

NEW STRATEGIES FOR FINDING ABANDONED WELLS AT PROPOSED GEOLOGIC STORAGE SITES FOR CO₂

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ABSTRACT

Prior to the injection of CO₂ into geological formations, either for enhanced oil recovery or for CO₂ sequestration, it is necessary to locate wells that perforate the target formation and are within the radius of influence for planned injection wells. Locating and plugging wells is necessary because improperly plugged well bores provide the most rapid route for CO₂ escape to the surface. This paper describes the implementation and evaluation of helicopter and ground-based well detection strategies at a 100+ year old oilfield in Wyoming where a CO₂ flood is planned. This project was jointly funded by the U.S. Department of Energy's National Energy Technology Laboratory and Fugro Airborne Surveys.

INTRODUCTION

Steel-cased wells have been located by ground-based electromagnetic^{1,2,3} and magnetic surveys^{4,5,6,7}. The National Energy Technology Laboratory (NETL, unpublished results) has used ground measurements of total magnetic field intensity to locate oil wells where the steel casing had been cut off; some more than 3 m below the ground surface. NETL⁸ also has used widely spaced airborne measurements of total magnetic field to locate oil and gas wells.

That ground and airborne magnetometry can detect steel-cased wells is well established and not the objective of this investigation. This investigation's purpose is to evaluate contemporary helicopter and ground-based magnetometer surveying systems for their ability to accurately locate wells, particularly wells in old oilfields where casing may be of varying length, diameter, and extent of corrosion. Further, the study intends to evaluate the ability of magnetometry to discriminate between well casing and other oilfield infrastructure such as steel pipelines, tanks, derrick anchors etc. An expected outcome of the study is the optimization of survey design (line spacing and direction; flight altitude).

Not all wells can be located with magnetometry. Very early wells had wood casing that exhibits no magnetic signature. Moreover, subeconomic wells may have had the steel casing pulled either for use elsewhere or for its scrap value. Therefore, a different detection strategy was needed for wells with no casing or non-magnetic casing. The hypothesis of this study is that leaking wells (both uncased and cased) as well as deep-seated fracture zones can be located by sensing volatile components from sedimentary strata that have migrated to the earth's surface via these pathways. Anomalous concentrations of light hydrocarbons, radon, or radon daughters on the surface can be indicative of leakage zones, either fracture zones or leaking oil and gas wells. The detection strategy is not new; soil gas sampling for light hydrocarbons has been used for many years as an exploration technique to evaluate oil and gas potential^{9,10,11,12,13,14}. Soil gas sampling has been proposed as a method for locating faults^{15,16}. Further, Armstrong¹⁷ and Johnston and others¹⁸ recommended the use of a portable hydrocarbon analyzer to reveal the exact location of wells because many abandoned wells have measurable methane emissions. On the ground, these techniques are time consuming, expensive, require landowner permission, and are only practical for small areas. Warner¹⁹ and Van der Meer and others²⁰ proposed remote sensing as a prospecting tool for hydrocarbon exploration. The sensitivity of airborne remote sensing methods has dramatically increased in recent years. New, more sensitive sensing techniques now may allow leaking wells and other conduits for gas migration to be found based on the airborne detection of anomalous concentrations of these substances. Furthermore, airborne techniques allow larger geographical areas to be evaluated more quickly and inexpensively than ground-based searching. This is especially useful when evaluating large fields, where the ability to locate CO₂ plumes in a timely manner translates to the more efficient deployment of resources in a sequestration or enhanced oil recovery (EOR) site.

This paper describes the results of helicopter and ground surveys of a one square mile area of the 100+ year old Salt Creek Oilfield near Midwest, Wyoming for the purpose of locating existing wells.

SURVEY DESCRIPTION

Site Selection

Claims were first located in the Salt Creek Oilfield, about 40 miles north of Casper, Wyoming in the 1880's and the first major oil strike was made in 1908. Since then, the field has been in continuous production. Currently, Howell Petroleum, a wholly owned subsidiary of Anadarko Petroleum is in the process of refitting existing wells and drilling new wells to implement a CO₂ flood of this old field that will enhance oil production. CO₂ flooding of Phase I areas has commenced and the reworking of wells within later phases is ongoing. Because of the long production history at Salt Creek Oilfield, there are more than 3000 wells, many with unknown or inaccurately known locations. Howell Petroleum intends to locate, inspect, and, if necessary, refit or re-plug every well within the proposed CO₂ flood areas.

In 2004, NETL approached Anadarko about using the Salt Creek Oilfield as a site to test new airborne and ground-based strategies for locating wells. With the assistance of Anadarko personnel, a rectangular area (approximately one square mile) within the planned zone of CO₂ flooding was selected (Fig. 1). The area is representative of most of the Salt Creek Oilfield in terms of well density and infrastructure. However, the terrain within the selected area is more subdued, which benefited the ground investigations.

Technical Approach

The objective of this study is to locate improperly plugged wells (with or without casing) that could allow CO₂ to move to the surface from injected formations. NETL's intention is to evaluate both airborne and ground-based well detection strategies with the expectation that a combination airborne/ground investigation will be required to search large areas yet provide the accurate locations needed for well refitting or plugging activities. Most wells in the Salt Creek Oilfield have steel casing. However, very early wells had wooden casing, and the steel casing has been pulled from some wells for use elsewhere. The selected study area contained 129 well locations listed in available well databases.

Wells with steel casing are located by their distinctive and strong monopole response in total field magnetic data. For this study, magnetic data were collected using airborne and ground vehicles equipped with two boom-mounted magnetometers. Airborne magnetic data were collected from the test area by Fugro Airborne Surveys using their Midas II system, a helicopter system with two cesium vapor magnetometers mounted on side booms (Fig. 2). Two Scintrex CS-2 magnetometers, each having an in-flight sensitivity of 0.01 nT and a sampling interval of 0.1 s were used. Sensor separation was 12 m, enabling the calculation of horizontal magnetic gradient. Real time compensation of the magnetic data for magnetic noise induced by maneuvering of the aircraft was accomplished using a flux-gate magnetometer. Corrections for diurnal variations in the earth's magnetic field were made using a magnetometer base station on the ground. Helicopter magnetic surveys of the test area were flown at altitudes of 35 m and 50 m in an NE-SW direction and an interline spacing of 25 m. Navigation and measurement locations were provided by differentially corrected GPS. Altitude was provided by laser altimetry. Following the completion of the test area flights, Anadarko Petroleum contracted with Fugro Airborne Surveys to fly a magnetic survey of the entire Salt Creek Oilfield. This flight was flown at a nominal altitude of 35 m in a north-south direction with an interline spacing of 25 m.

Ground magnetic surveys of about 10% of the test area were conducted using a Kubota RTV-900 four-wheel drive utility vehicle that was equipped with two boom-mounted Geometrics cesium vapor magnetometers (Fig. 3). The sensor separation was 6 m and the sensors were about 2 m above the ground on level terrain. Like the airborne sensors, the ground magnetometers had a sensitivity of 0.01 nT and a sampling interval of 0.1 s. Post processing of the ground magnetic data was performed to partially remove the magnetic response of the vehicle. Ground magnetic surveys were conducted in a northwest-southeast direction with a nominal interline spacing of 10 m. Measurement locations were provided by differential GPS that was also used in conjunction with a moving map-type presentation for navigation along a prescribed survey course.

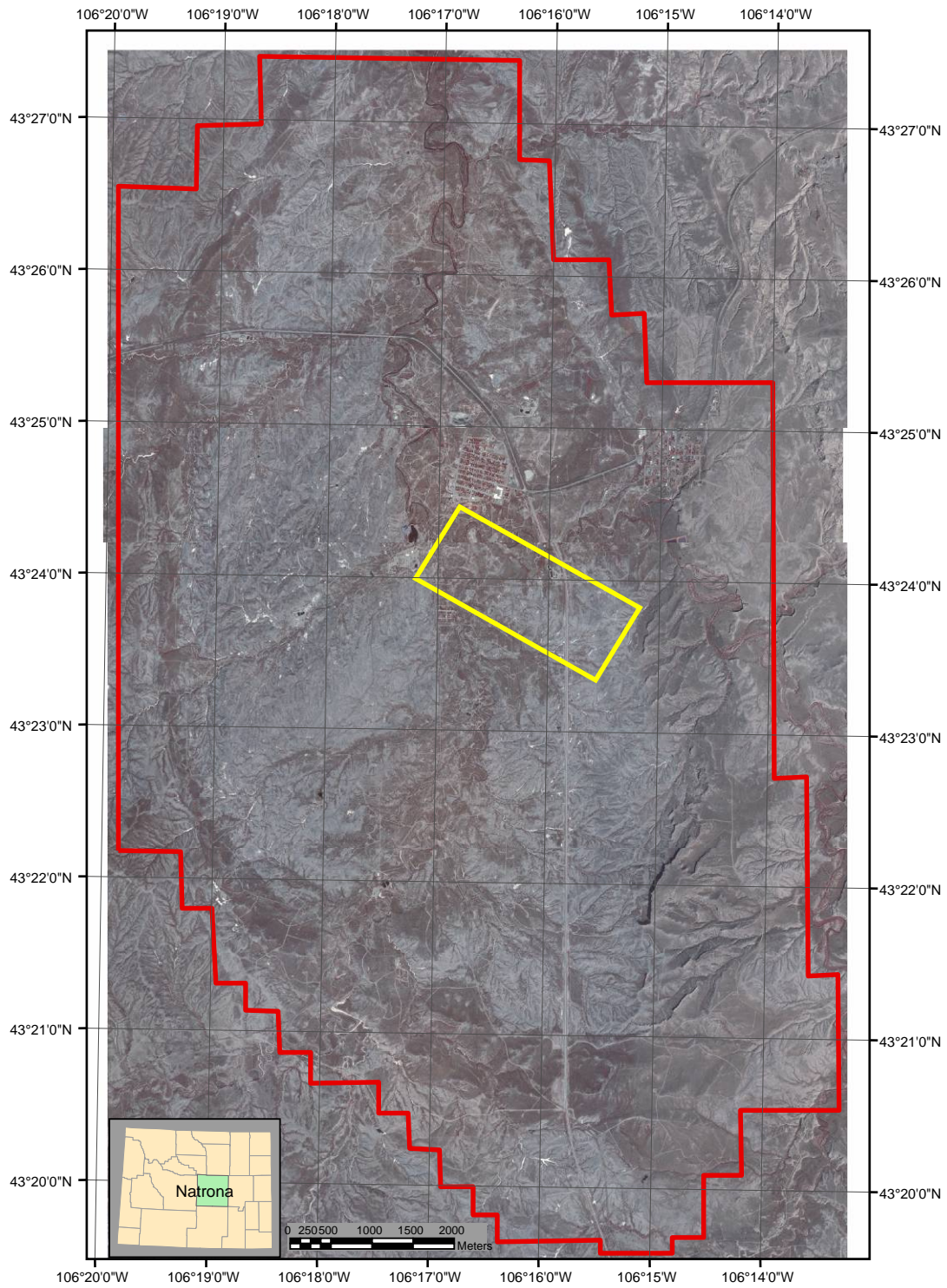


Fig. 1. Air photo showing the boundary of the test area (yellow) and the boundary of the helicopter magnetic survey of the entire Salt Creek Oilfield (red) in Natrona County, Wyoming.

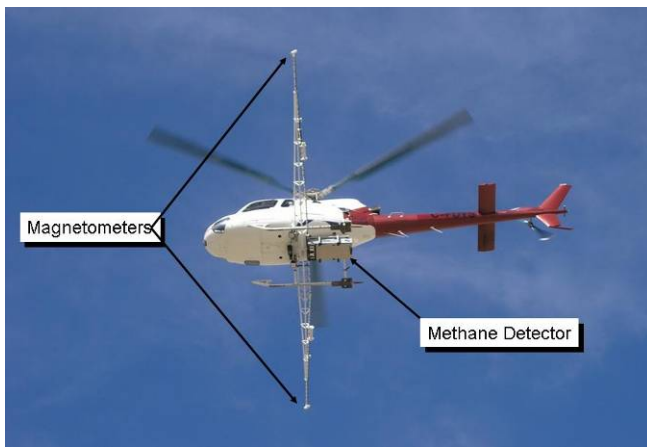


Fig. 2. Helicopter with Midas II (magnetic) and LaSen ALPIS (methane) sensors.

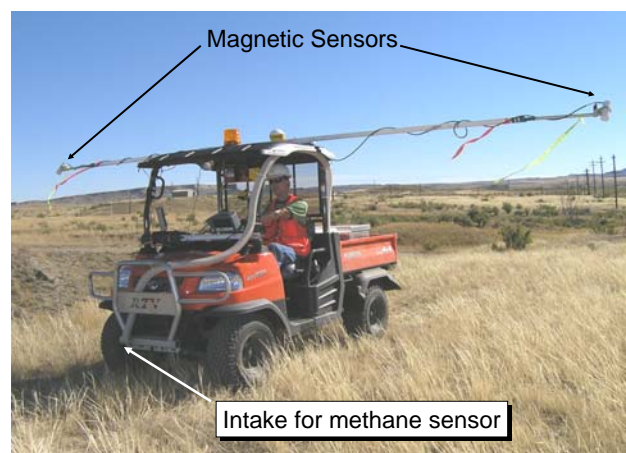


Fig. 3. Four-wheel drive utility vehicle with Geometrics (magnetic) and Apogee LDS (CH₄, CO₂, and HC) sensors.

Detecting leaking wells (with or without casing)

To locate wells and fracture zones that may leak following CO₂ injection, NETL intends to detect downwind plumes of methane that already may be emanating from the well or fracture zone.

Helicopter, methane-sensing surveys of the study area were flown by Fugro Airborne Surveys using the ALPIS differential absorption lidar (DIAL) sensor developed by LaSen, Inc (Fig. 2). The ALPIS sensor was selected for this study because it was found to be one of the best sensors in a round robin test of remote methane-sensing technologies sponsored by the US Department of Energy and the US Department of Transportation²¹. The ALPIS sensor uses two mid-IR laser beams: one with a wavelength in the methane absorption band and one with a wavelength outside the methane absorption band. Laser beams of both wavelengths are transmitted down from the helicopter to illuminate an area on the ground. After reflection from the ground, the beams are collected and the amount of received energy is measured. If the beams pass through a methane plume, the beam at the methane absorption wavelength will be diminished with respect to the beam that is not in the methane absorption band. Because changes in ground reflectivity and atmospheric opacity affect both beams equally, differential measurements made using the two-beam system can compensate for different atmospheric and ground conditions. However, one exception is that the ALPIS system does not provide accurate methane indications over highly reflective surfaces. Reflective surfaces, such as water bodies, saturate the instrument's sensors and prevent accurate readings. These data are removed during post processing. The ALPIS survey was flown at an altitude of 50 m, which resulted in an 8-m wide detection area (footprint) on the ground (measured perpendicular to and centered on the flight line). Interline spacing was 25 m so ground coverage was about 30%.

Ground methane surveys were conducted using a Kubota RTV 900 utility vehicle that was equipped with the Apogee leak detection system (LDS), a high-speed gas analyzer capable of measuring methane (CH₄), total hydrocarbons (HC) and carbon dioxide (CO₂) in sub part per million (ppm) concentrations at a sampling interval of 0.1 s (Fig. 4). Ambient air was drawn into the LDS system from the front of the vehicle by means of a hose containing an in-line fan and filter (Fig. 3). The LDS system uses an infrared analyzer to measure gas composition and has a computer-based data acquisition system for data logging and display. The computer monitor displays methane, total hydrocarbon, and carbon dioxide concentrations together with a moving map showing vehicle location. A differentially corrected GPS is used to determine the vehicle's location for navigation and sample location. The LDS was calibrated using certified calibration gases (Scott Specialty Gases) prior to the field work. The calibration was also verified at the end of the field program and found to have changed by less than 10%. Fugro Airborne Surveys used an Ecureuil AS350-B2 helicopter for the magnetic, methane sensing, and radiometric surveys. Midas II magnetic surveys are routine services offered by Fugro Airborne Surveys. However, the methane sensing survey using the ALPIS system required the fabrication of a special bracket on the base of the helicopter fuselage and a special air worthiness certification. Two surveys of the test area were flown: the first payload consisted of the Midas II system and the ALPIS system and was flown at an altitude of 50 m with an interline spacing of 25 m; the second carried a payload of only the Midas II system and was flown at an altitude of 35 m and an interline spacing of 25 m. All helicopter surveys of the test area were flown in azimuthal directions of 120° and 300° to intercept methane or radon plumes driven by primarily southwest

winds at this locality. However, the helicopter magnetic survey of the entire Salt Creek Oilfield, which was flown for Anadarko Petroleum with only the Midas II system on board, was flown in a north-south direction. The flight speed with the methane detection system was approximately 2.6 m/s, while the average flight speed with the Midas II only payload was 3.7 m/s.

RESULTS AND DISCUSSION

Airborne and ground magnetic surveys

Available databases containing well locations for the Salt Creek Oilfield were obtained from Anadarko Petroleum. When these databases were combined and duplicate entries eliminated, a comprehensive database was created that documented locations for 129 wells within the test area. An intensive ground search of the study area located 139 wells.

Total magnetic field intensity data from the magnetic sensors of the Midas II system were compensated for the magnetic effect of the aircraft and for diurnal variations in the earth's magnetic field. Processing algorithms were applied to these data to accentuate the distinctive monopole magnetic signature that is characteristic of vertical well casing and to obtain distinguishable magnetic anomalies of minimum radius that were located directly over wells and could be used to guide ground investigations. Two fast fourier transform (FFT) processing sequences were identified that when used together resulted in the most sensitive well detection capability with the most accurate well locations. One processing sequence was to take the FFT of the first vertical derivative data and to apply a log transform to the resulting data. When the transformed data were plotted on maps, a threshold was applied so that only the well anomalies were depicted. Processed data were then plotted as hill-shaded, color-scaled images. Images from magnetic data processed in this manner were found to enhance visualization of well casing irrespective of its age, diameter, and length. The second processing sequence applied a reduced-to-pole FFT correction to the compensated total magnetic field intensity data. The transformed data were then plotted as contour lines on the same map as the colored, hill-shaded well anomalies from the first processing sequence. Reduced-to-pole FFT data plotted as contours were found to provide a more spatially correct well location and were used to target subsequent ground searches to locate well heads.

Averaged two-sensor data

Initially, total magnetic field intensity data from the two Midas II magnetic sensors were averaged and reported at the location given by the GPS antenna on the tail of the helicopter. These data were processed, gridded, and depicted on a map of the study area in figure 4. The survey identified 127 distinctive monopole-type magnetic anomalies within the study area that were interpreted to be steel well casing. Additional processing to detect weak magnetic anomalies (lowering the magnetic threshold and applying logarithmic stretch) identified six more wells for a total of 133. Of the 133 wells interpreted from helicopter magnetic data, 34 were probable well locations not previously documented in available Anadarko databases. The ground search of the study area following the helicopter survey found 6 additional wells that were not detected using averaged two-sensor magnetic data.

Independent two-sensor data

Compensated total magnetic field intensity data from the two sensors were processed independently using location information from two boom-mounted GPS antennae located approximately 2 m inboard from each magnetic sensor. Using data from two independent sensors was expected to increase resolution by doubling the amount of magnetic data and to improve spatial accuracy by using location information that is closer to each magnetic sensor. Figure 5 is a map of magnetic data from two independent sensors. Although it is difficult to see at the resolution of this publication, maps made using independent (versus averaged) two-sensor magnetic data resulted in sharper, more intense anomalies over the well locations. Although maps made with the independent two-sensor data were visually more pleasing, the same number of wells (133 wells) were detected.

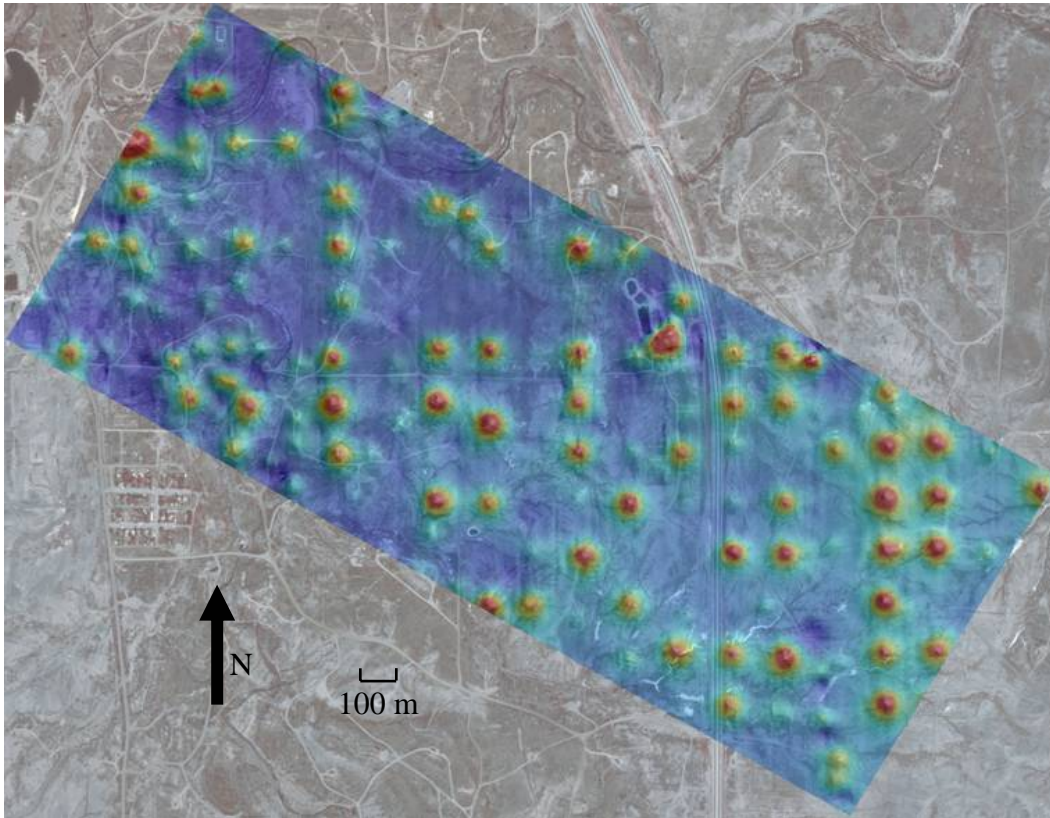


Fig. 4. Hill-shaded, color scale map of averaged total magnetic field intensity data from two sensors collected at 35 m altitude and 25 m flight line spacing.

The effect of flight altitude on well detection

Two helicopter surveys of the test area were flown with a NW-SE flight line orientation and an inter-line spacing of 25 m. One flight was conducted at an altitude of 50 m while the second flight was flown at 35 m. Maps showing the processed and gridded two-sensor magnetic data for both flights are shown in figure 6. Even at the low resolution of this document, one can easily see that the lower flight provided sharper, more distinct anomalies. Closely spaced anomalies are not resolved at the higher altitude.

The effect of flight line orientation on well detection

One helicopter magnetic survey of the test area was carried out using NW-SE trending flight lines. A few days later, helicopter magnetic surveys of the entire Salt Creek Oilfield (including the test area) were performed using N-S oriented flight lines. Both surveys were flown with the Midas II system using 25 m inter-line spacing and a nominal flight altitude of 35 m. This provided an opportunity to examine the effect that flight line orientation had on the ability of helicopter magnetic surveys to detect wells. Maps showing the processed and gridded two-sensor magnetic data for both flight line orientations are shown in figure 7. The magnetic survey acquired using N-S flight lines was preferred because the well anomalies were more localized. Also the N-S surveys contained less striping, which indicated that magnetic compensation was better in that direction. Microleveling of the magnetic data could remove the striping from images and changing the illumination angle of the hill shaded image could make the striping less apparent. Flight line orientation is probably not critical to the ability of helicopter magnetometry to detect steel well casing.

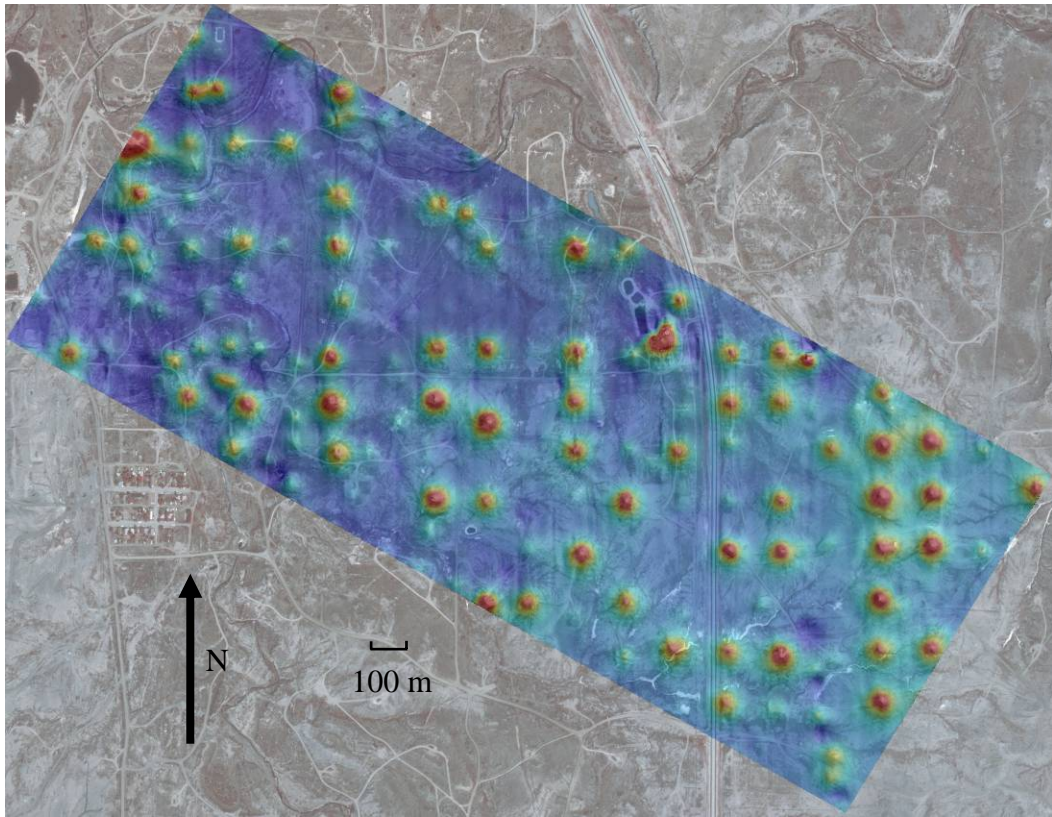


Fig. 5. Hill-shaded, color-scale map of total magnetic field intensity data when the two sensors are treated as separate measurements.

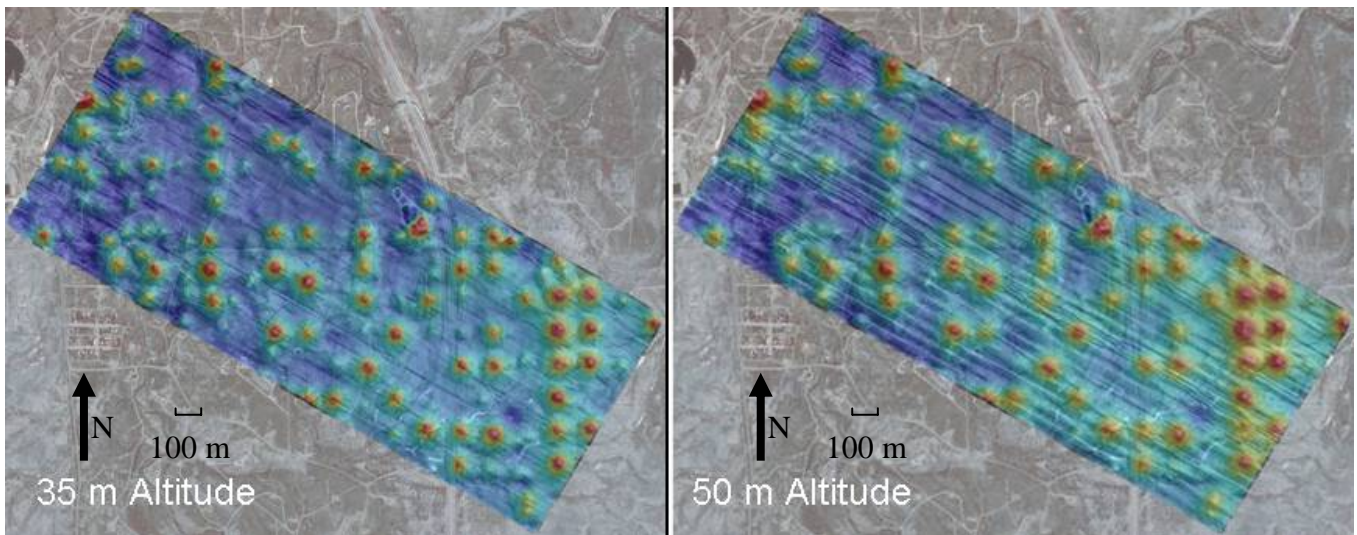


Figure 6. Comparison of the effect of altitude on the ability of helicopter magnetic surveys to detect wells. Hill-shaded, color scale maps prepared using independent two-sensor data.

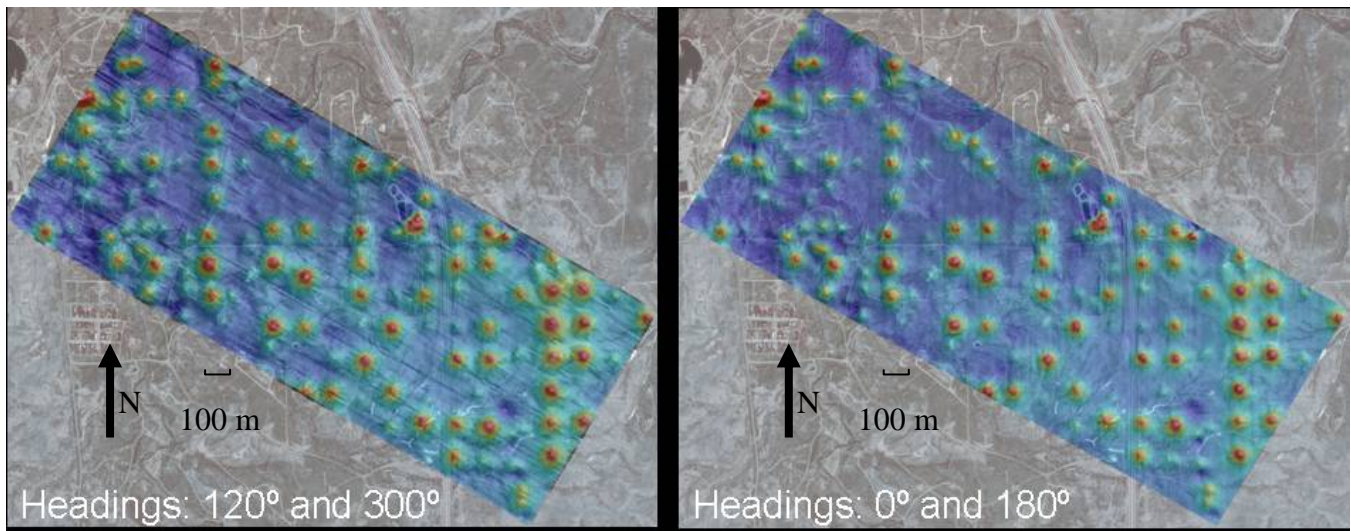


Fig. 7. Comparison of the effect of flight line orientation on the ability of helicopter magnetic surveys to detect wells. Hill-shaded, color scale maps prepared using independent two-sensor data.

Ground magnetic surveys

Ground magnetic surveys were performed on two sub-parcels of the test area (Fig. 8) using two, boom-mounted magnetometers on a Kubota RTV 900 utility vehicle (Fig. 3). Nine magnetic monopole anomalies were found within these sub-parcels that were interpreted to represent the locations of wells. Only eight wells were detected within these sub-parcels by the helicopter survey. Pipelines and other oilfield infrastructure can be discerned in the ground magnetic data. The helicopter survey at 35 m altitude is less sensitive to the near-surface oilfield infrastructure (pipelines, etc) that can complicate well detection. However, selecting a minimal “dig” area to unearth the well head is best done by ground magnetometry, which provides a more focused anomaly.

Airborne and ground methane surveys

Helicopter methane detection surveys using the LaSen ALPIS sensor were carried out at an altitude of 50 m using NW-SE trending flight lines with 25 m inter-line spacing. The survey identified four methane anomalies (A, B, C, and D; Fig. 9) that were elongated in a NE direction by a consistent SW wind that was blowing during the survey. Methane sources were identified by tracing the anomalies to their origin in an upwind direction. The sources were found to be: A) a leaking gas line, B) a leaking well head, C) a leaking oil:gas:produced water pipeline, and D) an oil:gas:water separation facility. These findings were useful to Anadarko, who had repaired all leaks by the following day. NETL’s purpose for conducting methane surveys was to detect leaking wells and fracture zones; conduits that are apt to leak when CO₂ is injected into underlying formations. Toward this purpose, the more subtle anomalies in the ALPIS data were examined and found to coincide with well locations, particularly those wells with pumping units.

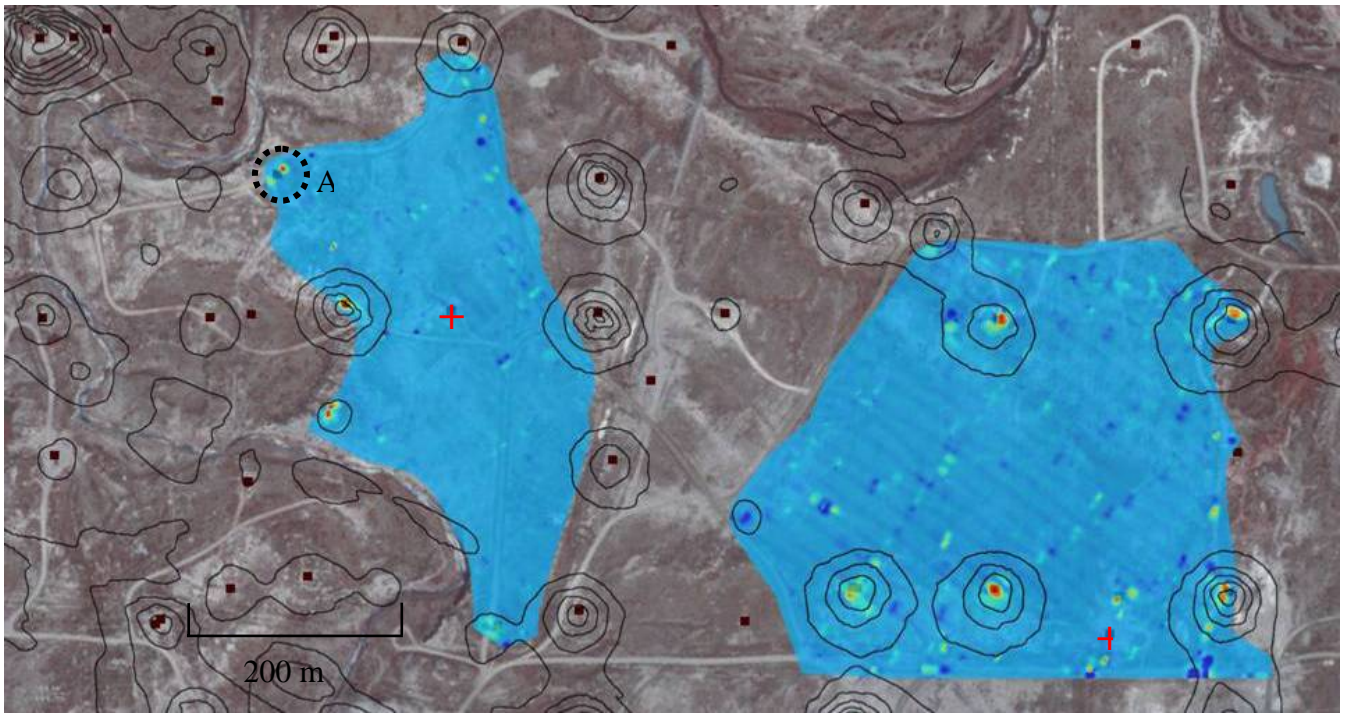


Fig. 8. Map showing results of ground magnetic surveys (color scale) and helicopter magnetic surveys (black contour lines) for two sub-areas of the test area. One well (A) in Anadarko's database was detected by the ground survey but not the helicopter survey. Two wells (+) were listed in Anadarko's database but were not detected by either the ground or helicopter survey.

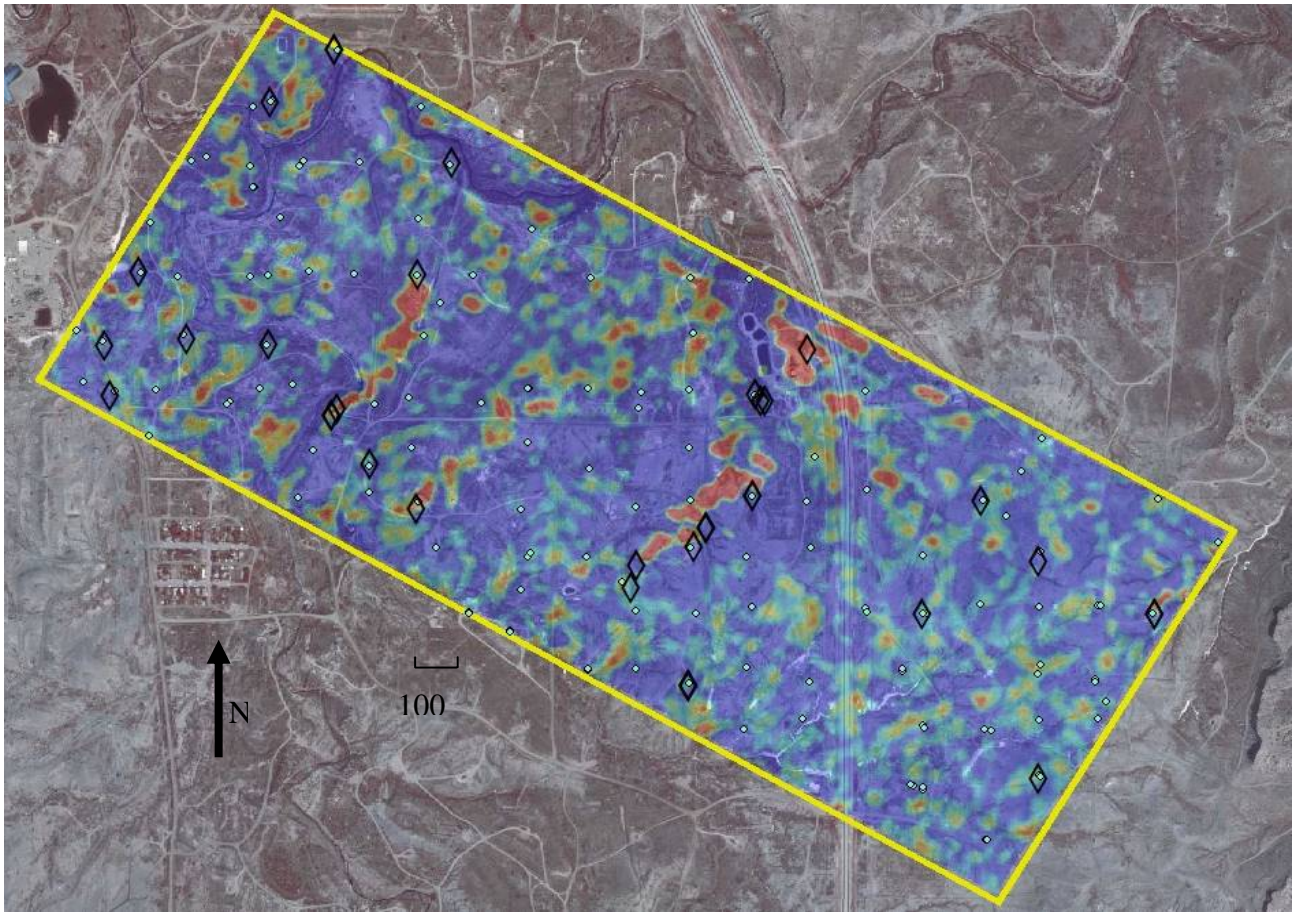


Fig. 10. Map of helicopter methane anomalies (color map) that also shows the location of ground methane anomalies (black diamonds). Green dots depict the location of wells in the Anadarko database.

CONCLUSIONS

Helicopter surveys with two boom-mounted magnetic sensors located 133 wells within the test area where an intensive ground search of the study area found 139 wells. Initially, the helicopter magnetic survey only identified 127 wells but the number of detected wells was increased to 133 by lowering the threshold and applying a logarithmic stretch to the magnetic data. Magnetic data below an arbitrary minimum threshold value were not shown on initial maps to minimize the effect of near-surface ferrous objects, which were not the target of this survey. The threshold takes advantage of the fact that well casing exhibits much stronger magnetic response (at the altitude of the helicopter) than do near-surface ferrous objects. In subsequent maps, the threshold value was decreased and six of the twelve previously undetected wells were detected. However, a further decrease of the threshold value did not result in the detection of additional wells. Ultimately, the helicopter magnetic survey detected 95% of the known wells within the study area.

Subsequent ground magnetic surveys were conducted at the locations of wells that were not detected by the helicopter magnetic surveys. The ground magnetic surveys found that these wells did exhibit a typical well-type magnetic anomaly albeit the magnitude of the response was less than that of other wells. Calculating the upward continuation of the magnetic response from these well casings showed that they would not be detected at an altitude of 35 m. The conclusion is that future well detection magnetic surveys will be flown at a lower altitude (reduce altitude from 35 m to 20 m) where possible to increase the likelihood that weak well anomalies will be detected.

This study found that better results were obtained when helicopter magnetic surveys were flown in a N-S direction and at an altitude of 35 m rather than 50 m. These results were expected. For surveys flown at higher altitudes, the magnetic anomalies are broader and less intense, which would result in a larger area for the ground search. The surveys flown at suboptimal

headings exhibited more striping from the uncompensated magnetic effects of the helicopter. Although visually less appealing, maps produced from suboptimal survey orientation proved to be adequate for locating wells.

Helicopter, methane-sensing surveys using the ALPIS sensor detected four methane plumes within the study area and numerous lesser methane anomalies. Methane sources were located by tracing the plume to its origin in an up-wind direction. Locations determined in this manner were within 20 m of the actual source. The four most substantial methane anomalies were at well heads, pipelines, and separation facilities and were quickly repaired when identified. At present, not all sources of the more subtle ALPIS methane anomalies have been investigated. However, one ALPIS anomaly is at a pumping unit where the Apogee LDS system detected 4 ppm methane at ground level. It is remarkable that a 4 ppm methane plume could be detected from a helicopter at 50-m altitude. However, the concentration and thickness of the methane plume in the atmosphere between the ground and the helicopter (which would affect detectability) is not known.

Ground methane surveys with the Apogee LDS detected numerous methane sources originating from pumping units. The observation that methane anomalies were commonly associated with older pumping units was made but not investigated. If this observation is correct, the Apogee LDS may provide an effective means of determining when maintenance is needed on pumping units.

The helicopter magnetic surveys have aided Anadarko Petroleum's effort to locate and re-plug, as necessary, all wells before their planned CO₂ flood of parts of the Salt Creek Oilfield. The survey has provided the location of numerous wells that were not in available databases.

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