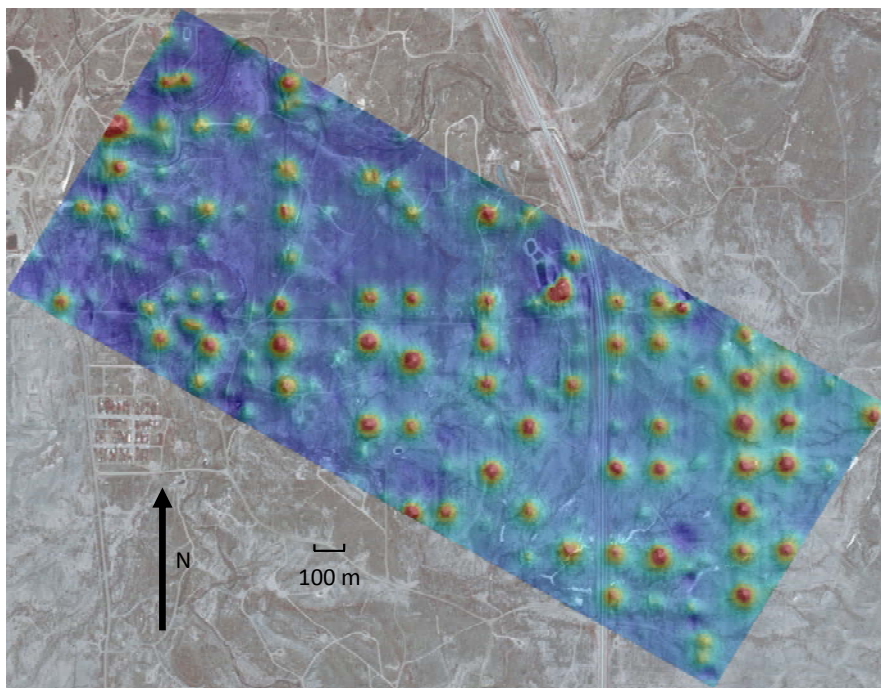




Methods for Finding Legacy Wells in Large Areas

16 June 2016

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Cover Illustration: Hill-shade, color-scale map of total magnetic field intensity data from the Mag 3 survey of the test area within the Salt Creek Oilfield, Wyoming. Well locations are depicted as yellow-orange-red dots.

Suggested Citation: Hammack, R. W.; Veloski, G. A.; Hodges, D. G.; White, C. M. *Methods for Finding Legacy Wells in Large Areas*; NETL-TRS-6-2016; EPAAct Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Pittsburgh, PA, 2016; p 28.

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Methods for Finding Legacy Wells in Large Areas

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NETL-TRS-6-2016

16 June 2016

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Acronyms, Abbreviations, and Symbols

Term	Description
CO ₂	Carbon dioxide
CVG	Calculated vertical gradient
DIAL	ALPIS Differential Absorption Lidar sensor
EOR	Enhanced oil recovery
FFT	Fast fourier transform
GPS	Global Positioning System
HC	Hydrocarbons
IGRF	International geomagnetic reference field
IR	Infrared
LDS	Leak detection system
NETL	National Energy Technology Laboratory
nT	nano Tesla
P&A	Plugged and abandoned
ppm	Part per million
RTP	Reduced-to-pole
TMF	Total magnetic field
TMI	Total magnetic intensity

Acknowledgments

This work was completed as part of National Energy Technology Laboratory (NETL) research for the U.S. Department of Energy's (DOE) Complementary Research Program under Section 999 of the Energy Policy Act of 2005. The authors wish to acknowledge Ray Boswell (NETL Strategic Center for Natural Gas and Oil) and Elena Melchert (DOE Office of Fossil Energy) for programmatic guidance, direction, and support.

The authors also wish to acknowledge Anadarko Petroleum Corporation for their cooperation and access to the well site.

EXECUTIVE SUMMARY

More than 10 million wells have been drilled during 150 years of oil and gas production in the United States. When abandoned, many wells were not adequately sealed and now provide a potential conduit for the vertical movement of liquids and gases. Today, groundwater aquifers can be contaminated by surface pollutants flowing down wells or by deep, saline water diffusing upwards. Likewise, natural gas, carbon dioxide (CO₂), or radon can travel upwards via these wells to endanger structures or human health on the surface. Recently, the need to find and plug wells has become critical with the advent of carbon dioxide injection into geologic formations for enhanced oil recovery (EOR) or carbon storage. The potential for natural gas or brine leakage through existing wells has also been raised as a concern in regions where shale resources are hydraulically fractured for hydrocarbon recovery. In this study, the National Energy Technology Laboratory (NETL) updated existing, effective well finding techniques to be able to survey large areas quickly using helicopter or ground-vehicle-mounted magnetometers, combined with mobile methane detection.

For this study, magnetic data were collected using airborne and ground vehicles equipped with two boom-mounted magnetometers, or on foot using a hand-held magnetometer with a single sensor. Data processing techniques were employed to accentuate well-casing-type magnetic signatures. To locate wells with no magnetic signature (wells where the steel well casing had been removed), the team monitored for anomalous concentrations of methane, which could indicate migration of volatile compounds from deeper sedimentary strata along a well or fracture pathway. Methane measurements were obtained using the ALPIS Differential Absorption Lidar (DIAL) sensor for helicopter surveys and the Apogee leak detection system (LDS) for ground surveys.

These methods were evaluated at a 100-year-old oilfield in Wyoming, where a helicopter magnetic survey accurately located 93% of visible wells. In addition, 20% of the wells found by the survey were previously unknown or inaccurately located. This study found helicopter magnetic surveys to be an accurate, cost- and time-effective means to locate steel-cased wells in large areas, and is a first step in evaluating whether well detection techniques can be applied effectively for well location screening across broad geographic areas.

1. INTRODUCTION

Since Edwin Drake's first successful oil well in 1859, several million wells have been drilled in the United States in pursuit of oil and gas. In Texas alone, over 1,500,000 oil and gas wells have been drilled (Celia et al., 2002, 2005) and many of those wells were drilled before 1920.

Additionally, innumerable wells have been drilled for water supply, mineral exploration and production, construction, and waste disposal.

Many early wells were abandoned without proper sealing, and today those wells can provide a pathway for the vertical movement of liquids and gases. Sources of groundwater for drinking, industrial, or agricultural use can be contaminated by surface pollutants flowing down unplugged wells or by saline water migrating upwards. Gases present in the subsurface, such as natural gas, hydrogen sulfide, or radon, can travel upwards via these wells to the surface. The advent of carbon dioxide (CO₂) injection into geologic formations for enhanced oil recovery (EOR) or carbon storage has made the finding and plugging of wells imperative because improperly plugged wells could allow CO₂ to leak from the target reservoir. Additionally, gas and fluids associated with unconventional oil and gas reservoirs, such as hydraulic fracturing fluids, formation brines, and stray gas, may migrate upward through improperly sealed wells and threaten underground sources of drinking water.

Before the hazards of abandoned wells can be mitigated, the wells must be located so that the integrity of the seals can be evaluated. Throughout the U.S., many early well locations were not recorded (especially dry holes) and records were sometimes lost. Even in locations where records of well locations have been kept, many location descriptions are incomplete or inaccurate.

Finding unrecorded wells is sometimes a daunting task, especially in highly vegetated areas or in areas where commercial and residential development has supplanted oil and gas production. In many cases, all visible features of the well have been removed and the top of the remaining casing may be buried 1–4 m below ground surface. Unrecorded wells have been found beneath buildings and paved parking lots.

This paper describes the National Energy Technology Laboratory's (NETL) field testing of well-finding strategies that are rapid, effective, and can be economically applied to large areas. The testing took place at a 100-year-old oilfield in Wyoming where, because of climate and sparse vegetation, there is still visual evidence of even the earliest wells.

2. TECHNICAL APPROACH

One goal for this study was to identify, update, and refine the most effective well-finding strategies from the past and to deploy the resulting technologies on mobile platforms, either helicopters or ground vehicles, so that large areas can be rapidly and inexpensively surveyed. A second goal of this study was to apply the techniques in a field setting, a Wyoming oilfield.

2.1 DETECTION OF WELL CASING

The magnetic method is an effective method for finding wells with steel casing due to its speed in detection, cost-effectiveness relative to other geophysical tools, and demonstrated ability to locate unknown wells (Jordan and Hare, 2002; Frischknecht et al., 1985; Baer et al., 1995; Xia and Williams, 2003). The geometry of vertical, steel-cased wells gives rise to positive, monopole, magnetic anomalies that clearly and accurately depict the well's location. Well-type magnetic anomalies can be distinguished from other magnetic anomalies by intensity, by anomaly type, and by the rate of magnetic intensity fall-off with elevation above the source. Generally, the magnetic anomaly from steel well casing is more intense and focused than the magnetic anomalies from other oilfield infrastructure. Well-type anomalies are most often positive monopole magnetic anomalies in the magnetic latitudes of the continental United States, whereas the magnetic anomalies from near-surface sources are commonly dipole (positive and negative) magnetic anomalies, relative to the international geomagnetic reference field (IGRF). The magnetic intensity fall-off with increasing height above a well is less than the magnetic fall-off from non-well magnetic sources. Therefore, by increasing the magnetic sensor height (i.e. airborne measurement versus ground measurement), one can effectively threshold the magnetic data so that only the most intense, well-type anomalies are depicted.

For this study, magnetic data were collected using airborne and ground vehicles equipped with two boom-mounted magnetometers, or on foot using a hand-held magnetometer with a single sensor. Airborne magnetic data were collected by Fugro Airborne Surveys using their Midas system (<http://www.cgg.com/default.aspx?cid=7787&lang=1>), a helicopter system with two cesium vapor magnetometers mounted on side booms (Figure 1). 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. 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 with an interline spacing of 25 m. Navigation and measurement locations were provided by differentially corrected GPS (Global Positioning System). Altitude was provided by laser altimetry.

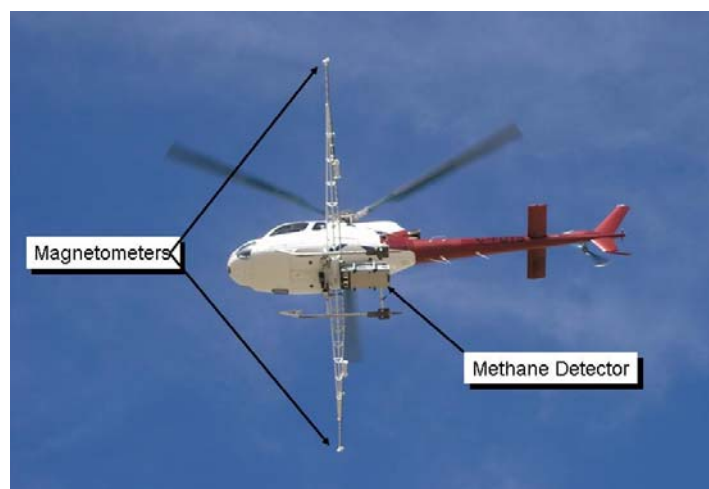


Figure 1: Helicopter with Midas II (magnetic) and LaSen ALPIS (methane) sensors.

Total magnetic field intensity data from the magnetic sensors of the Midas II system were corrected for the magnetic effect of the aircraft and for diurnal variations in the earth's magnetic field. Various processing schemes 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 calculate the first vertical derivative data and to apply a log transform to the resulting data. When the transformed data were plotted as maps, a threshold was applied so that only those anomalies having amplitudes in excess of the IGRF were depicted. Processed data were then plotted as sun-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 (RTP) transformation to the compensated total magnetic field intensity data. At the survey latitude, the appearance of a steel well casing anomaly resembles a semi-infinite vertical prism having a large positive lobe with a minor negative component to its north. It also produces the effect of shifting a monopole anomaly slightly (about 10–15 m) toward the north. RTP processed magnetic data makes all anomalies appear as they would if the magnetic inclination were 90 degrees; a large positive component centered over the magnetic body. However, RTP processing can have a negative effect on interpretation by making some dipole anomalies appear more like monopoles, thereby actually making the discrimination between wells and other ferromagnetic objects more difficult. Therefore, RTP transformed magnetic data are used to improve the positional accuracy of all magnetic targets, although they are less beneficial for interpretation. The transformed data were plotted as contour lines on the same map as the colored, sun-shaded well anomalies from the first processing sequence. Fugro Airborne Surveys also provided a proprietary calculated vertical gradient (CVG) dataset that very effectively enhanced all magnetic anomalies. CVG data

could be used as input for computer automated selection of magnetic targets using various peak selection algorithms.

Ground magnetic surveys were conducted using a Geometrics G-858 magnetometer either on foot or with the instrument mounted on a Kubota RTV-900 4-wheel drive utility vehicle. The Geometrics cesium vapor sensors had a sensitivity of 0.01 nT and a sampling interval of 0.1 s. Areas not accessible by vehicle were surveyed using a backpack mounted Geometrics G-858 with integrated sub-meter GPS for navigation and data location. The surveys were carried out by walking parallel lines nominally 2–3 m apart using a single magnetic sensor. Diurnal correction was deemed unnecessary in instances where magnetic field gradients surrounding targets exceeded a hundred nT per meter or the duration of the survey was only a few minutes.

For utility vehicle surveys, two Geometrics cesium vapor magnetic sensors were placed on opposite ends of a 6-m long aluminum beam that was attached to the top of the vehicle (Figure 2). The magnetic sensors were about 2 m above the ground on level terrain (Figure 2), which provided the clearance necessary for terrain and small bushes. A GPS antenna was placed midway between the two magnetic sensors. Post processing of the ground magnetic data corrected for the offset between the GPS antenna and each magnetic sensor location. Further post processing was performed to partially remove the magnetic response of the vehicle. Ground magnetic surveys were conducted with a nominal interline spacing of 10 m based on the vehicle centerline. Measurement locations were provided by differential GPS that was also used in conjunction with a moving map-type presentation for navigation over a predetermined survey course.

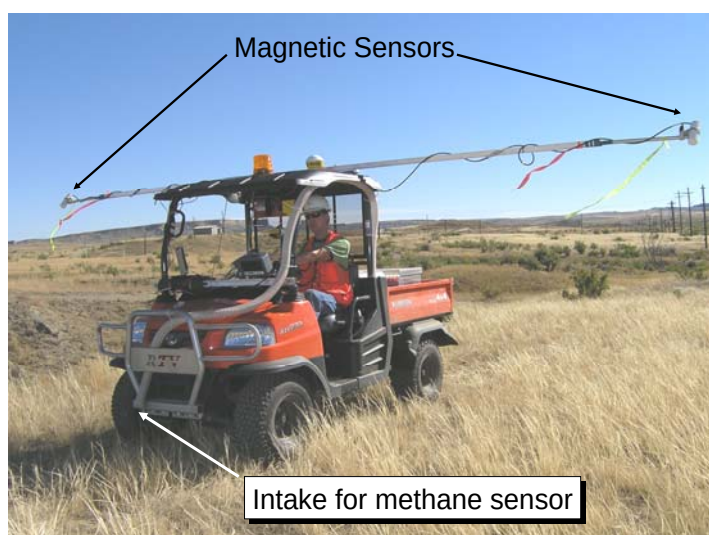


Figure 2: 4-wheel drive utility vehicle with Geometrics (magnetic) and Apogee LDS (CH₄, CO₂, and HC) sensors.

2.2 METHANE DETECTION

Magnetic methods only detect wells with steel casing. For wells where the steel casing has been removed or is severely corroded, other well detection methods are needed. This research tests the premise that leaking uncased oil and gas wells (as well as deep-seated fracture zones) can be located by detecting volatile components from sedimentary strata that have migrated to the

surface *via* these pathways. Therefore, anomalous concentrations of these volatile compounds on the surface are 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 (Jones and Drozd, 1983; Richers, 1985; Warner, 1999). Further, Armstrong (1973) recommended the use of a portable hydrocarbon analyzer to reveal the exact location of wells because many abandoned wells have measurable methane emissions. Because these techniques are time consuming, expensive, and require landowner access, they are only practical for small areas. Recent advances in airborne remote sensing may allow uncased and improperly sealed wells to be mapped quickly, accurately, and inexpensively. Further, airborne techniques allow a large geographical area to be evaluated quickly when compared to ground-based searching.

To locate improperly sealed wells and fracture zones, NETL focused on detecting methane plumes that may be emanating from the wells or fracture zones in the Wyoming oil field. Two methane sensors were evaluated for this purpose: the ALPIS Differential Absorption Lidar (DIAL) sensor developed by LaSen, Inc. was used for helicopter surveys (Figure 1) and the Apogee leak detection system (LDS) was used for all ground surveys (Figure 3). The ALPIS sensor was selected because it performed well in a comprehensive test of remote methane-sensing technologies sponsored by the U.S. Department of Energy and the U.S. Department of Transportation (Buckingham et al., 2004). The ALPIS sensor uses two mid-infrared (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 specular (smoothly reflective) surfaces. Reflective surfaces, such as water bodies, saturate the instrument's sensors and prevent accurate readings near such surfaces. These data are removed during post processing. The helicopter 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 approximately 30%.



Figure 3: Apogee LDS sensor mounted in bed of 4-wheel drive utility vehicle.

Ground methane surveys were conducted using a Kubota RTV 900 utility vehicle that was equipped with the Apogee LDS, a high-speed gas analyzer capable of measuring CH₄, total hydrocarbons (HC), and CO₂ in sub part per million (ppm) concentrations at a sampling interval of 0.1 s (Figure 3). 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 (Figures 2 and 3). The LDS system uses an internally calibrated, infrared analyzer with a White cell for high sensitivity. A computer-based data acquisition system is used for data logging and display. The computer graphically depicts methane, total hydrocarbon, and carbon dioxide concentrations together with a GPS-linked, moving map showing vehicle location and navigation information. A differentially corrected GPS was 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 airborne magnetic and methane sensing surveys. Midas II magnetic surveys are routine services offered by Fugro Airborne Surveys. 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.

3. DESCRIPTION OF TEST AREA

The well finding capability of magnetic and methane sensors deployed on a helicopter and a 4-wheel drive utility vehicle was tested at the Salt Creek Oilfield near Midwest, Wyoming. The Salt Creek Oilfield has been in continuous production for more than 100 years. Well drilling and completion technology evolved during this period and wells from two eras are represented here: 1912–1926 and 1965–1990. Since 1970, water has been injected into the oil-producing formations to increase oil production and now the field is undergoing a phased injection of CO₂ to further enhance oil recovery.

Improperly plugged wells threaten the success of EOR using injected CO₂ because they provide a conduit for the rapid escape of CO₂ from the oil bearing formation. The fugitive CO₂ migrates via wells to overlying formations or to the surface, where it can pose a health hazard to plants, animals, and humans. When CO₂, a purchased commodity, migrates from the oil-bearing formation, it does not result in oil production. Anadarko Petroleum, who owns the Salt Creek Oilfield, has taken the proactive approach of locating and reworking all wells prior to CO₂ injection. Locating wells in a 100-year old oilfield is problematic because no records were kept for early wells, and the locations provided for recorded wells are often inaccurate. Further, special well-finding methods need to be developed so that large oil fields can be surveyed in a reasonable time and at reasonable cost.

A 259 hectare (1 square mile) test area within the Salt Creek Oilfield was selected for testing airborne (helicopter) deployments of magnetic and methane sensors for locating wells (Figure 4).

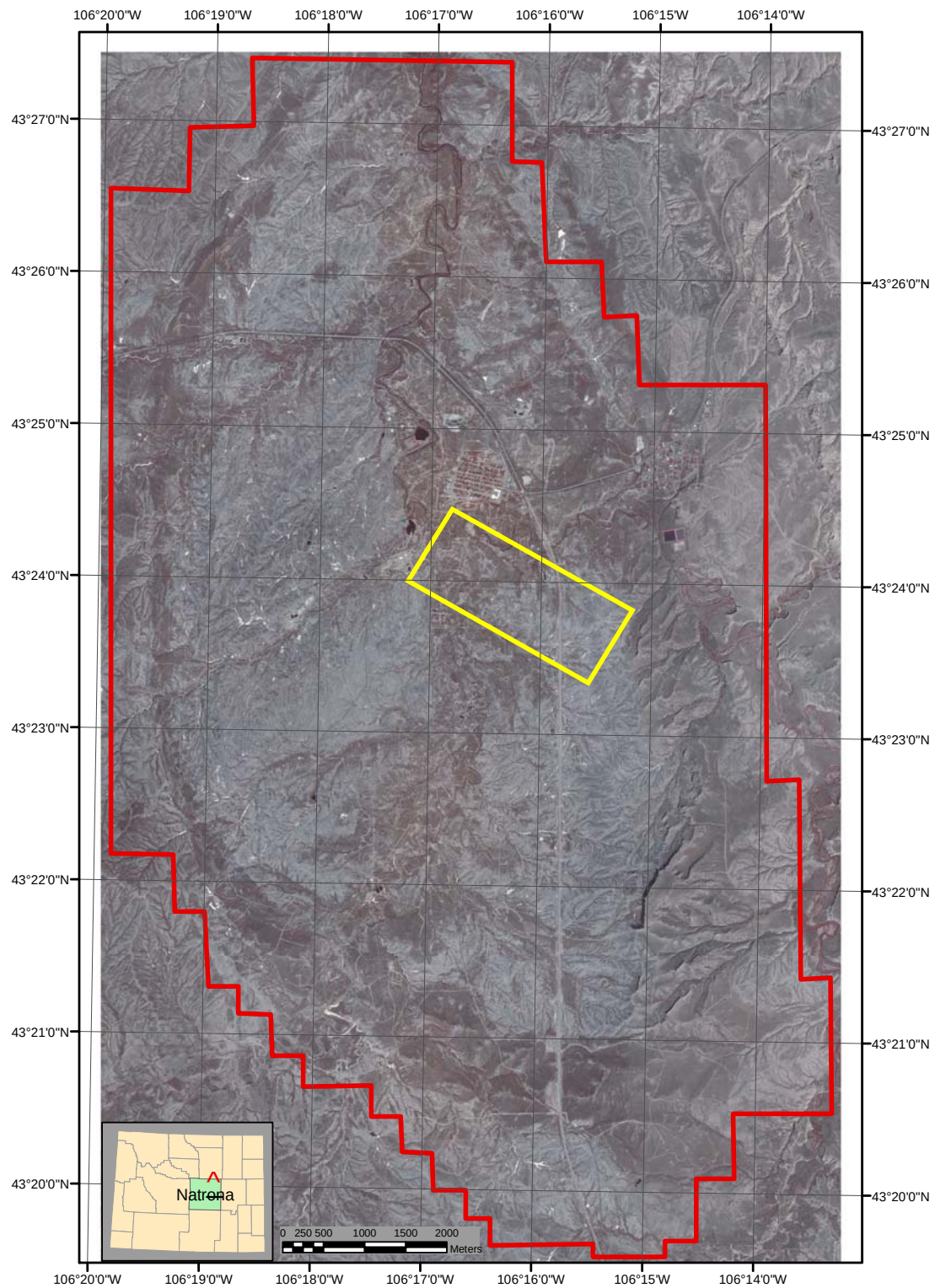


Figure 4: Map showing location of test area (yellow boundaries) within the Salt Creek Oilfield (red boundaries) at Midwest, Natrona County, Wyoming. The red triangle indicates the direction of North on the map.

4. RESULTS AND DISCUSSION

4.1 HELICOPTER MAGNETIC SURVEYS

Helicopter magnetic and methane surveys for the purpose of locating wells were evaluated on a 259 hectare (1 mi²) test area within the Salt Creek Oilfield near Midwest, Wyoming (Figure 4). Three helicopter magnetic surveys of the test area were flown using a boom-mounted, dual-sensor system to determine optimum flight parameters and data processing procedures. Nominal flight parameters for the three surveys are shown in Table 1. The best results were achieved in the Mag 3 Flight where surveys were conducted at an altitude of 35 m and the bidirectional flight lines were oriented north or south (Hammack et al., 2006). Inferred well locations from the Mag 3 flight were compared with well locations that had been verified by a thorough ground search of the test area.

Table 1: Flight parameters for helicopter magnetic surveys of the test area in Salt Creek Oilfield

Flight No.	Headings (azimuth)	Altitude (m)	Line Spacing (m)	Flight Speed (m/s)
Mag 1	120° and 300°	50	25	2.6
Mag 2	120° and 300°	35	25	3.7
Mag 3	0° and 180°	35	25	3.7

Available databases of well locations within the test area were obtained from Anadarko Petroleum Corporation and the Wyoming Oil and Gas Conservation Commission (<http://wogcc.state.wy.us/>). When the 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 test area located the 129 wells that were in the database, plus 12 undocumented wells for a total of 141 confirmed well locations. Total magnetic field (TMF) data from the Mag 3 flight were processed as described above and overlain on an air photo (Figure 5). Distinctive monopole magnetic anomalies were identified at 129 of 141 known well locations. The 12 undetected wells were further investigated to determine why they were not located by sensors during the helicopter magnetic survey.

Electronic flight logs were reviewed to determine if course or altitude deviations could have caused the wells to be missed. However, all flight parameters were normal in the vicinity of the undetected wells. Next, a portable magnetometer (Geometrics G-858) was used to obtain ground magnetic profiles from three of the twelve undetected wells and from one nearby well that was detected. The ground magnetic profiles (Figure 6) show that wells not detected by the helicopter survey had weaker magnetic responses than the well detected by helicopter. In fact, the calculated upward continuations of the ground magnetic response for missed wells indicate that the magnetic effect of the well casing would be less than 1 nT at a flight altitude of 35 m, too small of a change to be detected above the noise background.

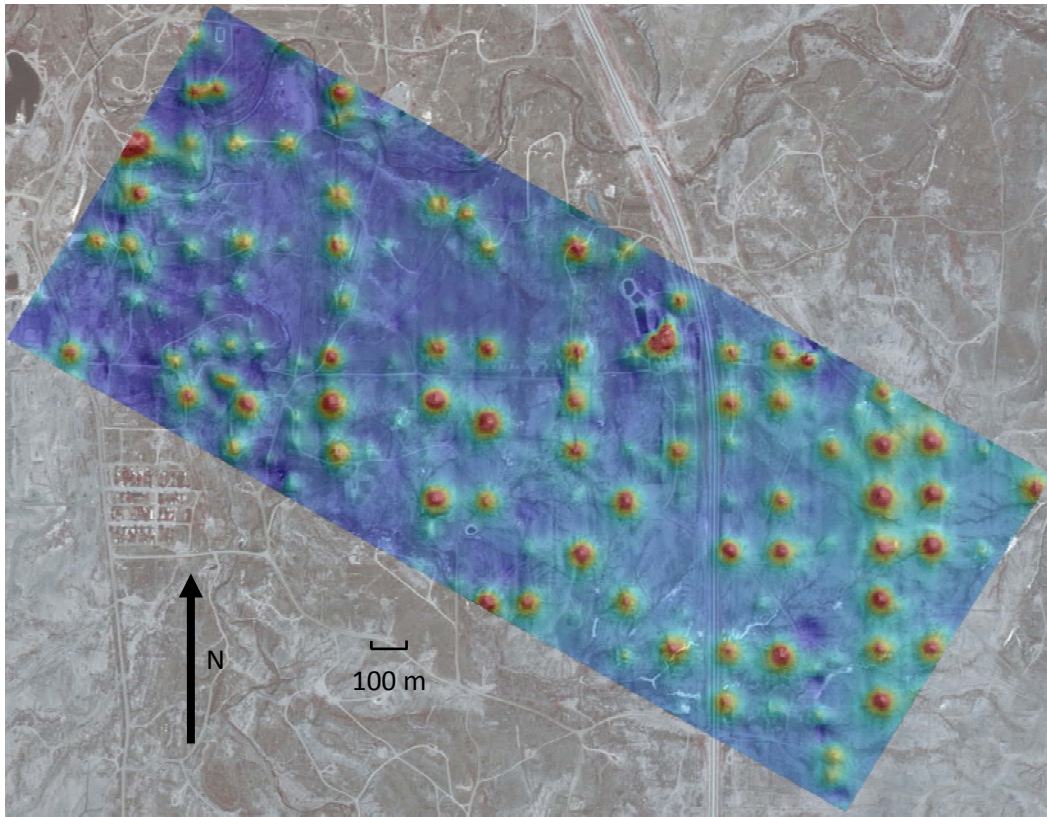


Figure 5: Hill-shade, color-scale map of total magnetic field intensity data from the Mag 3 survey of the test area within the Salt Creek Oilfield. The warmer colors depict well anomalies.

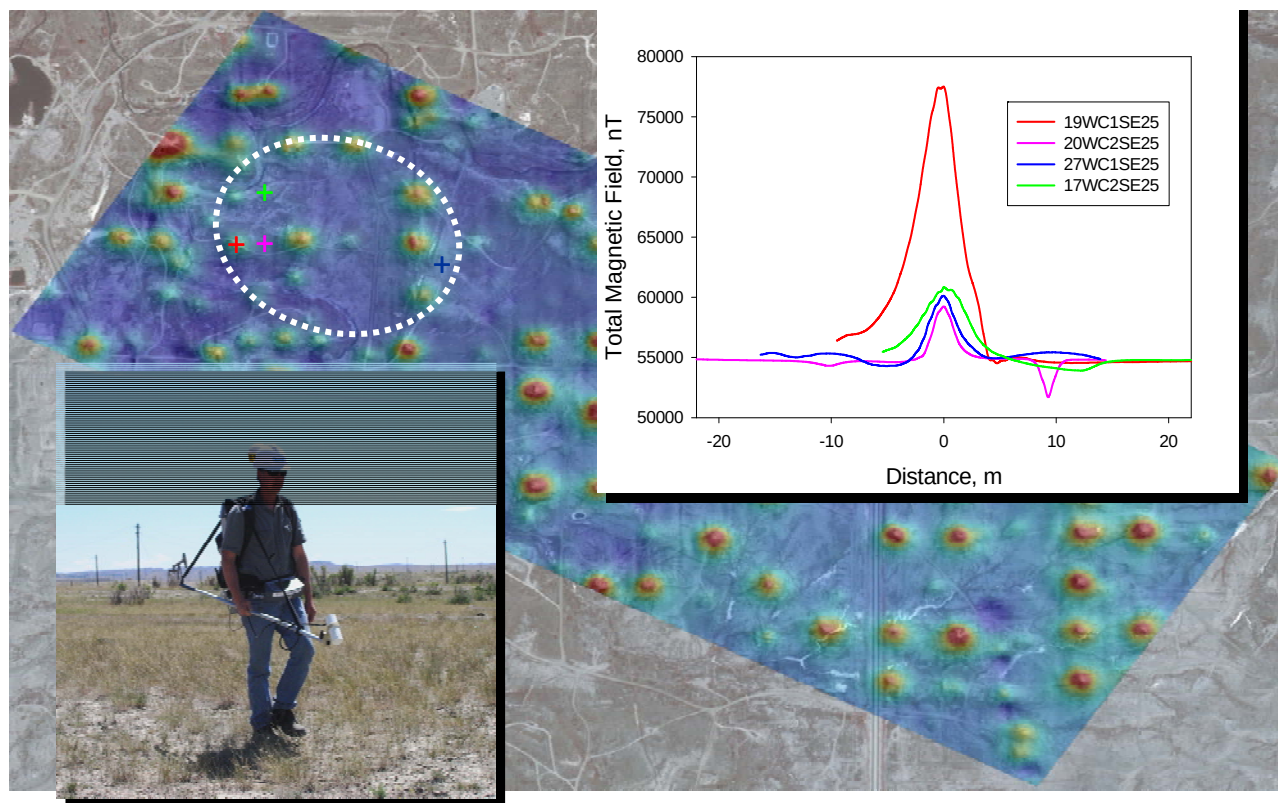


Figure 6: Ground TMF profiles were acquired at the location of three wells that were not detected by the helicopter survey (20WC2SE25, 27WC1SE25, and 17WC2SE25) and one well that was detected (19WC1SE25). Well locations for each profile are shown in the white, dashed oval. Symbol color corresponds to profile color.

Records from the Wyoming Oil and Gas Conservation Commission Database (<http://wogcc.state.wy.us/>) indicate that wells within the test area were drilled during two periods: 1910–1926 and 1965–2000. The most intense magnetic anomalies are located over wells drilled during the 1910–1926 period; all wells drilled during this period were detected by the helicopter magnetic survey. The magnetic anomalies over more recent (1965–2000) wells are generally less intense than those of the early period wells. The 12 wells that were not detected by the helicopter survey were drilled during the later period. Table 2 contains historical information pertaining to the 12 undetected wells.

Table 2: Information (<http://wogcc.state.wy.us/>) pertaining to 12 wells not detected by the initial NETL analysis of helicopter magnetic survey data. Table indicates if a TMF anomaly and/or a CVG anomaly from Fugro interpretation coincided with the well site; both CVG and TMF anomalies were required for well detection. For well status, plugged and abandoned (P&A) and active categories are listed. Shut-in wells are considered active. Well type indicates most recent use.

Well Name	Completion Date	Status	Well Type	Casing Diameter (in) @ length (ft)	Magnetic Anomalies		Detect (Y/N)
					CVG (Y/N)	TMF (Y/N)	
12WC2SW25	1977	Active	Injection	9"@ 126 7@1508	Y	N	N
14WC2SW25	1983	Active	Production	8"@ 100 5½@1710	Y	N	N
34WC2SW25	1985	Active	Injection	-	N	N	N
27WC1SE25	1967	P&A	Production	8"@ 32 5½@1597	N	N	N
20WC2SE25	1990	P&A	Production	9"@ 99 7@1765	N	N	N
33WC2NE25	1982	Active	Injection	9" @98 5½@1710	N	N	N
38WC2SW30	1974	P&A	Production	-	N	N	N
8WC2NW31	1973	P&A	Production	8"@44 5½@2097	Y	Y	Y
22WC2NW31	1973	Active	Injection	8"@41 5½@2202	Y	Y	Y
27WC2NE31	1972	Active	Injection	-	Y	N	N
34WC1NE31	1974	Active	Production	8"@43 5½@2093	N	N	N
43WC2NE31	1972	P&A	Injection	-	Y	N	N

Fugro Airborne Surveys re-examined the helicopter magnetic data to determine if different processing could identify additional wells. For total magnetic field data, Fugro averaged the response of the two boom-mounted magnetic sensors and assigned the resultant value to a location midway between the sensors. In contrast, the NETL analysis (this study) treated the response from the sensors as two independent measurements and assigned each reading to its sensor's location. Also, Fugro generated a map of calculated vertical gradient (CVG). Figure 7 contains three maps of the study area: A) a TMF map generated with two independent sensor data (NETL); B) a TMF map that used averaged data from two sensors (Fugro); and C) a CVG map (Fugro). All maps were prepared from their respective datasets by NETL to provide display uniformity.

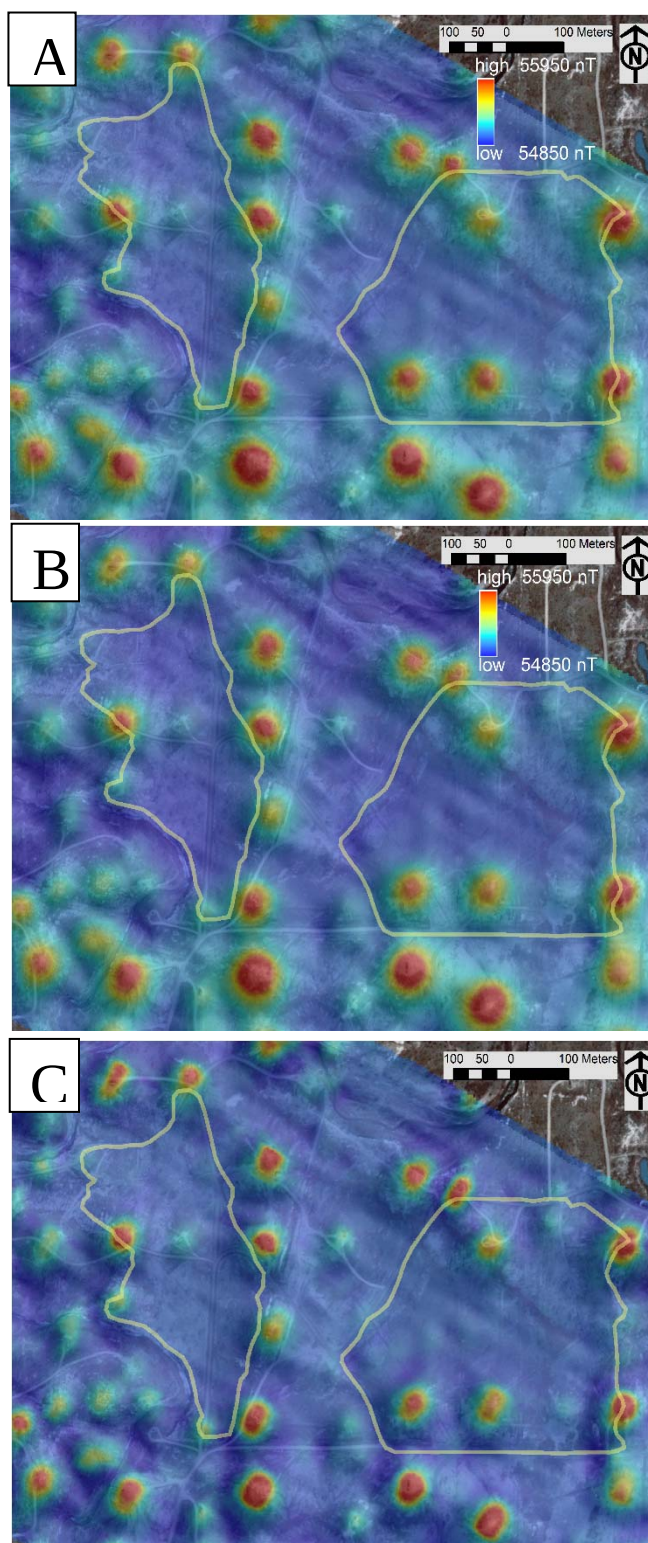


Figure 7: Comparison of helicopter magnetic results in the area of ground-based surveys: A) TMF map processed by NETL, B) TMF map processed by Fugro Airborne Surveys (averaged data), and C) CVG map generated by Fugro Airborne Surveys. Yellow lines denote boundaries of ground magnetic survey areas.

The TMF map prepared using two independent magnetic sensor data (A), was not significantly different from the TMF map prepared from averaged magnetic sensor data (B). Because the magnetic response from one well can be detected on multiple adjacent flight lines, the extra data provided by two independent TMF measurements (versus one averaged measurement) was not needed for accurate well location. The CVG map was found to be better than TMF maps for identifying wells with weak magnetic signatures. For example, Fugro identified 224 well-type anomalies in the test area when using a CVG map in conjunction with a TMF map. In contrast, NETL, using just a TMF map, identified only 153 well-type anomalies in the same area. The ground search of the test area located 141 wells; 129 wells coincided with the location of NETL picked well-type magnetic anomalies, and 131 wells coincided with the magnetic anomalies picked by Fugro. The number of magnetic anomalies that could not be correlated with wells found by the ground search ranged from 24 to 93. Of the 93 non-correlated targets, 15 were interpreted as “definite wells” based on magnetic anomalies that matched the normal range of anomalies over known wells. Another 24 magnetic anomalies were classified as “probable wells,” exhibiting either well-like anomaly shape and strength or an “on pattern” location within the oilfield. It is likely that the “definite well” and “probable well” anomalies coincide with wells where the casing was buried and not found by the ground search. The remaining 66 uncorrelated magnetic anomalies have shapes and amplitudes that do not match known wells, and probably are caused by near-surface oilfield infrastructure and discarded ferromagnetic objects (Figure 8).



Figure 8: A pipeline bridge made from well casing and a pile of buried ferromagnetic trash created helicopter magnetic anomalies that resembled wells. Twenty four of 153 TMF anomalies were not visible wells; 93 of 224 CVG anomalies were not visible wells.

To summarize, 91.5% of the known wells within the test area were apparent on both NETL and Fugro TMF maps. When TMF maps were used in conjunction with CVG maps to select targets, two more wells (93%) were located. Inclusion of all CVG anomalies as targets raised the detection rate to 97% of known wells. Although CVG maps are especially useful for detecting wells with weak magnetic responses, CVG anomaly picks include more non-well anomalies than TMF anomaly picks. Because all anomalies must be verified by a subsequent ground investigation, the greater number of CVG anomalies will increase the time and cost of ground verification activities. The decision whether to use either TMF anomalies or CVG anomalies to target potential well locations should be based on the risk associated with missing a well versus

the increased cost of the ground follow-up activities. The best strategy might be to consider both TMF and CVG anomalies, but only target those CVG anomalies that correspond to well-type anomalies in the TMF dataset.

4.2 GROUND MAGNETIC SURVEYS

Ground magnetic surveys were performed on two parts of the test area (Figure 9) using two, boom-mounted magnetometers on a Kubota RTV 900 utility vehicle (Figures 2 and 3). This served two purposes: 1) it provided ground confirmation of helicopter magnetic survey results, and 2) it demonstrated that a well-finding magnetic survey could be carried out from a vehicular platform. Nine well-type magnetic anomalies were found within these sub-parcels by the Kubota vehicle ground survey; the same wells were detected by the helicopter magnetic survey, showing that the airborne magnetic survey is highly effective in locating wells. Pipelines and other oilfield infrastructure can also be discerned in the ground magnetic data.

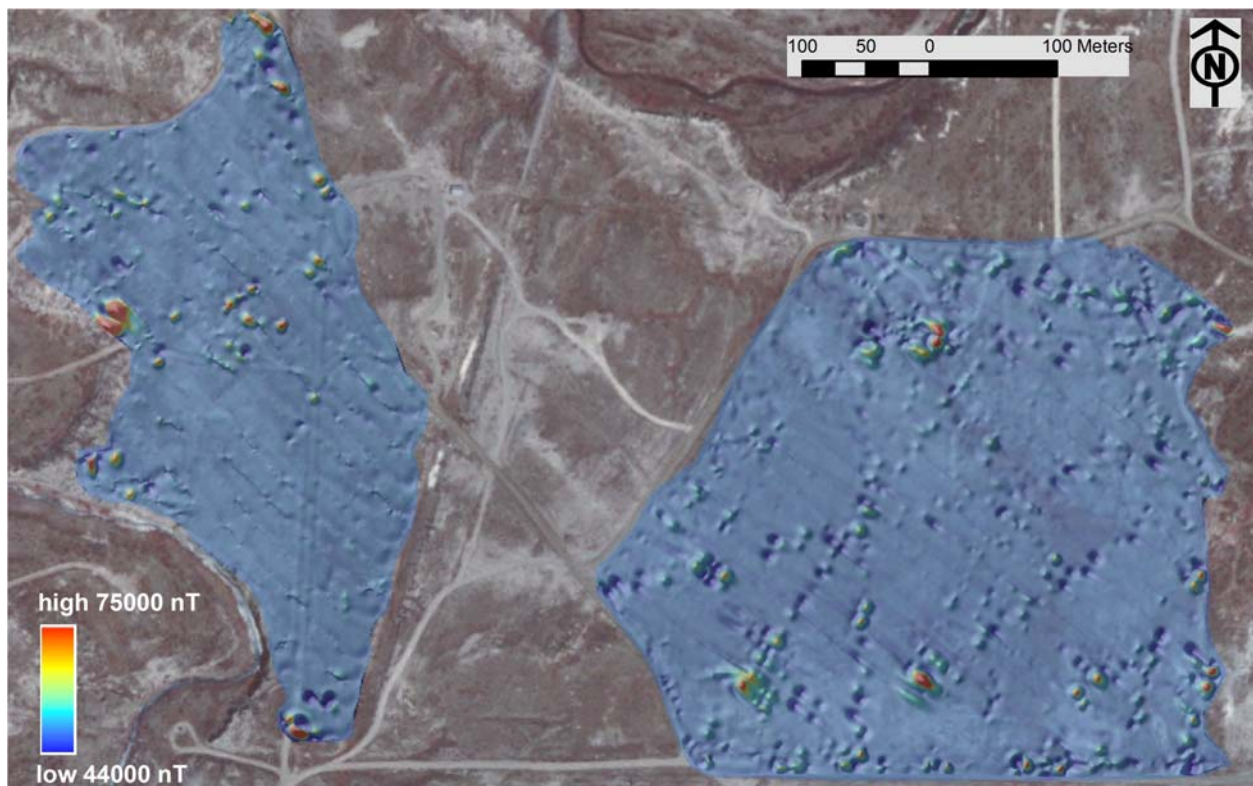


Figure 9: Total magnetic field maps acquired using two boom-mounted magnetic sensors on a 4-wheel drive utility vehicle. These maps can be compared with the helicopter magnetic maps presented in Figure 8.

4.3 HELICOPTER METHANE SURVEYS

Helicopter methane surveys were conducted to locate leaking wells, particularly wells without steel casing that could not be detected with magnetic sensors. Methane surveys were performed using a helicopter-mounted LaSen ALPIS sensor at an altitude of 50 m using NW-SE trending flight lines with 25 m inter-line spacing. The survey identified four large methane anomalies (A, B, C, and D, in Figure 10) that were elongated in a NE-SW direction by a persistent SW wind. Methane sources were identified by tracing the anomalies to their origin in an upwind direction. Only methane source B was due to a leaking well. Other methane sources were: A) a ruptured gas line at a pipeline dropout tank, C) a leaking coupling on a production pipeline, and D) emissions from an oil:gas:water separation facility. The ALPIS location of these methane sources was always within 20 m of the actual source location. The more subtle anomalies in the ALPIS data were examined and sometimes found to coincide with well locations, particularly those wells with active pumping units. However, the ALPIS data also contained numerous anomalies that could not be related to leaking wells or oilfield activities within the test area.

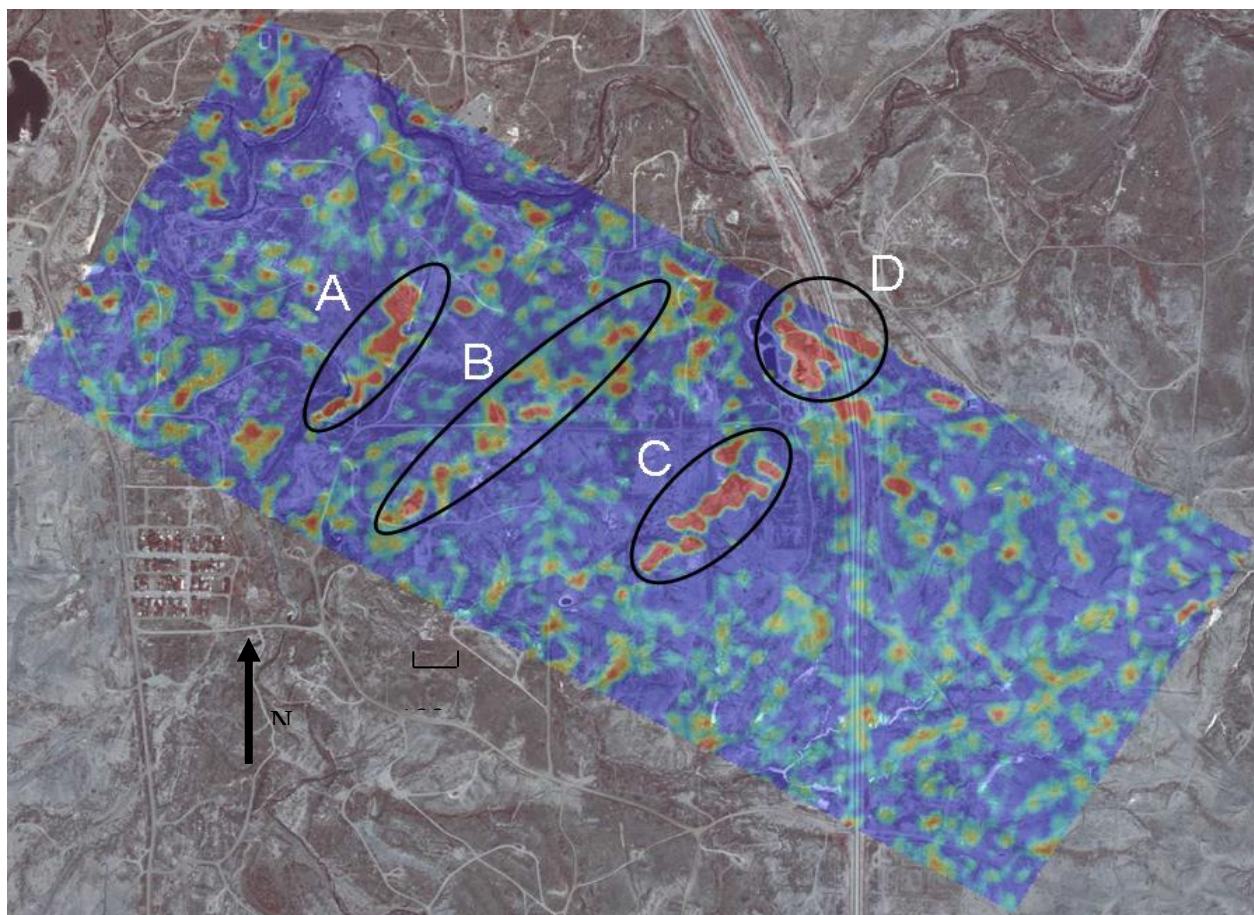


Figure 10: Helicopter methane (LaSen ALPIS) survey of test area. Warm colors (red-orange-yellow) indicate areas of higher methane concentrations. Methane anomalies designated A–D are discussed in text.

4.4 GROUND METHANE SURVEY

The ground methane survey was carried out using a Kubota RTV 900 utility vehicle equipped with an Apogee LDS (Figure 3). The numerous access roads within the test area were surveyed using the Apogee LDS to intercept and detect wind-blown methane plumes. Figure 11 is a map showing relative methane concentrations detected during the road survey. When a methane anomaly was encountered, the vehicle was turned upwind and the plume was followed to its source, usually a well head or pumping unit. The ground survey with the Apogee LDS independently located the sources of the four strong methane plumes found by ALPIS in the helicopter survey. The Apogee LDS survey identified 29 locations where methane concentrations were more than 4 ppm, about twice background (Figure 11). Methane emissions generally coincide with the location of pumping units; almost all active pumping units were the source of minor methane emissions that were detectable using the LDS.

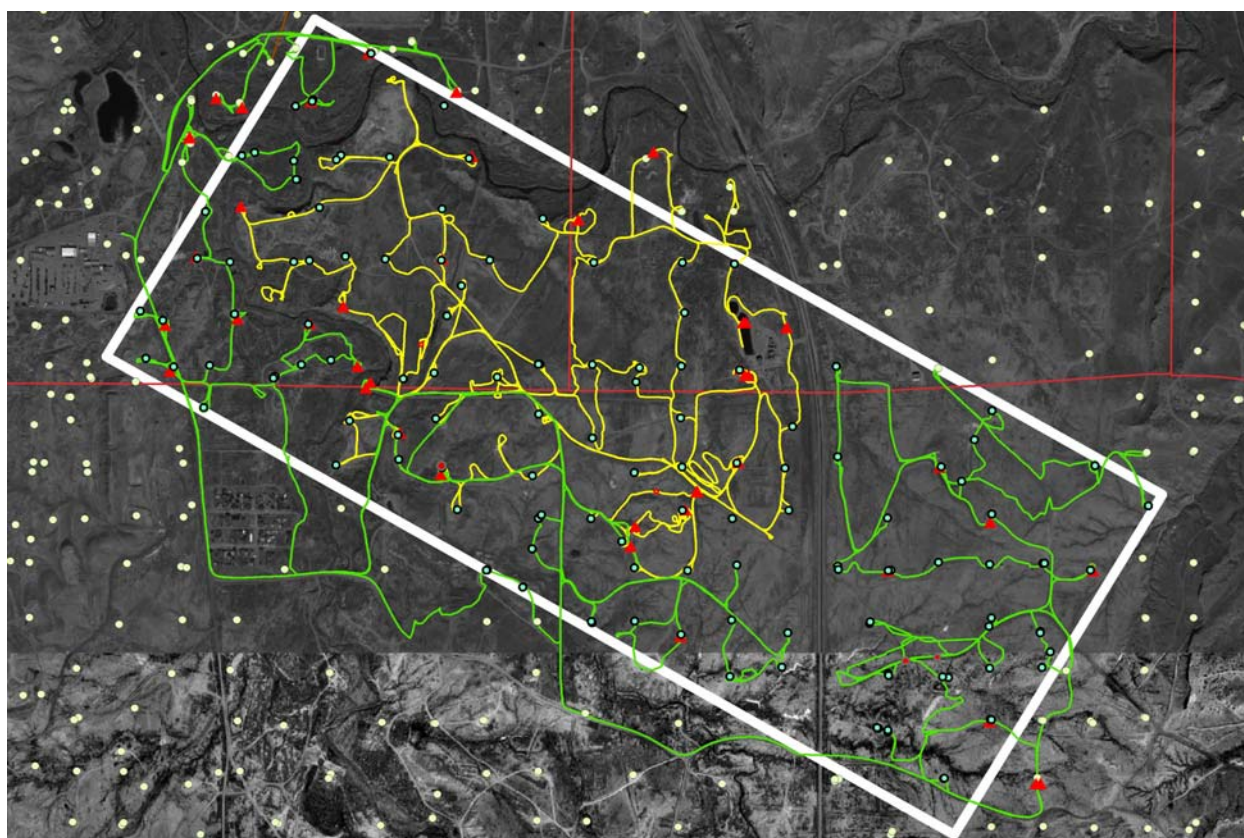


Figure 11: Map showing the Apogee LDS methane survey of roads within the test area. Survey was conducted on two consecutive days denoted by yellow (day 1), and green (day 2). Areas with anomalous methane concentrations (> twice background) are denoted by red triangles and are usually associated with wells denoted by blue-green dots (within test area) or light yellow dots (outside test area).

5. CONCLUSIONS

This study found helicopter magnetic surveys to be an accurate, cost- and time-effective means to locate steel-cased wells in large areas. Helicopter magnetic surveys of the NETL test area located 129 of 141 wells (91%) using TMF data. When TMF data were used in conjunction with CVG data, 131 of 141 wells were located (93%) but the number of magnetic anomalies that could not be correlated to visible well heads also increased from 25 to 93. It is likely that some wells were not found by the ground survey because the well heads were buried. Assuming that this is the case, the 93 uncorrelated CVG anomalies could be classified further as 15 definite wells, 25 probable wells, and 66 non-well anomalies. The decision to use TMF data alone, TMF and CVG data together or only CVG data depends on the consequences of missing a well versus the added cost of investigating numerous anomalies that probably are not wells. Wells within the test area were completed during two time periods: 1912–1926 and 1965–1990. Wells from the earlier period exhibit stronger magnetic anomalies and 100% of wells from this period were detected by the helicopter magnetic survey. The intensity of magnetic anomalies from the more recent wells is varied, but overall is less intense than that from the early period wells.

Only 82% of late period wells were detected by the helicopter magnetic survey. Smaller casing diameter and lower magnetic susceptibility that may result from different casing metallurgy are possible explanations for the less intense magnetic anomalies from late period wells. In future helicopter well-finding surveys, the survey altitude will be reduced from 35 m to 20 m where possible, a change that will increase the intensity of magnetic anomalies significantly, and improve the detection of weak magnetic well anomalies.

Results of well finding surveys made with two magnetic sensors deployed on a 4-wheel drive utility vehicle were not appreciably better than the results from helicopter magnetic surveys. The advantage of having more intense magnetic anomalies at ground level was offset by a greater magnetic effect of the vehicle. Unlike the helicopter survey, the areas suitable for the vehicular ground survey were limited by terrain and vegetation.

Magnetic sensors deployed on helicopters can quickly search large areas to locate steel-cased wells. Results of this study indicate that helicopter magnetic surveys detected 100% of early wells (pre-1926), the wells most likely to be unknown, unplugged, or incorrectly located. The early wells typically exhibit very intense magnetic anomalies that sometimes can conceal a less intense magnetic anomaly from a nearby well. When a newly drilled well could not be completed, it was a common practice to move the drill rig 20–30 m and drill a replacement well. This was termed “skidding” a well and resulted in multiple wells being drilled in close proximity. Therefore, a ground magnetic survey of the entire anomalous area (from the helicopter magnetic survey) should be undertaken to resolve individual wells if present.

All methane plumes detected by the helicopter survey of the NETL study area originated from active oilfield operations. Most methane plumes detected by ground surveys could be traced to active wells with pumping units. The methane emissions survey did not detect any previously unknown wells within the NETL study area.

6. REFERENCES

- Armstrong, F. E. *Locating uncharted oil and gas wells: state-of-the-art: U.S. Bureau of Mines Tech. Prog. Rep.*; TPR 65; 1973; p 11.
- Baer, L. J.; Overfelt, R.; Faile, T. Total field magnetic surveys to locate abandoned wells: three case histories. *The Leading Edge* **1995**, *14*, 237–241.
- Buckingham, J. C.; Grimley, T. A.; Burkey, R. C. *Field Testing of Remote Sensor Gas Leak Detection Systems*; Paper 58; Southwest Research Institute; United States Department of Transportation, Publications & Papers, 2004. <http://digitalcommons.unl.edu/usdot/58>
- Celia, M. A.; Bachu, S.; Gasda, S. A framework to estimate CO₂ leakage associated with geological storage in mature sedimentary basins. 2002 Fall Meeting American Geophysical Union, Fall Meeting Suppl., 2002; Abstract U22A-06.
- Celia, M. A.; Bachu, S.; Nordbotten, J. M.; Gasda, S. E.; Dahle, H. K. Quantitative estimation of CO₂ leakage from geological storage: analytical models, numerical models, and data needs. In *Proceedings of 7th International Conference on Greenhouse Gas Control Technologies*; Volume 1: Peer-Reviewed Papers and Plenary Presentations; Rubin, E. S., Keith, D.W., Gilboy, C. F., Eds.; IEA Greenhouse Gas Programme: Cheltenham, UK, 2005.
- Frischknecht, F. C.; Grette, R.; Raab, P. V.; Meredith, J. *Location of abandoned wells by magnetic surveys; acquisition and interpretation of aeromagnetic data for five test areas*; USGS Open-File Report 85-614A; United States Geological Survey, 1985; p 64.
- Hammack, R. W.; Veloski, G. A.; Hodges, D. G.; McLaren, S. E.; White, C. M. An evaluation of helicopter and ground methods for locating existing wells. In *Proceedings of the 2006 Symposium for the Application of Geophysics to Engineering and Environmental Applications (SAGEEP)*, Seattle, WA, April 6–9, 2006.
- Jones, V. T.; Drozd, R. D. Predictions of oil or gas potential by near-surface geochemistry. *AAPG Bull.* **1983**, *67*, 932–952.
- Jordan, P. W.; Hare, J. L. *Locating abandoned wells; a comprehensive manual of methods and resources*; Research Project Report No. 2002-1-SMRI; Solution Mining Research Institute: Encinitas, CA, 2002; p 170.
- Richers, D. M. Some methods of incorporating remote sensing and surface prospecting with hydrocarbon exploration. Assoc. Petrol. Geochem. Explorationists: Denver, CO, Special Publication; 1985, pp 11–30.
- Warner, T. A. Integration of remotely sensed geobotanical and structural methods for hydrocarbon exploration in a closed canopy forest. In *Proceedings of the IAMG 1999S*; Lippard, J., Naess, A., Sinding-Larsen, R. Eds.; 1999; p 451–456.
- Xia, J.; Williams, S. L. High-resolution magnetic survey in locating abandoned brine wells in Hutchinson, Kansas. Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) 2003 Annual Meeting of EEGS, Las Vegas, Nevada, April 6–10, 2003; p 12.

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