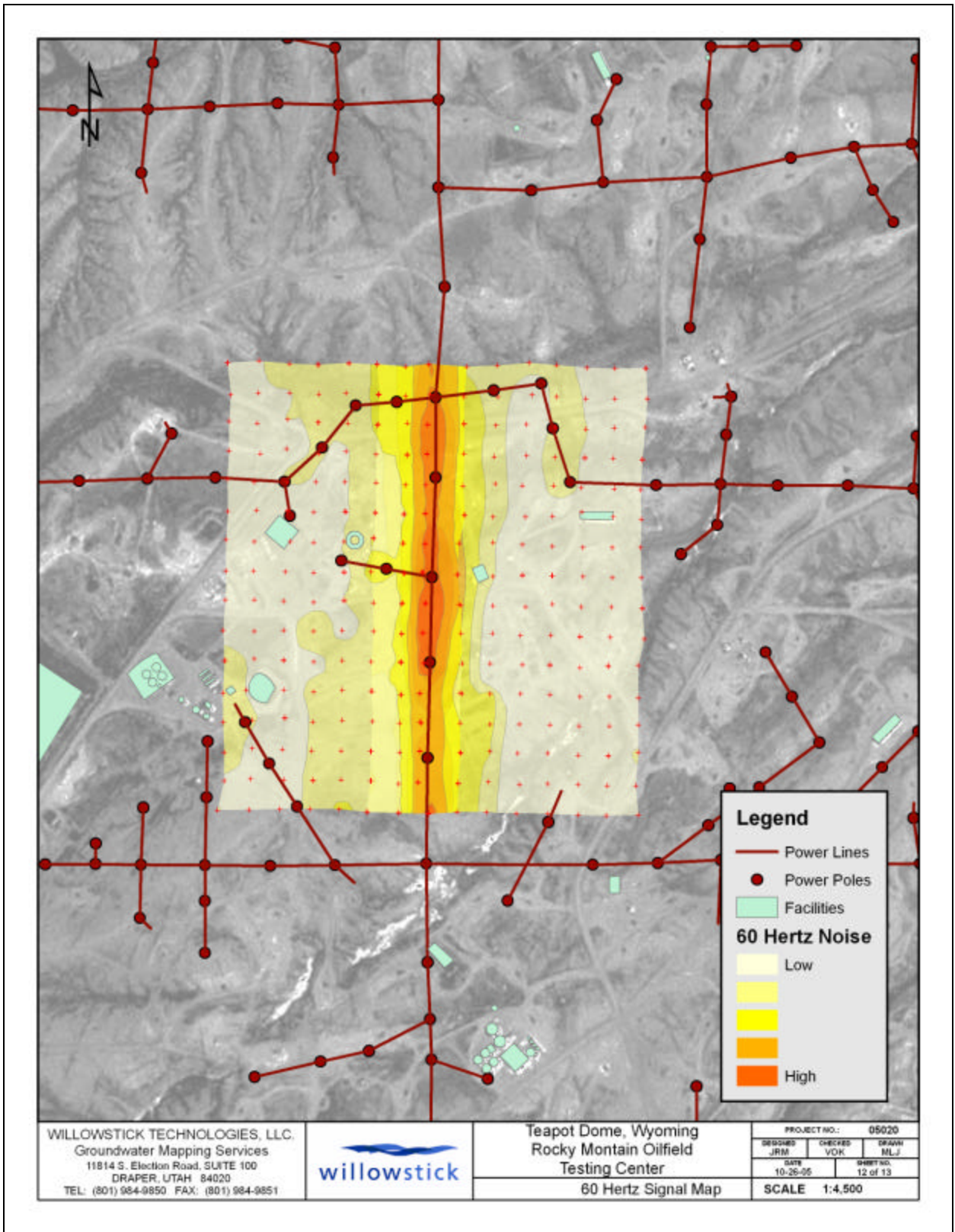


Figure A4. Map showing 60 Hertz signals detected during the AquaTrack survey.

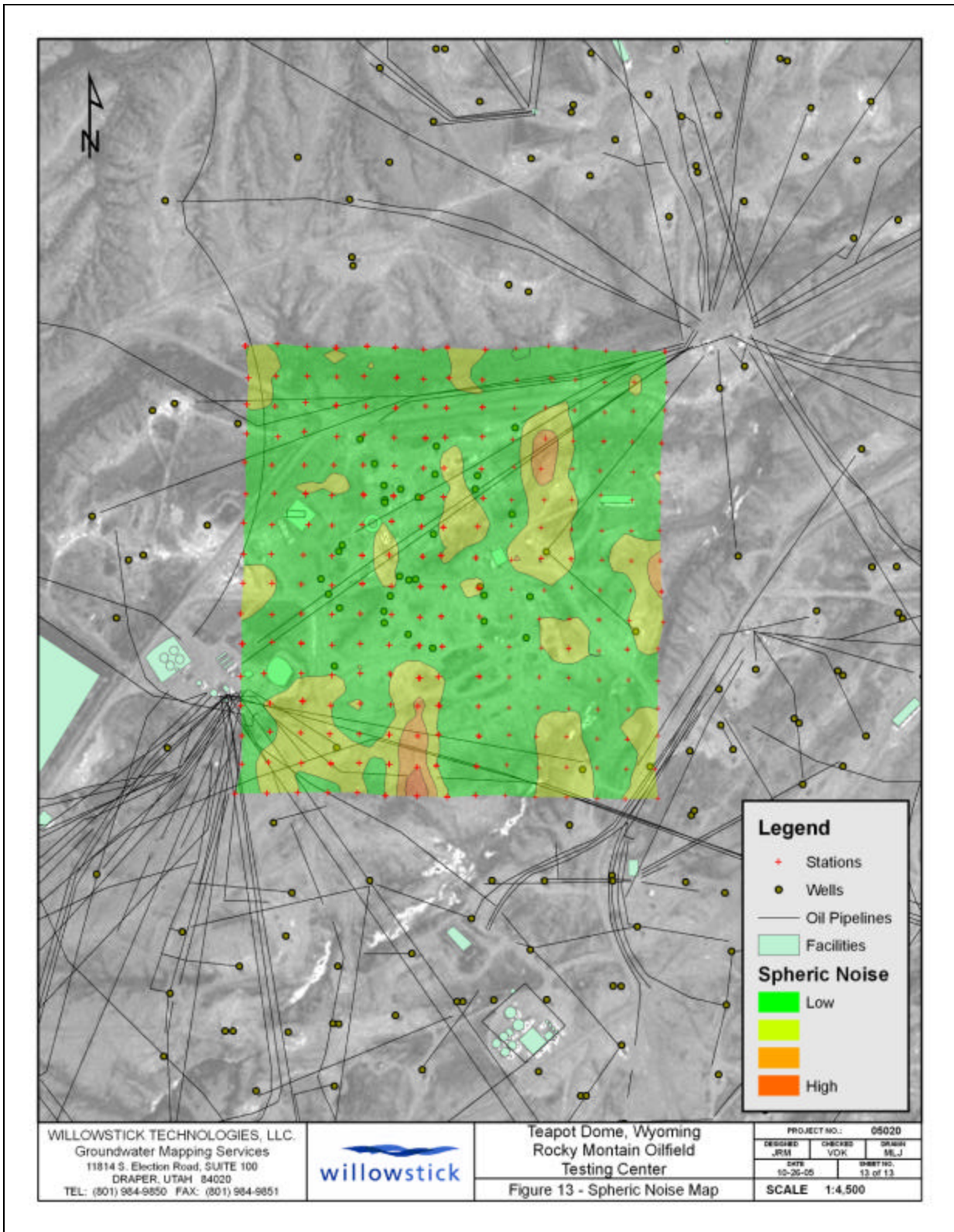


Figure A5. Map showing detected spheric noise.