NATIONAL ENERGY TECHNOLOGY LABORATORY

Methods for Finding Legacy Wells in Residential and Commercial Areas

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Disclaimer

Cover Illustration: A legacy well was located beneath a paved lot using the magnetic signature of steel well casing; methane was detected seeping through cracks in the asphalt at this location.

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Methods for Finding Legacy Wells in Residential and Commercial Areas

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Acronyms, Abbreviations, and Symbols

Term	Description
AOC	Area of Concern
CO_2	Carbon dioxide
CH_4	Methane
DOQ	Digital orthophoto quadrangle
GIS	Geographic information system
GPS	Global positioning system
HC	Hydrocarbon
Hz	Hertz
LDS	Leak detection system
nT	Nanotesla
NETL	National Energy Technology Laboratory
ppm	Parts per million
WAAS	Wide Area Augmentation System

Acknowledgments

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The authors also wish to acknowledge the McKeesport Heritage Society for providing access to historical maps and photographs showing the location of gas wells in Versailles Borough, PA.

EXECUTIVE SUMMARY

In 1919, the enthusiasm surrounding a short-lived gas play in Versailles Borough, Pennsylvania resulted in the drilling of many needless wells. The legacy of this activity exists today in the form of abandoned, unplugged gas wells that are a continuing source of fugitive methane in the midst of a residential and commercial area. Flammable concentrations of methane have been detected near building foundations, which have forced people from their homes and businesses until methane concentrations decreased. Despite mitigation efforts, methane problems persist and have caused some buildings to be permanently abandoned and demolished.

This paper describes the use of magnetic and methane sensing methods by the National Energy Technology Laboratory (NETL) to locate abandoned gas wells in Versailles Borough where site access is limited and existing infrastructure can interfere. Here, wells are located between closely spaced houses and beneath buildings and parking lots. Wells are seldom visible, often because wellheads and internal casing strings have been removed, and external casing has been cut off below ground level.

The magnetic survey of Versailles Borough identified 53 strong, monopole magnetic anomalies that are presumed to indicate the locations of steel-cased wells. This hypothesis was tested by excavating the location of one strong, monopole magnetic anomaly that was within an area of anomalous methane concentrations. The excavation uncovered an unplugged gas well that was within 0.2 m of the location of the maximum magnetic signal.

Truck-mounted methane surveys of Versailles Borough detected numerous methane anomalies that were useful for narrowing search areas. Methane sources identified during truck-mounted surveys included strong methane sources such as sewers and methane mitigation vents. However, inconsistent wind direction and speed, especially between buildings, made locating weaker methane sources (such as leaking wells) difficult. Walking surveys with the methane detector mounted on a cart or wagon were more effective for detecting leaking wells because the instrument's air inlet was near the ground where: 1) the methane concentration from subsurface sources (including wells) was a maximum, and 2) there was less displacement of methane anomalies from methane sources by air currents. The Versailles Borough survey found 15 methane anomalies that coincided with the location of well-type magnetic anomalies; the methane sources for these anomalies were assumed to be leaking wells.

For abandoned well locations where the wellhead and all casing strings have been removed and there is no magnetic anomaly, leaking wellbores can sometimes be detected by methane surveys. Unlike magnetic anomalies, methane anomalies can be: 1) ephemeral, 2) significantly displaced from the well location, and 3) from non-well sources that cannot be discriminated without isotopic analysis. If methane surveys are used for well location, the air inlet to the instrument should be kept as close to the ground as possible to minimize the likelihood of detecting methane from distant, wind-blown sources.

1. INTRODUCTION

Locating abandoned oil and gas wells in populated areas challenges well finding methods that perform satisfactorily in rural areas. In urban areas, well finding surveys are impeded by infrastructure which 1) can prevent access to areas that may contain wells, and 2) may be a source of interference for well finding methods. This paper is a case study by the National Energy Technology Laboratory (NETL) that employed traditional well finding methods to locate abandoned, 90-year-old gas wells in a small town. Here, wells were drilled before accurate well location records were kept and were abandoned before laws were enacted that required plugging.

In 1919, a short-lived gas play in Versailles Borough (a small suburban town south of Pittsburgh, Pennsylvania; Figure 1) resulted in “the drilling of about 600 wells in an area that could have been drained by 10” (Johnson, 1929). Because the area was already divided into small residential lots when the field was discovered, the drilling of many needless wells was demanded by landowners anxious to partake in the potential windfall (Figure 2). Gas production was short lived but the legacy of this activity exists today in the form of many abandoned, unplugged gas wells in the midst of a residential and commercial area. During World War II, steel well heads and casing strings were removed where possible to aid the war effort, leaving little or no surface indication that wells had once been there. Buildings and parking lots were constructed over well sites.

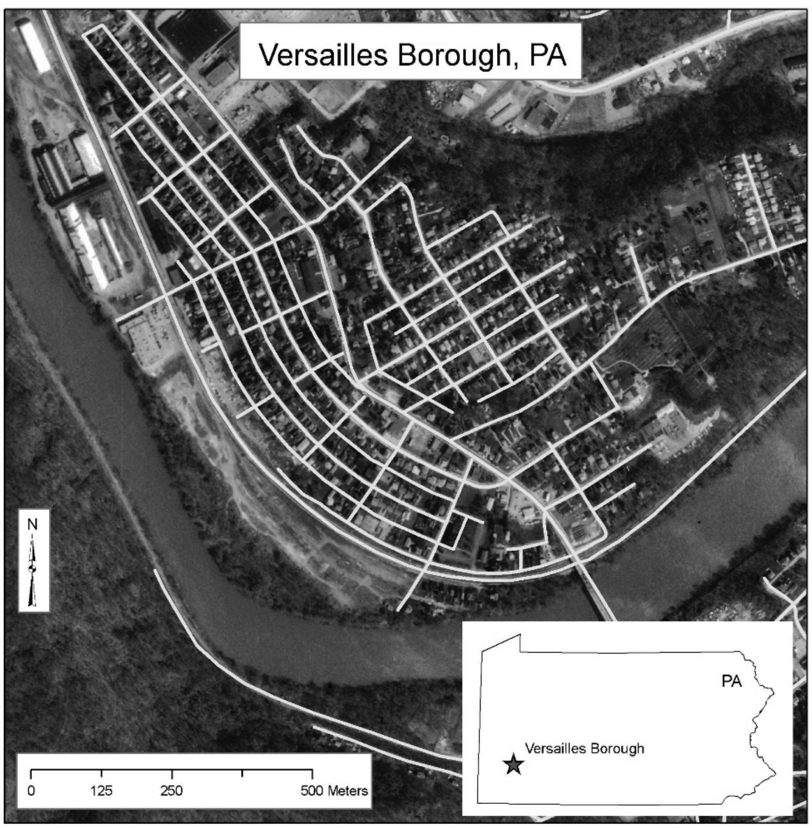

Figure 1: Location map of Versailles Borough, PA.

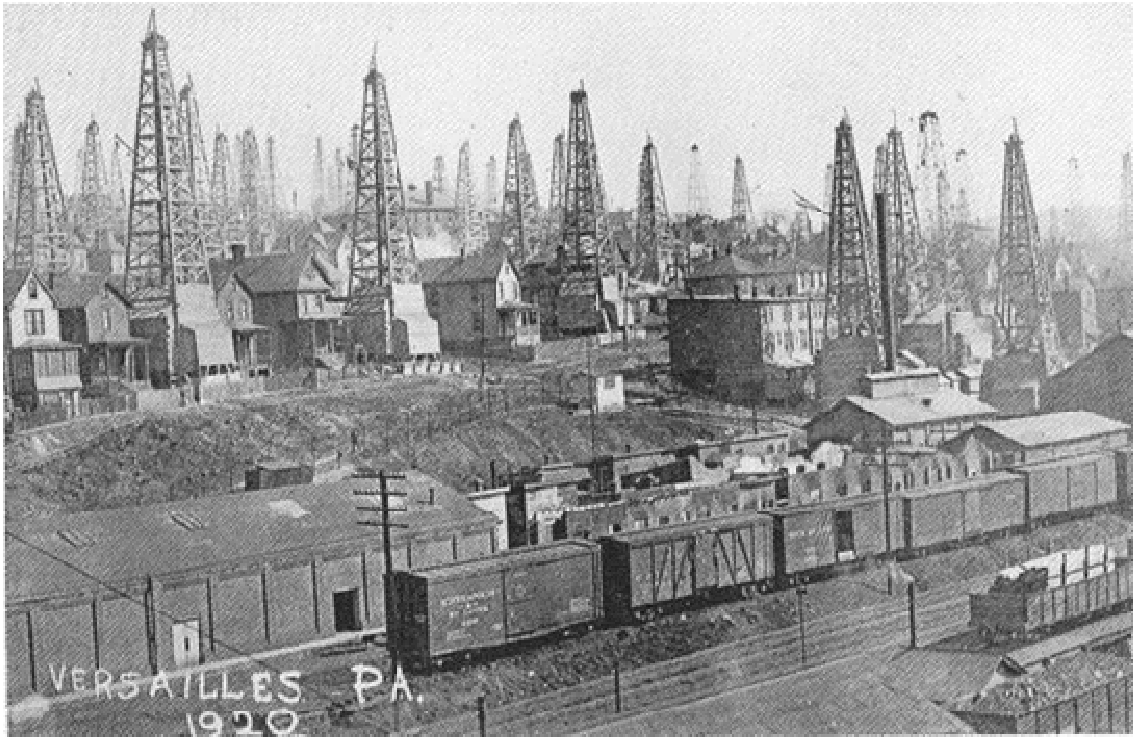

Figure 2: Photograph of Versailles Borough, Pennsylvania in 1920 showing gas well derricks interspersed between houses (photo courtesy of McKeesport Regional History and Heritage Center http://mckeesportheritage.org/research).

Starting about 1960, flammable concentrations of methane (CH_4) were detected near building foundations in some areas. Local utilities responded by disconnecting natural gas and electrical services to affected buildings, thereby forcing people from their homes and businesses until CH_4 concentrations decreased. Since then, electric and wind powered vents have been installed in many lots to draw CH_4 away from foundations (Figure 3). However, persistent problems with high CH_4 levels have caused some buildings to be permanently abandoned and demolished. High CH_4 levels are still a problem and people have been forced from their homes as recently as 2007.

The objective of this study was to locate legacy wells in Versailles Borough so that the Pennsylvania Department of Environmental Protection could mitigate dangerous CH_4 concentrations in the community by venting or plugging leaking wells.

Figure 3: High CH_4 concentrations from leaking gas wells forced residents of these houses to live elsewhere for almost a month in 2003. Vertical white pipes are vents installed to draw CH_4 away from foundations.

2. METHODS

Two methods were used to determine the location of abandoned wells in Versailles Borough. The methods included: 1) the detection of the distinctive monopole (bull's-eye) magnetic anomaly arising from the perturbation of the earth's magnetic field caused by vertical steel well casing, and 2) the detection of CH_4 that is migrating to the surface via unplugged gas wells.

The magnetic method is the best method for finding wells with steel casing. Jordan and Hare (2002) stated "*the magnetic method is relatively fast and cost-effective compared to other geophysical methods, and it has a proven track record for locating abandoned wells. In most cases, it should be considered the primary tool to be employed before other methods are implemented, especially if competent, steel-cased wells are suspected*." Other authors, Frischknecht et al. (1985), Baer et al. (1995), and Xia and Williams (2003) concur. 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 ferrous metal objects. Well-type anomalies are usually positive monopole magnetic anomalies (unless the well casing extends above the magnetic sensor), whereas magnetic anomalies from near-surface sources are commonly dipole (positive and negative) magnetic anomalies. 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, one can effectively threshold the magnetic data, increasing the likelihood that only well-type anomalies are detected.

For this study, total field magnetic data were collected on foot using a hand-held magnetometer (Geometrics G-858) with a single cesium vapor sensor (0.01 nanotesla (nT) sensitivity and 10 hertz (Hz) sampling rate). The surveys were carried out by walking parallel lines nominally 2-m apart using navigation and data location stamping provided by a sub-meter geographic positioning system (GPS) integrated with the magnetometer (Figure 4). Because the magnetic response to well casing is orders of magnitude more intense than the diurnal variations of the earth's magnetic field, correction of the magnetic data for diurnal variations was not required for this application.

Figure 4: Magnetic surveys were conducted using a Geometrics 858 magnetometer with GPS.

Magnetic methods only detect wells with steel casing. When searching for wells in areas where there is reason to suspect that well casings may have been removed or are severely corroded, magnetic methods should be augmented with other well detection methods. One alternative method is based on the observation that many wellbores, even after the casing has been removed, provide a conduit for the upward migration of volatile compounds from the subsurface. For example, anomalous concentrations of light hydrocarbons or radon at 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 CH_4 emissions.

In this study, CH_4 surveys were conducted using an Apogee leak detection system (LDS), a gas analyzer capable of measuring CH_4 in sub part per million (ppm) concentrations at a sampling interval of 0.1 s (Figure 5). The LDS used a flow-through, long path-length, sample cell (White cell) in conjunction with a Fourier transform infrared detector to increase sensitivity. The LDS employed an internal CH_4 standard to maintain instrument calibration during surveys. The instrument's internal calibration and function were verified prior to each survey using an external 1 ppm CH_4 standard gas mixture.

Ambient air was drawn into the LDS system through a hose containing an in-line fan and filter. The LDS system has a computer-based data acquisition system, which records and displays CH_4 concentrations together with a moving map showing instrument location. A differentially-corrected GPS was used to determine the detector's location for navigation and sample location. The instrument software outputs an audible tone that notifies the user of elevated CH_4 concentrations, a useful feature when operating in search mode.

The LDS detector and GPS location system were installed into: 1) the bed of a pickup truck for street surveys, and 2) a light-weight, two-wheeled cart (Figures 5 and 6) for walking surveys. The two-wheeled cart was highly maneuverable and excellent for surveying between buildings and in small yards.

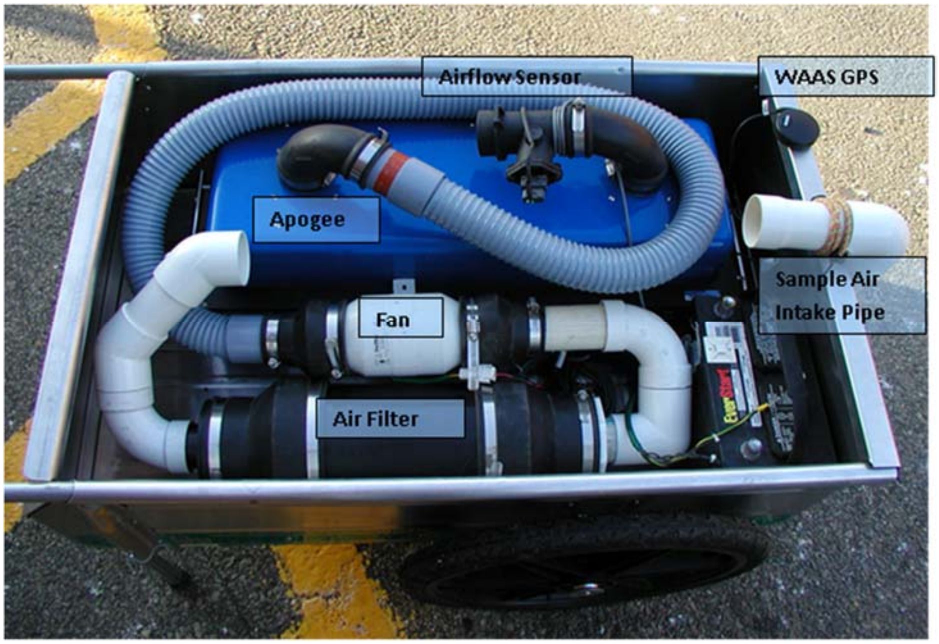

Figure 5: An LDS was deployed in a lightweight cart to detect trace amounts of CH_4 emanating from leaking wells and other sources. The tablet computer and a portion of the inlet pipe were removed for clarity.

Figure 6: LDS was used to map areas with above-normal atmospheric CH_4 concentrations.

3. OBSERVATIONS

The objective of the Versailles Borough survey was to locate abandoned gas wells, particularly those wells with detectable CH_4 emissions, within a 20-hectare (50-acre) “Area of Concern” (AOC, Figure 7). The AOC contains houses with small, fenced yards, commercial buildings, abandoned lots, sidewalks, and parking lots. Approximately 16% of the AOC was occupied by buildings that were inaccessible and excluded from the search. Fortunately, many buildings predate the drilling of gas wells and probably do not overlie wells. The AOC is too small for helicopter surveys to be economical and barriers such as fences, walls, narrow gates, and steps preclude the use of motorized vehicles other than along city streets. Therefore, well reconnaissance in Versailles Borough was primarily carried out on foot using a backpack-mounted magnetometer and the LDS installed in a wagon or a two-wheeled, aluminum cart (Figures 5 and 6).

The Versailles Borough well location survey was initiated by compiling all available information pertaining to gas wells in the area. Historical photographs (Figure 2) were used to determine well locations with respect to dwellings and landmarks that still exist today. McKeesport Regional History and Heritage Center (http://mckeesportheritage.org/research) provided access to a hand drawn map that depicted approximate locations for many wells. The map was georeferenced and well locations were integrated as layers in a geographic information system (GIS) with modern digital orthophoto quadrangles (DOQ), topographical maps, and property maps.

Initially, magnetic and CH_4 surveys were conducted in an area of Versailles Borough that contained a known leaking gas well which was expected to exhibit magnetic and CH_4 signatures similar to that of unknown wells. The magnetic survey of the known well’s location revealed a prominent monopole, magnetic anomaly that was later excavated to reveal a 0.25-m (10-in.) diameter by 4.5-m (20-ft) long steel well casing with cap. Prior to excavation, the LDS, mounted on a truck, recorded a significant CH_4 response about 10 m downwind from the well. For this study, CH_4 concentrations were defined as anomalous when measurements were greater than 2 standard deviations above the mean background CH_4 concentration of about 2 ppm.

Three CH_4 surveys of Versailles Borough streets were conducted on different days using the truck mounted LDS. The street surveys were intended to target areas with high CH_4 concentrations for subsequent magnetometer and CH_4 surveys that would be conducted on foot. The LDS street surveys (Figure 7) detected several CH_4 anomalies, but because of variations in wind direction, only a few anomalies could be traced to their sources, which were commonly CH_4 mitigation vents located above abandoned gas wells. However, not all CH_4 anomalies were from leaking gas wells. In fact, the highest CH_4 concentration (13.6 ppm) detected by the street survey was traced to a sanitary sewer vent. Evidence of CH_4 plumes can be observed in the color-coded CH_4 concentration profiles derived from the street survey (Figure 7). These data show that plumes from major sources (mostly CH_4 mitigation vents) can persist for considerable distances. Ideally, CH_4 surveys should be conducted by traversing parallel lines that are oriented in a crosswind direction and gradually approach the source from downwind. However, surveys confined to streets are seldom of optimal orientation. Wind speed and direction were light and variable during two of the three street surveys, which made it difficult to ascertain the source direction. Further, even at times when wind speed was strong and the direction constant, localized wind direction and velocity between and around buildings was highly variable because of obstruction-induced turbulence. Such conditions made it impossible to discriminate between weak CH_4 anomalies that may denote nearby, unknown gas well locations and ephemeral, dilute

CH_4 plumes originating from distant, known CH_4 sources. Although the LDS street survey did not locate any previously unknown, leaking gas wells, it was valuable because it identified areas with elevated CH_4 concentrations and was used to target subsequent surveys that took place on foot.

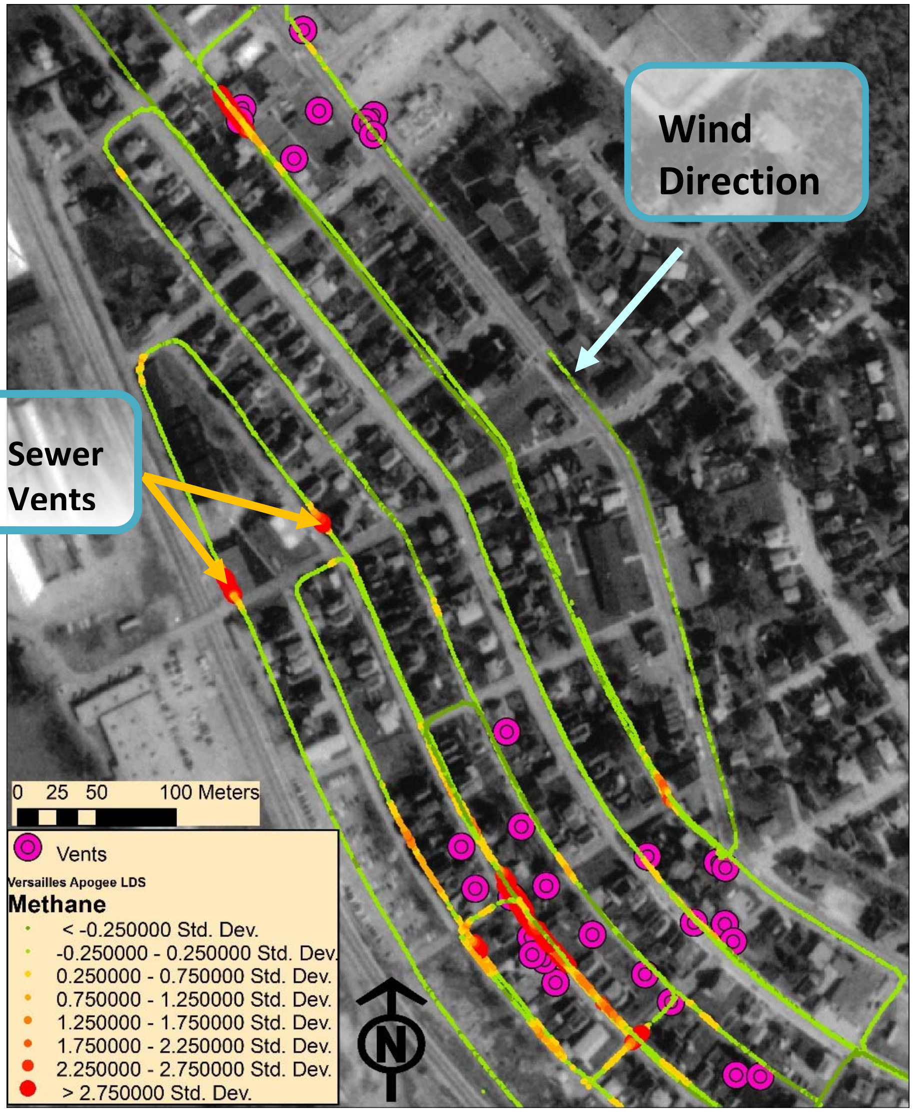

Figure 7: Map showing areas of above-normal CH_4 concentrations detected by a truck-mounted CH_4 survey of Versailles Borough. Methane concentrations are represented by symbols with graduated size and color; magenta symbols denote the locations of CH_4 mitigation vents.

A systematic survey of accessible lots in Versailles Borough was performed over the course of several days using a wagon- or cart-mounted LDS. The LDS configuration used for these surveys featured a sampling inlet that was within 10 cm of the ground to minimize the detection of windblown plumes from CH_4 mitigation vents. Data positions were corrected for a 3-s sample induction delay. Numerous localized anomalies with high CH_4 concentrations (100–1,500 ppm) were detected although CH_4 concentrations often decreased to near background only 2–3 m away from the location of maximum readings. Within these anomalies, the highest CH_4 concentrations were observed when the sample inlet was on the ground, indicating a soil gas source for CH_4. Because of the small lateral extent of CH_4 anomalies, the interline spacing for consecutive traverses was set at 2 m to lessen the likelihood of missing a leaking well.

Figure 8 shows a leaking gas well that was detected first by the LDS survey (location of high CH_4 measurements denoted on map by yellow circles). A subsequent magnetic survey (gridded color scale map, Figure 8) was used to refine the well's location; excavation showed that the well was within 0.2 m of the location of the magnetic maximum. The well is depicted in the color-scale map (Figure 8) as a strong, positive monopole magnetic anomaly. Surveys located 53 similar magnetic anomalies in Versailles Borough (Figure 9) that were interpreted to be abandoned gas wells based on the strong monopole magnetic signature exhibited. Independent of the magnetic surveys, the cart- or wagon-mounted LDS instrument measured elevated CH_4 concentrations (> 2 X background) at or near the locations of 15 well-type magnetic anomalies (Figure 9).

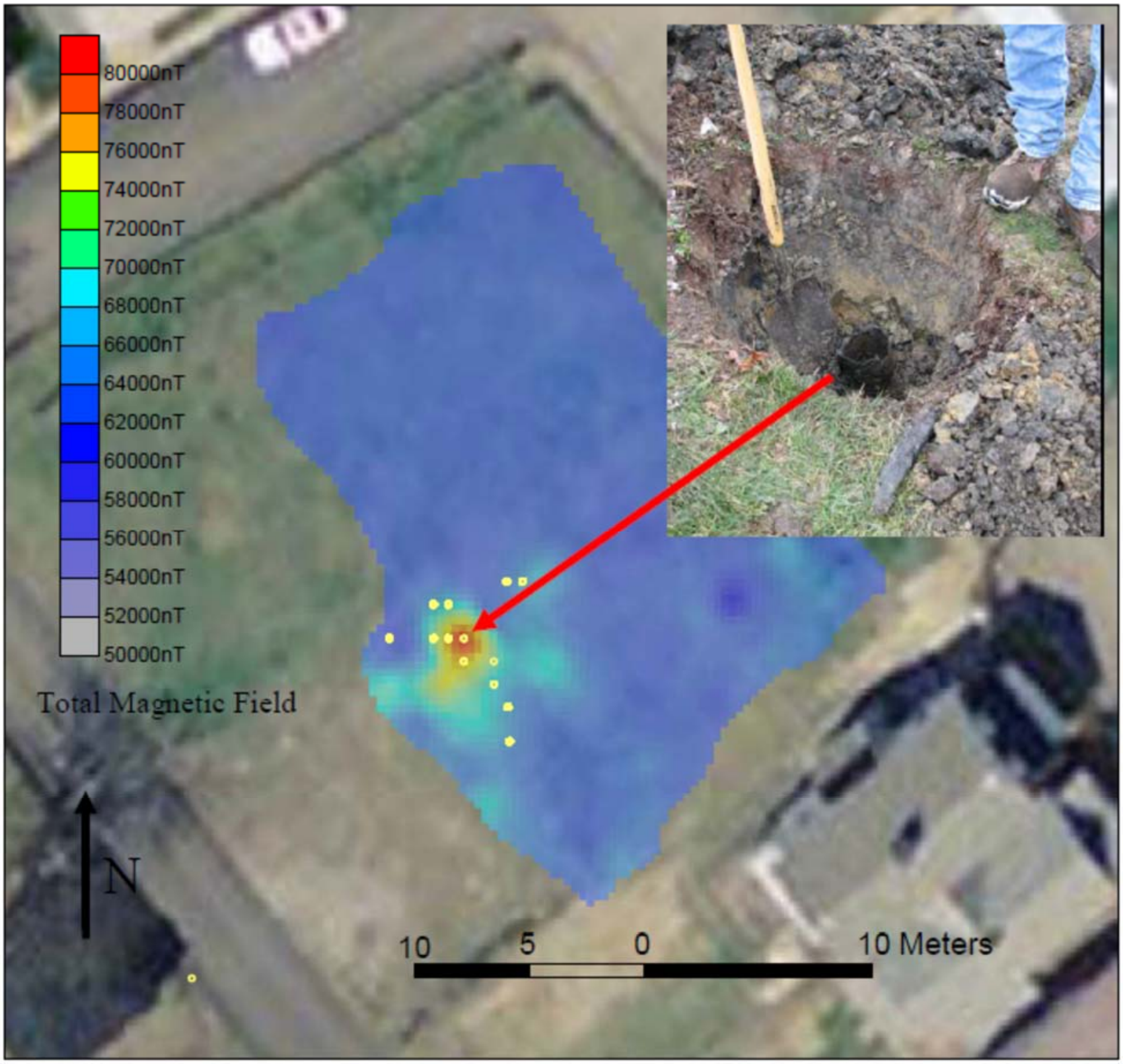

Figure 8: Color-scale magnetic map containing a strong monopole anomaly that denotes the location of an abandoned gas well. Yellow circles indicate locations where CH_4 levels exceeded 100 ppm. Inset is a picture of the gas well casing excavated at this location.

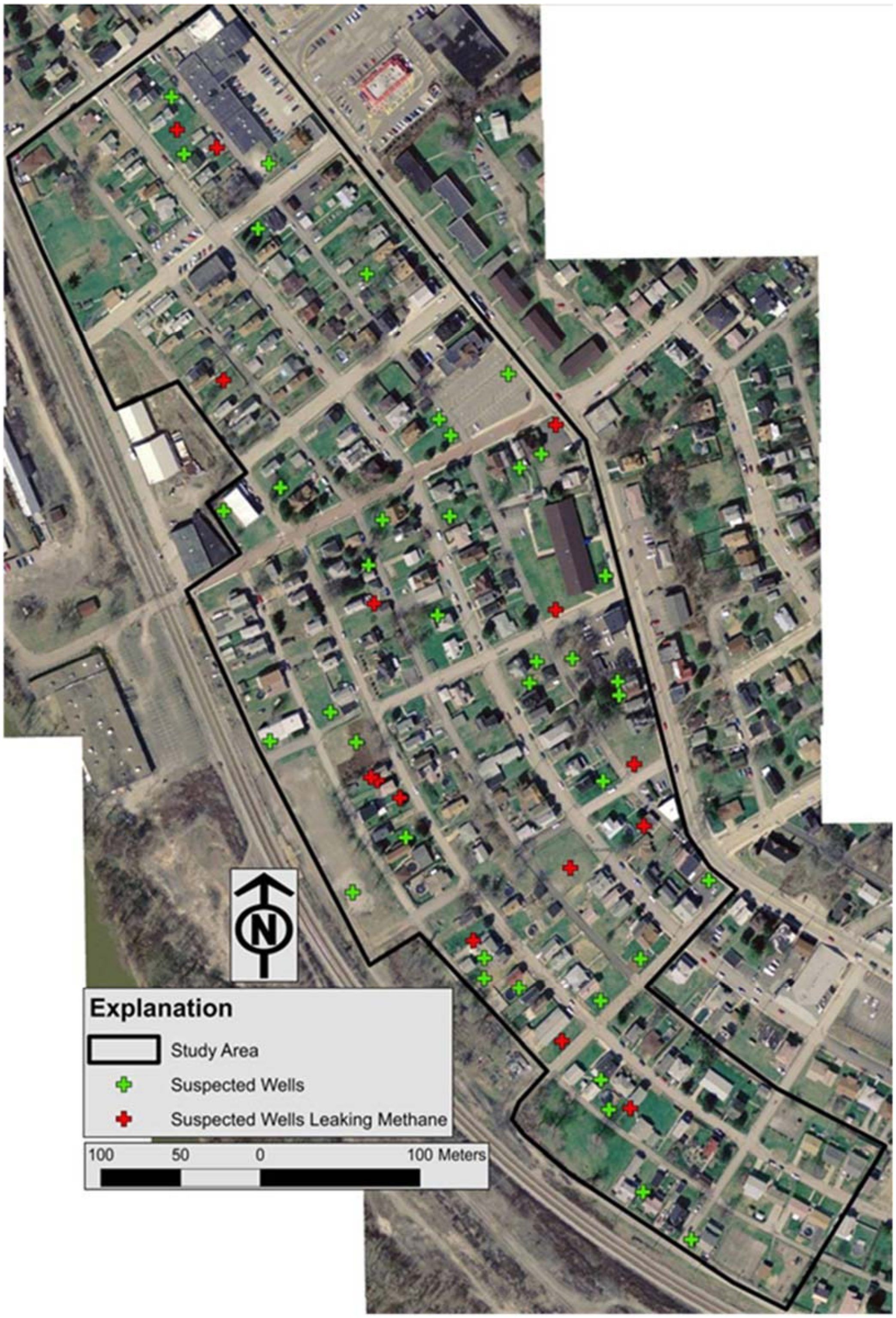

Figure 9: Google Earth image of Versailles Borough showing the locations of well-type magnetic anomalies (+) and well-type magnetic anomalies with anomalous CH_4 concentrations (+).

Figure 10 shows the location of a leaking well beneath an asphalt parking lot that was detected by both the CH_4 survey and the magnetic survey. The asphalt was cracked, allowing leaking CH_4 to seep upwards so that the CH_4 and magnetic anomalies coincided. More commonly, the CH_4 anomaly is displaced some distance from the actual location of a buried well because CH_4 follows the path of least resistance through the soil to the surface, which is seldom directly over the well. Figure 11 is a photograph of a paved parking lot where magnetic data indicate that a well is located. No CH_4 anomalies were observed at this locality suggesting either that the well was not leaking or that CH_4 was not permeating through the pavement. Figure 12 is a color-scale map of magnetic data overlain on a georeferenced Google Earth™ image. This map shows the location of magnetic anomalies interpreted to be gas wells. Two interpreted well locations had detectible CH_4 emissions and are denoted by red arrows.

Figure 10: Leaking gas well underlies this paved lot. Red arrow shows location of maximum CH_4 concentration; magnetic sensor (yellow arrow) shows location of magnetic maximum.

Figure 11: Magnetic survey indicates that a well is located beneath this parking lot (yellow arrow). There was no corresponding CH_4 anomaly.

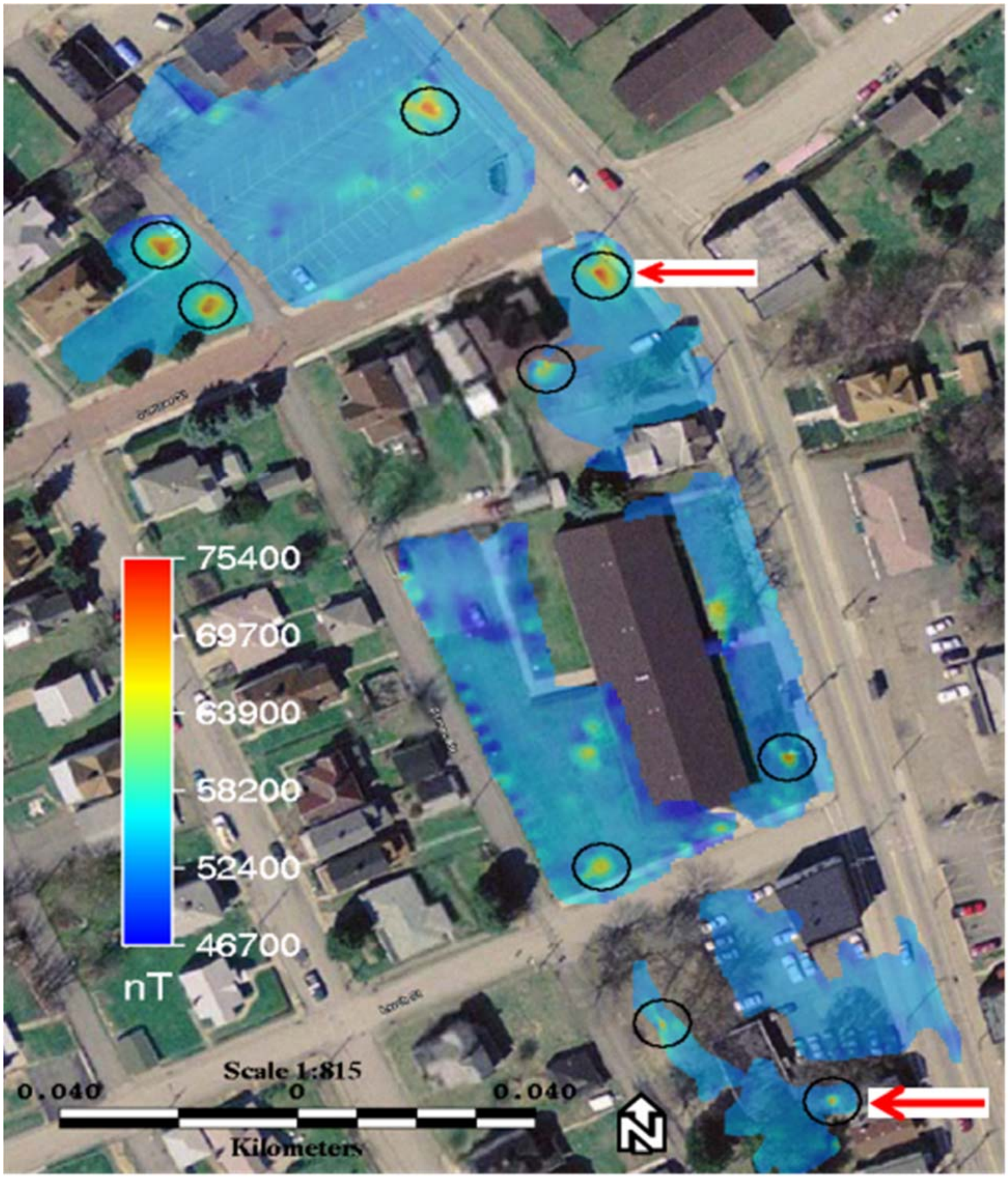

Figure 12: Color-scale map of total field magnetic data overlain on georeferenced Google Earth™ imagery from Versailles Borough. Circled features are magnetic anomalies exceeding 60,000 nT and believed to be unmarked wells. Red arrows denote the locations of well-type magnetic anomalies that are associated with CH_4 anomalies.

4. CONCLUSION

The magnetic survey of Versailles Borough identified 53 strong, monopole magnetic anomalies that are presumed to indicate the locations of steel-cased wells. This hypothesis was tested by excavating the location of one strong, monopole magnetic anomaly that was within an area of anomalous CH_4 concentrations. The excavation uncovered an unplugged gas well that was within 0.2 m of the location of the maximum magnetic signal.

Truck-mounted CH_4 surveys of Versailles Borough detected numerous CH_4 anomalies that were useful for narrowing search areas. Methane sources identified during truck-mounted surveys included strong CH_4 sources such as sewers and CH_4 mitigation vents. However, inconsistent wind direction and speed, especially between buildings, made locating weaker CH_4 sources (such as leaking wells) difficult. Walking surveys with the CH_4 detector mounted on a cart or wagon were more effective for detecting leaking wells because the instrument's air inlet was near the ground where: 1) CH_4 concentration from subsurface sources (including wells) was a maximum, and 2) there was less displacement of CH_4 anomalies from CH_4 sources by air currents. The Versailles Borough survey found 15 CH_4 anomalies that coincided with the location of well-type magnetic anomalies; the CH_4 sources for these anomalies were assumed to be leaking wells.

This field study reconfirms Jorden and Hare's (2002) assertion that the magnetic method *"should be considered the primary tool to be employed before other methods are implemented, especially if competent, steel-cased wells are suspected."* The strong monopole magnetic signature is unique to vertical well casing and allows well anomalies to be easily distinguished from magnetic anomalies arising from near-surface, ferro-metallic objects. The magnetic maximum of a well-type magnetic anomaly is an excellent location to begin the excavation to uncover a well.

Methane surveys can augment magnetic surveys for locating wells, but should never be the primary tool. Unlike magnetic anomalies, CH_4 anomalies can be: 1) ephemeral, 2) significantly displaced from the CH_4 source, and 3) from non-well sources that cannot be discriminated without isotopic analysis. If CH_4 surveys are used for well location, the air inlet to the instrument should be kept as close to the ground as possible to minimize the possibility of wind-blown CH_4 from distant sources. Despite these drawbacks, CH_4 surveys are the best method to detect leaking wellbores where the casing has been removed.

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