USE OF REMOTE SENSING AND GEOPHYSICAL TECHNIQUES FOR LOCATING ABANDONED OIL WELLS, WOOD COUNTY, OHIO

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ABSTRACT

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Northwest Ohio was the site of extensive oil production at the end of the 1800’s, which has left many abandoned wells throughout the region, presenting a possible source of groundwater pollution. Although some wells can be located by their casings, many landowners have buried or removed them, making the wells almost impossible to locate. The focus of this study was to develop and refine a rapid, low-cost method for locating abandoned oil using geophysical techniques (magnetics, resistivity) and remote sensing (spectrometry).

The hand-held spectrometer was used in the field and the laboratory to collect soil spectra. The field readings were taken adjacent to the well, 1 m from the well, and 100 m from the well. Samples from nine wells were collected at the well and four locations around it. The magnetic data were collected using a Geometrics 856 proton precession magnetometer on an 8 m x 8 m grid centered on the well. The resistivity data were collected using a Geometrics Ohmmapper capacitively-coupled resistivity apparatus on an 8 m x 28 m grid centered on the well.

Three-band ratios were calculated in a spreadsheet and plotted. These ratios were applied to the Advanced Spaceborne Thermal Emission and Reflection Radiometer, (ASTER) data collected on April 22, 2006, and used to produce a grey-scale image. The magnetics data were analyzed using Golden Surfer 8 yielding total magnetic field intensity
contour maps. The resistivity pseudo-sections were processed with MagMap2000. These pseudo-sections were exported to Res2dinv and depth inversion profiles were created.

Though the spectral data showed a 2.2 μm band in soil samples from all 9 sites, no satellite sensor had both the correct spectral bands and appropriate spatial resolution to locate the abandoned wells using this small absorption band. The magnetic field contour maps showed a circular high within 2 m of each of the known wells. Resistivity depth inversions show an increase in resistivity in the vicinity of the well casing. This study concludes that the most effective approach for finding abandoned wells involves collection of magnetic data first and then electrical resistivity and inversion modeling over positive magnetic anomalies.
I dedicate this work to my fiancé, James R. Verhoff, who braved both the hottest days of the summer and the subzero days in February to help me haul geophysical equipment across farm fields. Thank you dear; I love you.
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INTRODUCTION

In 1885, only one year after a gas boom in northwest Ohio, an oil boom occurred. The need for an alternate energy source followed the 1850’s shortage of whale oil. Even though the oil was originally unwanted because the associated sour gas fumes made people sick and the oil itself polluted water sources (WBGU-TV, 1985), the shortage led people to look for energy for their lamps. The first new energy source was kerosene, which was distilled in Nova Scotia by Abraham Guessner. Following that discovery, people wondered if the oil they found seeping through springs and river tributaries and laying in pools on their property could be useful. At the time, oil was being used for medicine by the Seneca Indians, who rubbed it on their bodies and drank it, and by farmers as a lubricant.

It was Samuel Kier who first distilled kerosene from the crude oil in Pennsylvania. In the 1860’s, there was an unsuccessful attempt at drilling for oil in Ohio. The first oil strike in the U.S. was by Edwin L Drake, in Pennsylvania. However, by the mid-1880’s most of the wells in Pennsylvania began to dry up. As a matter of fact, the first oil companies in Ohio were the result of an accident. Henry Furrow, while drilling for natural gas in Lima in May, 1885, hit oil. The boom made its way to Wood County in late-1886/early-1887 with their “great gushing wells,” which gushed over 1000 barrels of oil per well. Due to the large amounts of oil being produced in Wood County, the price of oil decreased and the wells of Lima could not afford to operate. John D. Rockefeller and his company, Standard Oil, purchased over 75 percent of the oil fields. He wanted to shut down these fields while his scientists found a way to distill the sulfurous, “sour” crude oil into useable crude, “sweet” crude (WBGU-TV, 1985).
At this point in time (1889), the laws governing drilling changed (WBGU-TV, 1985). Originally, oil was treated as a mineral under your property. However, oil could flow from one property to another. To solve this problem, the Pennsylvania Supreme Court applied the hunting laws to oil ownership, specifically, the law of capture. This meant that the oil was not yours until you captured it or brought it up to the surface. This change caused people to start what was referred to as closeology. Rather than using geology to find where to drill, people would drill directly across from existing wells on other people’s property. Then, they would drill in a line on their property to “protect” their supply. It all came down to who could bring up the oil the fastest. These quick-draw standoffs ruined Rockefeller’s plans of shutting down his leases. If he were to stop drilling and come back to the well, it could be dry due to a well on an adjacent lease. This mindset made it so that towns were full of derricks. It got so bad that one could traverse an entire boomtown without touching the ground (WBGU-TV, 1985). There were some that still wildcatted for wells, used widgets, dreams, angels, or drilled wherever they broke down in the swamp. They even moved cemeteries to drill wells because of superstition.

This frenzy ended abruptly in 1901, when the boomers found out about Spindle Top, a gusher near Beaumont Texas that yielded 100,000 barrels a day. The new quantities of oil lowered the price to three cents a barrel. Falling prices caused many of the Ohio wells to close, and by 1903, most of the wells appeared to have gone dry. As the boomers moved on, they left the remains of thousands of abandoned, unplugged wells in Wood County.

Many would attribute this loss to the new laws saying that the law of capture caused the pressure to drop in the oil and gas reservoirs, which lowered production and made them
unprofitable. There was another small boom in 1963, starting in Marle County, Ohio. This new boom brought in drillers from the west who drilled with a well spacing of one well per 40 acres and at least 440 ft from other wells. However, Ohio was still abiding by the capture theory of well drilling and drillers still drilled offset wells under the mindset of closeology. Natural gas was cheap and flared off along the streets. Derricks were in city lots, school yards, and church yards and slant-drilled under cemeteries. City and county governments could not control the excitement. On March 9, 1964, legislation was passed that limited well density to one well per 10 acres, and there had to be at least 660 ft between wells. The legislation also eliminated town drilling by stating that a well must be at least 200 ft from any dwelling. By October 1965, the boom was over. Although many wells are still being drilled in Ohio, their production is small.

The end result of the boom frenzy is that there are numerous wells that were abandoned between 44 and 100 years ago scattered throughout the area. Many of these consist of casings sticking out of the ground. In other cases, the casing has been removed or buried by farmers who plowed right over the old wells. Although the pressure in these wells is greatly reduced, it is believed that there is still oil in the Trenton Formation (Ordovician) (Vincent, 1997). If this is so, gas and oil could be seeping through uncapped or improperly capped wells. The Ohio Department of Natural Resources (ODNR) has a program to help farmers cap their old wells, but this program has two major flaws. First, it costs a considerable amount of money to cap a well, which means that the landowners are not always willing to report an old well on their property. Of course, they might not even know that they have wells on their property. With all the hustle of the boom days, well records of that time are not very complete, and the randomness of the locations due to the
capture legislation makes figuring their locations from past records extremely difficult. Secondly, when wells have been reported, it takes time to cap the thousands that are believed to have existed. One landowner said that her well has been on the capping list for over 10 years (Mrs. Augsburger, pers. comm.).

The purpose of this investigation is to find an inexpensive and rapid procedure for locating abandoned oil wells and to test this procedure in an area of Wood County, OH known to have numerous abandoned oil wells. Though some wells can be found by visual inspection of casings sticking out of the ground, many landowners have either buried or removed the casings making an alternative method of locating the wells necessary. These wells were at one time open to the environment and could have altered their surroundings. With the use of spectroscopic analysis on the surface, soil alterations caused by escaping hydrocarbons can be sought. The hypothesis proposed is that an old well can be detected by a characteristic reflectance spectrum of the soil, and that geophysical techniques can then be used to reveal subsurface effects of the escaping hydrocarbons.
SITE INFORMATION

The study area is in Wood County, which is located in northwest Ohio (Fig. 1). The location of the 10 wells used as test sites is shown in Figure 2.

Figure 1. Map of Ohio showing the location map of Wood County in northwest Ohio. Adapted from a State of Ohio department of Natural Resources map (2004).

Figure 2. Map of Wood County showing the location of wells used in this study. The dots denote well locations. Wells 1 and 2 are the northeast wells. They are on the same field so their dots overlap. Well 4 is the northwest dot. Wells 7, 8, 9 and 10 are on the same field in the center of the map with Well 5 just below, Well 3 is in the southwest and Well 6 is in the southeast. (BG) Bowling Green. (F) Fostoria. (NB) North Baltimore. (23) Route 23, the eastern border of Wood County.
The majority of the study area is between 0 and 6 percent slope, as can be seen in the topographic map of Wood County (Fig. A-1). Wood County has a relatively shallow water table. The majority of the wells are in an area where the water table lies at a depth of 1.5 to 4.5 m. Most of the aquifer media is massive limestone and dolomite, as denoted by the depth to water table in Figure A-2. The majority of the soil media in the region is aggregated clay (Fig. A-3). According to a soil survey of Wood County issued in 2007, many of the typical pedons in and around Wood County contain iron, for example the Fulton Series has small masses of iron accumulation in the soil (Robbins and Lantz, 2007). The soil map units that are in the vicinity of the 10 wells in this study are the: Hoytville Association, Hoytville-Ottokee-Rimer Association and the Mermill-Aurand-Hoytville Association. The major soils of these units are the Hoytville, Mermill, Aurand, Ottokee and Rimer soils. Iron masses can be found in each of these soils.
BACKGROUND INFORMATION

Following the old methods of superstition and dumb luck that were common at the turn of the 19th century, many new methods for locating hydrocarbons were developed. Many of these new methods focused on the physical and chemical properties of hydrocarbons and the impact that they have on their surroundings. The specific methods used in this analysis are remote sensing, magnetics, and electrical resistivity.

ALTERATIONS DUE TO HYDROCARBON ESCAPE

Hydrocarbons interact with the soil in many ways, changing both physical and chemical characteristics. Canet et al. (2006) discusses two structures that are formed on the seafloor around hydrocarbon seeps; for example, the authors discuss authigenic carbonates that form hard pavement-like surfaces on the seafloor and concretions that form at the seawater-sediment interface (Canet et al., 2006). At the surface, both the hydrocarbons and the soils are affected by weathering. Processes such as, biodegradation, leaching, polymerization, auto-oxidation, and gelation can alter hydrocarbons at the surface (Hunt, 1996). During biodegradation, organic compounds, such as hydrocarbons, are transformed into simpler inorganic compounds through oxidation. In aerobic environments, it was found that aromatic hydrocarbons could degrade from a concentration of 150 μg/L to less than 2 μg/L in less than a month (Schwartz and Zhang 2003). As the compounds get to be more complex, the rate of biodegradation decreases. Although these rates decrease, they still can be observed on human timescales (Röling et al., 2003).
According to Yang et al. (1998), biodegradation tends to yield red-bed bleaching, clay mineral alteration, carbonate anomalies, and geobotanical anomalies. The red-bed bleaching comes from the reduction of iron and precipitation of iron oxides. The clay mineral alteration tends to yield an abundance of kaolinite and illite when compared to non-altered clays (Yang et al., 1998). Light crude is digested first by microbes, leaving behind more complex hydrocarbons. Leaching along with water washing cause light compounds, including aromatic hydrocarbons, to be washed away. As a result of combining molecules, polymerization yields more complex structures. Gelation yields a solid structure over time (Hunt, 1996).

These physical alterations can aide in hydrocarbon exploration. Geochemical processes happen as the hydrocarbons migrate to the surface. During this migration, hydrocarbons take the path of least resistance to the surface, as demonstrated by Dou and Chang (2003), who note the relationship between faults, half grabens and the occurrence of petroleum systems. Because hydrocarbons travel the path of least resistance, which is often along fractures, faults or other geologic structures, it is often helpful to combine geochemical investigations with geologic and geophysical investigations (Hunt, 1996).

Another concern regarding hydrocarbons is their impact on groundwater. There are many ways for hydrocarbons to get into groundwater. Buried tanks, overturned trucks, service stations, and unplugged wells can all potentially leak. Once the hydrocarbons enter the soil, meteoric waters flow through the ground and contaminate the groundwater. Drinking this contaminated water can lead to any number of health risks. Consumption of organic compounds, such as hydrocarbons, “may cause cancer in humans and animals, and a host of other problems, including liver damage, impairment of cardiovascular function,
depression of the nervous system, brain disorders, and various kinds of lesions” (Schwartz and Zhang 2003).

REMOTE SENSING

Multi-spectral sensors record reflected (sunlight) and emitted (heat) by detecting electromagnetic rays from objects at the Earth’s surface. The wavelengths of these electromagnetic waves range from ultraviolet (0.2-0.4 µm) to visible (0.4-0.67 µm) to reflective infrared (0.67-4 µm) to thermal infrared (4-1000 µm) to microwave (1 mm-100 cm). The trace element chemistry of an object can be determined using the visible and ultraviolet wavelengths, while the thermal and reflective infrared wavelengths yield information about the bulk compositions (Vincent, 1997).

In 1989, Edward A. Cloutis proposed using remote sensing for hydrocarbon exploration. He found that in tar sands with medium-to-high bitumen concentrations, the depth of a bitumen absorption band spectrally located near 1.7 µm is related to the amount of bitumen in the sample. For hydrocarbon detections, he preferred this band over other C-H bands because they occur near 2.3 and 2.6 µm, which are close to water and OH absorption bands (Cloutis, 1989). Schumacher (1996) found that Landsat MSS and Thematic Mapper data can be used to test for three types of soil, sediment, and plant alterations related to hydrocarbon escape: reduction of ferric iron in red bed bleaching, kaolinite production due to the conversion of clays and feldspars, and unexpected vegetation reflectance where the vegetation is sparse (Schumacher, 1996).

Yang et al. (1999) used the Modular Airborne Imaging Spectrometer (MODIS) to find a red shift that may be associated with ethane concentration (Yang et al. 1999). This
red shift is found in the vegetation spectra. They believe it is due to anomalous chlorophyll content in areas of hydrocarbon seepage. In their study, this is observed through a color difference between wheat that grows above contaminated and non-contaminated areas (Yang et al., 1999). Almeida-Filho et al (1999) used LANDSAT TM ratios of Band 2/3 to determine iron-poor regions and Band 4/3 to distinguish those regions from vegetation. Then combining those ratios by taking the difference of Band 2/3 – Band 4/3 ratios to map areas of bleached materials (Almeida-Filho et al., 1999).

Horig and Kühn (2001) found that by using Hymap SWIR-1 bands 21 (1668.22 nm), 26 (1729.31 nm) and 31 (1788.98 nm) and creating a red, green and blue image, materials either contaminated by or made from hydrocarbons were distinguishable in the visible and near-infrared spectra. Van der Meer et al. (2002) found that natural gas seeps can be located indirectly by observing anomalous spectral responses of stressed vegetation. From these anomalies, they applied statistical methods and a Bayesian approach to identify known seeps.

From the above research, it is known that hydrocarbon seeps are associated with the production of carbonate cements and build-ups that may result from the anaerobic bacteria utilizing a two-stage process of carbonic acid reacting with calcium silicates to form diagenetic carbonate mineralization (Saunders et al., 1999). Biodegradation is present in both aerobic and anaerobic environments. It is a multi-phase process that generally starts by producing carbonates, then sulfates and nitrates. Another feature related to hydrocarbon seepage is a low potassium anomaly over the petroleum deposit (Saunders et al., 1999), as well as other mineralogical changes, such as the formation of pyrite, uranium, sulfur, and some magnetic iron oxides (Schumacher, 1996). However, with regards to remote sensing,
the most significant alteration to the surroundings due to hydrocarbon seepage would be a change in vegetation reflectance (Noomen et al., 2003).

MAGNETICS

The magnetic properties of a material are related to its composition. Magnetic methods utilize the magnetic properties of the iron oxides that are often found near the reducing environment of a hydrocarbon seep. For these magnetic materials to be found at all they need to be present in the soil surrounding the hydrocarbon seeps. In the case of Wood County, as noted in the site information, iron is often found accumulated loosely cemented in the soil. Magnetism is utilized in the form of magnetic susceptibility, the ease with which a material becomes magnetized in the presence of an external field (Reynolds, 1997). The susceptibility of a material is not only dependent upon composition but also upon the orientation and shape of the grains or the magnetic fabric of the material (Reynolds, 1997).

There are four magnetic categories that materials belong to: diamagnetic, paramagnetic, ferromagnetic and ferrimagnetic. Diamagnetic materials, such as halite, have paired electrons that cannot move between shells because all the shells are full. This arrangement yields a weak negative susceptibility (Reynolds, 1997). The electrons in paramagnetic materials have more freedom because they are not paired and do not have full shells. This allows for alignment in the presence of external fields. So, paramagnetic materials, such as amphiboles and garnets, have a weak positive susceptibility in the presence of an external magnetic field (Reynolds, 1997).
Ferromagnetic materials also have unpaired electrons, as well as the ability to overlap orbitals with neighboring atoms. This additional ability gives ferromagnetic materials a larger susceptibility; they contain substances such as iron, cobalt and nickel (Reynolds, 1997). The anti-parallel, unequal lattice structure of ferrimagnetic materials, such as magnetite, also yields a large magnetic susceptibility. These materials not only exhibit a large susceptibility in the presence of an external field, they also produce their own spontaneous magnetism (Reynolds, 1997). The magnetic susceptibility differences in each of these cases are due to the arrangement of the electrons in each type of material.

Saunders et al. (1999) used a combination of (1) airborne microwave sensing and laboratory analyses of gas hydrocarbons, (2) shallow-source aeromagnetic and soil magnetic susceptibility measurements, (3) aerial and surface gamma-ray measurements, and (4) geomorphology to find productive oil and gas deposits. Among their findings, they state that many deposits of petroleum show low potassium anomalies; many oil and gas regions display an apparently shallow source of magnetic anomalies. This change in magnetic susceptibility can be detected in as little as 10-20 years of contamination near hydrocarbon seepage (Saunders et al., 1999). As biodegradation breaks down the hydrocarbons, ions can be freed and then redeposit in an alignment that could either increase or decrease the magnetic susceptibility. In 2002, Gonzalez et al. (2002) found that highs in magnetic susceptibility and organic matter free radical concentration “roughly” coincide with high ethane concentrations.
ELECTRICAL RESISTIVITY

Electrical resistance of a material as defined by Ohm’s law is the ratio of the voltage divided by the current (Reynolds, 1997). It is a function of the geometry of the body and resistivity, which is a material property that describes its aversion to the flow of an electrical current. This property is potentially useful in hydrocarbon exploration because of the association that hydrocarbons have with minerals such as pyrite that have a low resistivity (Reynolds, 1997). Another possible resistivity low near a drilling site could be due to salt water. Saltwater is found in deep basins of permeable units (Schwartz and Zhang 2003). Once drilling commences, saltwater may be disturbed by drilling through it, pumping it up, and causing mixing between a fresh water aquifer and a deep salt water source. The aquifer, which might have been pure water, now has dissolved ions, hence, a resistivity low.

Benson and Mustoe (1998) combined electric resistivity, ground penetrating radar and very low frequency electromagnetic induction techniques to map groundwater contamination due to hydrocarbons leaking from underground storage tanks. While doing so, they found that sand that contains hydrocarbons exhibited a high resistivity. In contaminated soils, resistivity highs could come from two possible sources. Hydrocarbons in liquid form could be suppressing ion movement, yielding a resistivity high, or hydrocarbon gas could be filling the pore spaces acting as an electrical insulator, raising the resistivity.
METHODS

Wells were located through the ODNR’s orphan well list. Six property owners gave permission to study the wells on their land. These properties include wells that are in soybean, corn, and wheat fields, as well as wooded areas. Multiple photos were taken at each well and each well location was given a site number. Soil samples were collected from each site, and labeled with the date, site number, UTM coordinates recorded in NAD83, and grid locations relative to the proposed position of the abandoned well. The photographs and NAD83 coordinates of the wells are depicted in Figures A-4 to A-13.

Wells 1 and 2 are located on the same farm field. Comparatively, the diameter of well 1 is larger than well 2. These soil samples were collected on a rainy, windy day and a dark patch of soil was found next to Well 1, located on the edge of the farm field. Well 2 is surrounded by the corn field and appears to have a liquid (water) in it, most likely from the recent rain.

Well 3 is a buried metal casing topped with a metal plate at the location of the well. The land owner mentioned a past salt water and oil problem. There are other capped wells on this farmer’s property, but not near this location. The soil is dark north of the proposed location and the crop stubble is sparse and tilted toward the east, possibly indicating less healthy crops in this region. The proposed location of the well was determined according to information given to the farmer by a local agency.

Well 4 is located adjacent to a home owner’s driveway. The well has been filled with soil and covered with a ceramic tile. The owner believes this well to be a gas well, not an oil well. There is a lot of shrubbery east of the well.
Well 5 is located at the far end of a winter wheat field. The field was recently sprayed with nitrogen. The well is in the middle of a large sandy mound that is sparsely covered with vegetation. The coloration of the vegetation closest to the well changes from pale green to yellowish as it gets closer to the well.

Well 6 is a buried well. The first approximate location was between two coordinates. While collecting the geophysical data, a third location was given by the farmer’s son that was located southeast of the original location. There was a collapse at this location and the farmer’s son had to fill in the area with another soil type that looks paler than the rest of the field.

Wells 7, 8, 9 and 10 are all in one field. Well 7 is closest to the road and furthest east. The top of the casing is bent closed but open to the air. There is a pale patch of soil close to the road. However, this patch is most likely rubble from a building that used to stand there. Well 8 is also close to the road, but more westerly. Well 9 is north of Well 8. It has an odor and the air above the well appears to have gas flowing from the casing. Well 10 is located north from Well 7. There is shrubbery near well 10.

REMOTE SENSING

An ASTER image of the study area from April 22, 2006 was downloaded from Ohioview for spatial analysis with the ERMapper commercial software package.

Preliminary field data

The handheld-spectrometer (Fig. 3), was taken out in the field to a known well. This well is not numbered. It is located south of Bowling Green off of Defiance Road. A
spectral reading was taken immediately adjacent to the well, about 0.5 m from the well, over 10 m from the well, and over 100 m from the well toward the owner’s house, north from the well.

Figure 3. Set-up for the hand-held spectrometer in the lab.

Lab data

Because the in-situ method of measuring the spectral data of the preliminary field study was not easily repeatable, soil samples were collected in the field and the spectra were collected in the lab for all numbered well sites. This procedure controlled the amount of light and also limited the dependence on weather for data collection. The spectra between 0.4-2.5 µm were collected in the laboratory.
MAGNETICS

Total field magnetic intensity data were collected on an 8 m x 8 m grid with a Geometrics 856 proton precession magnetometer (Figure A-14). The center point of this grid is the well location or the proposed well location in the case of buried wells. From this total field intensity data, contour maps were created with Golden Software Surfer 8.

ELECTRICAL RESISTIVITY

Continuous electrical resistivity data were collected with a dipole-dipole array using a Geometrics Ohmmapper capacitively-coupled resistivity apparatus as seen in Figure 4. The data were first collected by traversing along the magnetometer grid lines, using transmitter-receiver separations (S-values) of 2.5, 5, 7.5 and 10 m to image the subsurface resistivity at various depths.

Figure 4. Schematic of the ohmMapper device that was used in the resistivity dipole-dipole survey, adapted from MagMap2000 OhmMapper Geometry. (F) length of the cable and weight, 2 m. (P) cables and receiver length 5 m. (C) cables and transmitter length, 5 m. (S) transmitter - receiver separation distance varied from 0.1 m to 10 m.

After viewing the first set of data, it was determined that a longer grid was needed. So, the grid range was changed to 0-8 m on the x-axis and 0-28 m on the y-axis, and the
well is at position 4, 14, the center of this new grid (Fig. A-15). The S-values were changed to 0.1, 2.5, 5 and 7.5 m to accommodate the new grid and in order to take readings closer to the surface. The contour maps were created with Golden Surfer8 software. Then, pseudo-sections were developed from the MagMap2000 software along the \( x = 4 \) line of the 8 m x 28 m grid. These pseudo-sections were used to create a depth inversion model with the Res2dinv software package least square option. This model shows two-dimensional resistivity for the subsurface of the studied area. In order to create this model, the subsurface is divided into blocks, and the size and location of these blocks is determined according to the data in the pseudo-section. The program will continually adjust the block resistivity values until it reaches a reasonable root mean square error between the recorded and calculated resistivity values. Once the program produces a model that agrees with the collected data set, the thickness of the first layer is set to 0.3 times the electrode spacing for the dipole-dipole array and the thickness of the deeper layers increases by 10 percent with depth (Geomoto, 2006).
RESULTS

As seen in the ground photos (Figs. A-4 to A-13), each well has a unique appearance. Many have a soil discoloration near the well. However, this effect becomes less visible closer to the well. As a matter of fact, when looking into the field from the street, the discolorations are not visible. In some cases, there is a small dark spot right next to the well. In most cases, there is a region, of varying size, of pale (possibly bleached) soil.

REMOTE SENSING

Preliminary field data

The preliminary field spectra data (Fig. 5.) showed absorption bands at 1.4, 1.9, 2.2 and 2.3 μm for the topmost spectrum (labeled oilsoila). Oilsoila, nearest to the well, shows a 2.3 μm absorption feature. Oilsoilb, less than a meter away, does not show the 2.3 μm absorption feature. Soil 1 and soil 2a, taken 20 m away, do not show the 2.3 μm absorption feature. Soil 2, taken along the edge of the farm field, over one hundred meters from the well, does not show the 2.3 μm absorption feature. All of the spectra in Figure 5 are field spectra, which were collected only in the vicinity of the preliminary well, which does not have a number.
Figure 5. Field study spectral data.

Lab data

Figure 6 shows the laboratory spectral data for soil samples from eight of the ten wells that were studied in the laboratory. Every spectrum showed a small reflectance minimum near 2.2 μm. A three-band ratio calculation was done for all of the collection points at each well. (Band 1 was to the left of the 2.2 μm reflectance minimum, a shorter wavelength, Band 2 was at the minimum and Band 3 was to the right of the minimum, a longer wavelength.) These absorption features are similar to those found by Yang et al. (1998) of 1.72 μm, 1.76 μm, 2.31 μm and 2.33 μm. Yang et al. (1998) states that these features are common to altered minerals and are similar to kaolinite, illite and calcite absorption bands. This article also states that in areas of hydrocarbon contamination the clays were found to have more kaolinite and illite than non-contaminated areas.

In order to locate the 2.2 μm feature in this study, the calculation performed was the three-band ratio of the average of Bands 1 and 3 divided by Band 2. This calculation is shown in Table 1. Looking at the results of this calculation, two things can be noted. First, this ratio is not always largest when nearest the well, and secondly, the result can vary as
little as one thousandth in any given direction from the well. That is, the largest ratio is not always at the well; sometimes it is in either direction of the well, possibly due to hydrocarbon migration. A larger image of each graph, along with the three-band ratio calculations for nine of the wells, is in the appendix, Figures B-1 to B-8.

Although the ratio calculations were highly variable, a grey scale image of this three-band ratio was attempted with ASTER. The following ASTER bands were employed as Bands 1, 2, and 3 in the three-band ratio calculation described above: ASTER Band 5 (2.145 – 2.185 μm), ASTER Band 6 (2.185-2.225 μm), and ASTER Band 7 (2.235-2.285 μm), respectively. As seen in Figure B-9 of the appendix, the information from this image was inconclusive because the greatest ratio value was not always closet to the well.
Figure 6. In Lab Spectral results. Absorption bands at 1.4 μm and 1.9 μm, often denoted as water absorption bands, and small absorption bands at 1.75 and 2.2 μm, associated with hydrocarbons are found on all spectra. (A) Well 1. (B) Well 2. (C) Well 3. (D) Well 4. (E) Well 5. (F) Well 7. (G) Well 9.
Figure 6 continued.
Figure 6 continued.
Figure 6 continued.
Table 1. Three-band ratio calculation for wells 1-5, 7 and 9. Band 1, wavelength less than 2.2 μm absorption feature. Band 2, contains the 2.2 μm absorption feature. Band 3, wavelength greater than 2.2 μm spectral feature. The equation shows the three-band ratio which took the average of bands 1 and 3 and divided that by band 2.

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MAGNETICS

Figure 7 shows the total field magnetic intensity contour maps for all 10 wells. All 10 showed magnetic anomalies ranging in intensity from 2600 to 4400 gamma. In most cases, the magnetic field intensity increases in the vicinity of the well. However, there are
some variations. Well 5 has a magnetic low near it with a general increase in the magnetic field intensity around it. Both Wells 3 and 6 have no exposed casing and have magnetic highs within the grid, but not directly over the proposed location, probably due to the uncertainty of the proposed well position. Larger versions of each contour map can be found in the appendix (Figs. C-1 to C-12).

Figure 7. Contour maps of total magnetic field intensity (in gammas) for all 10 wells. Figures A through J correspond to Well 1 through Well 10.
Figure 7 continued.
ELECTRICAL RESISTIVITY

The first resistivity survey used S-values (see Figure 4) of 2.5, 5, 7.5 and 10 m on an 8 m x 8 m grid (Fig. A-14). These data showed a relative low in resistivity within 5 m of the well, probably because the device had stopped too close to the well site and had not advanced the center point of the S-value across the well site. Since there were not any readings taken over the well site, the contour maps made from this data yielded a relative low where no data was present. The second survey used S-values of 0.1, 2.5, 5 and 7.5 m over an 8 m x 28 m grid with the well located at position 4, 14 m (Fig. A-15). Contour maps of the second data collection reveal a resistivity high within 5 m of the well at S-values of 0.1, 2.5, 5 and 7.5 m (Figs. C-13 to C-17). Using the second collection of resistivity data, the depth inversion models were calculated with the Res2dinv software, and the least square option. These cross sections show a resistivity high within 2 m of the well for all five surveyed wells, as is seen in Figure 8 and in a larger scale in the appendix (Figs. C-18 to C-22). The V-shapes in the depth inversion models are due to the relationship between the S-value and the depth of the reading. Since readings were taken in alternating direction along the grid, the reading depths are not repeated on the opposite side of the grid, leaving null data on alternating sides.
Figure 8. Resistivity depth inversion models Wells 3, 6, 7, 8 and 9 (A through E, respectively). The well locations are approximated by rectangles. The middle image is the least square model applied to the actual data and the bottom image is the depth inversion.
Figure 8 continued.
Figure 8 continued.
Figure 8 continued.
DISCUSSION

REMOTE SENSING

The spectra collected in the field show an absorption band near 2.3 μm. According to Liefer et al. (2006), a strong absorption band near 2.3 μm represents methane (CH₄). The gaseous nature of methane makes it unlikely to be detected from the samples that were brought back to the lab. The soil samples collected in the field and measured in the laboratory showed an absorption band around 2.2 μm. According to the application notes of Analytical Spectral Devices, Inc., the manufacturer of the hand-held spectrometer, this band corresponds to bitumen. However, the gray scale, three-band ratio image produced using bands 5, 6 and 7 in ASTER was found to be inconclusive. It is thought that this image does not reveal any anomalies because the absorption minimum is relatively small and the 30 m spatial resolution of the ASTER is too large to show alterations from escaped hydrocarbons around individual abandoned wells. Furthermore, the absorption bands for vegetation may be overpowering those of the hydrocarbons because the fields with crops in them (at the time of ASTER overpass, which was on April 22, 2006) appear bright in the image. Comparing grayscale and color images, it seems as if the brightness is due to vegetation. Since the brightness of the well locations is not consistent, this method was found to be inconclusive.

The three-band ratio, as depicted by the calculations in Figures B-1 to B-8, shows that a device would need extremely fine spectral resolution to detect the 2.2 μm minimum. The 2.3 μm absorption band found in the field was much wider than the 2.2 μm absorption band found in the lab. However, attempting the closest facsimile of this three-band ratio
possible with ASTER spectral bands was also found to be inconclusive. This 2.2 μm absorption feature of bitumen is unlikely to be found with the current spatial and spectral resolution of ASTER. Other methods that may prove interesting in the future could use the hydrocarbon equation method employed by Yang et al. (2000) and Kühn et al. (2004). Yang et al. (2000) used a Modular Airborne Imaging Spectrometer (MAIS) that was on an airplane that flew 4000 m over the study site. Their equation used a band centered at 758.25 nm, one centered at 739.00 nm and one centered at 719.75 nm and the reflectance of those bands in order to look for the red edge shift in the spectra, probably caused by varying chlorophyll contents, in vegetation around the micro-seep. Kühn et al. (2004) used HyMap data that were collected at a height of 1137 m over the field site. They used SWIR Bands 24 (1705 nm), 26 (1729 nm) and 27 (1741 nm). Kühn et al. (2004) was looking for the 1.73 μm absorption feature. They found that stretching of the grey scale image had a large impact on the quality of the resulting image. They both used airborne technologies, which are much more expensive, cover smaller regions at one time, and have many more and narrower spectral bands than ASTER.

MAGNETICS

The positive magnetic anomaly over the 10 wells is either a result of the well casing, the soil around the wells, or a combination of both. It is intuitive that a buried vertical casing should yield a map with concentric contours. For the most part, the magnetic contour maps display this pattern. Wells 8, 9 and 10 have casings lying horizontally on the ground next to the wells, parallel to the elongation of the contours on the map.
A magnetic study of hydrocarbon seeps by Cisowski and Fuller (1987) found that magnetic anomalies resulting from petroleum seeps are insufficient for correlation purposes. Yet, Liu et al. (2004) found a relationship between soil magnetism and the formation of magnetic minerals in the vicinity of hydrocarbon seeps that supports the findings of this current study. However, his findings were high frequency and low magnitude and the findings of the current study are high magnitude and low frequency. Considering the fact that casings were present at all of the sites in the study, the anomaly may be due to the casing and could possibly be shielding any anomalies that may be due to biodegradation. It is also interesting to note that Liu et al. (2004) found that the anomaly could be either positive or negative, depending on the specific site, due to the complexity of soil magnetism. Although the biodegradation process can cause deposition of iron rich materials, the deposits may occur down stream, depleting the area nearest the contamination and producing a low susceptibility at the site.

Considering the fact that this study found a relative high at all ten wells, and it is known that there is a metal casing in at least nine of the ten wells, the high magnitude anomaly is most likely the result of the well casing, whereas the variation in the shape of the anomaly may result from magnetic mineral formation, such as iron oxides, during hydrocarbon escape.

ELECTRICAL RESISTIVITY

Considering the metal casing, the resistivity highs found within 5 m of the five resurveyed wells were at first perplexing. Not only would the metal in the casing yield a resistivity low, but possible mineralization and salt water would also yield a resistivity low.
If materials around the well have pore spaces that are filled with gas, the resistivity would be lower than if the pores were filled with water. As for the saltwater that was most likely present during drilling, abundant rainfall typical of the moist environment of northwest Ohio, would have dissolved and carried it away. The well casings could also produce a possible route for hydrocarbon escape, which could yield a resistivity high. Delaney et al. (2001) states that hydrocarbons are “excellent insulators and exhibit very high values of resistivity.” Gases that make their way toward the surface of the soils would fill the pore spaces that could have been filled with water, a more conductive material (assuming that water found in farm fields contains some form of dissolved solids); thus, the resistivity of the soil increases with an influx of natural gas.

Another possible cause of the resistivity highs could be the residue of any hydrocarbon seeps that might be associated with the wells. Geochemical processes, such as leaching and water washing, rid areas near a seep of ions that lower the resistivity. The ground that is washed of ions becomes more resistive. This model is less plausible because biodegradation would also affect the area simultaneously. Biodegradation would result in a resistivity low because organic acids released by life forms are much less resistive to electron flow than are hydrocarbons.

An additional consideration of this study is that the original data collection was in the spring and early summer, whereas the second survey was in the winter, under sub-zero temperature conditions. Delaney et al. (2001) performed a study that compared the resistivity of contaminated areas, frozen areas, and frozen hydrocarbon contaminated areas. This study showed that electrical resistivity increases when the ground is frozen and that contaminated ground has an even higher resistivity when frozen. These results are
definitely something to consider when taking into account absolute resistivity readings.
However, the findings of the present study focus on relative resistivity highs. There were resistivity highs in locations further from the well. These highs were not as pronounced as those nearest the well and the magnetic data only coincided with the highs found nearest to the wells. There are a number of possible sources for these highs including, variable moisture content and soil compaction throughout the farm field.
CONCLUSIONS

Ultimately, satellite remote sensing was found not to be very useful for finding abandoned wells. Due to the small width of the 2.2 µm absorption band and the 30 m spatial resolution of the ASTER SWIR bands and LANDSAT TM bands (too coarse for finding abandoned oil wells), the use of those two satellites to detect abandoned wells is not feasible. Contrary to the remote sensing technique, the geophysical techniques were found to be quite useful.

The total field magnetic intensity contour maps yielded a high magnitude low frequency anomaly that is most likely due to the well casings. If the anomalies were due to ferrimagnetic or ferromagnetic materials as in Lui et al. (2004), these anomalies would be high frequency and low amplitude. Thus, it may be possible to detect hydrocarbon seeps with ferromagnetic and ferromagnetic materials that form during the biodegradation of hydrocarbons even without the well casings. Unfortunately, this study did not have such an opportunity and can neither support nor refute the findings of Lui et al. (2004.)

Residual petroleum contamination is another possible source of the resistivity high, as suggested by Delaney et al. (2001). However, the processes that would have yielded the residue take time and could have been occurring at the same time as the biodegradation. Thus, there are possibly multiple types of geochemical processes interacting with each other and it is unclear as to which process is dominant in this situation.

It is thought that these 44 and 122 year-old wells are possibly seeping hydrocarbons. The wells were never plugged. Also, if there was not a continual source of
contamination, biodegradation would have altered the hydrocarbons, yielding organic acids and creating a relative resistivity low rather than the highs found at the five surveyed wells.

Though this study did not revisit all 10 wells during the second resistivity survey, it seems reasonable to suspect that they would have similar anomalies. These similar anomalies would lead one to the conclusion that they are all likely seeping. Not only are all of them unplugged, the flat terrain of northwest Ohio, in conjunction with its quiescent tectonic setting, makes it reasonable to extrapolate the findings of the five surveyed wells onto the other five because hydrocarbons tend to follow the path of least resistance.

The exact quantity of escaped hydrocarbons is unclear. Further investigation into these sites is needed, to determine whether they are currently seeping or simply marked from the residue of past activity. After further study the degree to which these materials are contaminating the groundwater could be determined. Either way, however, this resistivity high proved useful in locating unplugged abandoned wells.

The consistency of the magnetic and resistivity surveys indicates that these two geophysical methods are useful in locating abandoned wells. This consistency suggests that the most effective method for locating abandoned oil and gas wells in regions similar to northwest Ohio is a two-step process: first, magnetics should be used to detect positive anomalies; second, over the area found to have a positive magnetic anomaly, electrical resistivity measurements and depth inversion models of the data should be implemented to search for an area of relative high resistivity. The location where these two highs coincide is likely the location of a well that needs to be plugged.
REFERENCES


(Available at the Wood County District Library, 251 North Main Street, Bowling Green, Ohio).


APPENDIX A: SITE INFORMATION

Appendix A contains Geologic Maps of Wood County and photographs of each well, along with the grid layouts for both the magnetic and electrical resistivity surveys.
Figure A-1. Topographic map, Wood County, Ohio. Adapted from ODNR DRASTIC map. [http://www.dnr.state.oh.us/gims/report.asp](http://www.dnr.state.oh.us/gims/report.asp)
Figure A-2. Depth to water table, Wood County, Ohio. Adapted from ODNR DRASTIC map. [http://www.dnr.state.oh.us/gims/report.asp](http://www.dnr.state.oh.us/gims/report.asp)
Figure A-3. Soil media Map, Wood County, Ohio. Adapted from ODNR DRASTIC map. http://www.dnr.state.oh.us/gims/report.asp
Figure A-4. Photographs of Well 1. (A) Well casing. (B) Stained soil adjacent to well. Well located at 4584693 N, 297884.2 E NAD83.
Figure A-5. Photographs Well 2. (A) Well casing (B) Inside well showing liquid. Well located 4584714 N 297892.7 E NAD83.
Figure A-6. Photograph of Well 3 location. Well located at 4561160 N, 278933 E NAD83.

Figure A-7. Photograph Well 4. Well located at 4583490 N 274849E NAD83.
Figure A-8. Photograph Well 5. Well located at 4572992 N, 283575.7 E, NAD83.

Figure A-9. Photograph Well 6. Proposed well location 4561850 N, 291757.1 E, NAD83.
Figure A-10. Photograph Well 7. Well location 4574952 N 284943 E NAD83.

Figure A-11. Photograph of Well 8. Well located at 4574951 N, 284781.7 E, NAD83.
Figure A-12. Photograph Well 9 Well located at 4575103 N, 284780 E, NAD83.
Figure A-13. Photograph Well 10. Well located at 4575111 N, 284951 E, NAD83.
Figure A-14. Magnetics 8 m x 8 m grid layout. Centered on well.
Figure A-15. Resistivity 8 m x 28 m grid layout with 2 m separation. Well located at 4, 14.
APPENDIX B: REMOTE SENSING DATA

Appendix B contains the spectral graphs, three-band ratio calculations and the ASTER images from this study.
Figure B-1. Well 1 Spectral graph and three-band ratio calculation.
Figure B-2. Well 2 Spectral graph and three-band ratio calculation

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Figure B-3. Well 3 Spectral graph and three-band ratio calculation.
Figure B-4. Well 4 Spectral graph and three-band ratio calculation.
Figure B-5. Well 5 Spectral graph and three-band ratio calculation.
**Figure B-6.** Well 7 Spectral graph and three-band ratio calculation.
Figure B-7. Well 9 Spectral graph and three-band ratio calculation.

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Figure B-8. Well 10 Spectral graph and three-band ratio calculation.
Figure B-9. ASTER Images. (Northeast dot) Wells 1 and 2. (Southerly central dot) Well 5. (Southernmost dot) Well 6. (Central dots) Wells 7-10. Zoomed images Wells 1 and 2, Well 5, Well 6 and Wells 7-10 respectively. Figure A. bands 1-3, Blue, Green, Red. Locations yellow vegetation red. Figure B. Grey scale three-band ratio locations red, band 5 plus band 7 divided by band 6.
APPENDIX C: GEOPHYSICAL DATA

Appendix C contains the total field intensity magnetic contour maps, the resistivity contour maps and the resistivity depth inversions.
Figure C-1. Well 1 total field magnetic intensity contour map. (Y-axis) northing (m). (X-axis) Easting (m) NAD83. Contours of total field magnetic intensity are gammas.
Figure C-2. Well 2 total field magnetic intensity contour map. (Y-axis) northing (m). (X-axis) easting (m) NAD83. Contours of total field magnetic intensity are gammas.
Figure C-3. Well 3 total field magnetic intensity contour map. (Y-axis) north (m). (X-axis) east (m). Contours of total field magnetic intensity are gammas.
Figure C-4. Well 3, extended grid, total field magnetic intensity contour map. (Y-axis) north (m). (X-axis) east (m). Contours of total field magnetic intensity are gammas.
Figure C-5. Well 4 total field magnetic intensity contour map. (Y-axis) north (m). (X-axis) East (m). Contours of total field magnetic intensity are gammas.
Figure C-6. Well 5 total field magnetic intensity contour map. (Y-axis) north (m). (X-axis) east (m). Contours of total field magnetic intensity are gammas.
Figure C-7. Well 6, first proposed position, total field magnetic intensity contour map. (Y-axis) northing (m). (X-axis) Easting (m) NAD83. Contours of total field magnetic intensity are gammas.
Figure C-8. Well 6, second suggested location, total field magnetic intensity contour map. (Y-axis) northing (m). (X-axis) easting (m) NAD83. Contours of total field magnetic intensity are gammas.
Figure C-9. Well 7 total field magnetic intensity contour map. (Y-axis) north (m). (X-axis) east (m). Contours of total field magnetic intensity are gammas.
Figure C-10. Well 8 total field magnetic intensity contour map. (Y-axis) north (m). (X-axis) east (m). Contours of total field magnetic intensity are gammas.
Figure C-11. Well 9 total field magnetic intensity contour map. (Y-axis) north (m). (X-axis) east (m). Contours of total field magnetic intensity are gammas.
Figure C-12. Well 10 total field magnetic intensity contour map. (Y-axis) northing (m). (X-axis) easting (m) NAD83. Contours of total field magnetic intensity are gammas.
Figure C-13. Well 3 resistivity contour maps labeled and scaled according to S-values. These data were from the second survey using an 8 m x 28 m grid and S-values of 0.1, 2.5, 5, and 7.5 m. (A) 0.1 m S-value. (B) 2.5 m S-value. (C) 5.0 m S-value. (D) 7.5 m S-value. Contour intervals 0.3, 2, 15, 250 respectively.
Figure C-13 continued.
Figure C-14. Well 6 resistivity contour maps labeled and scaled according to S-values. These data were from the second survey using an 8 m x 28 m grid and S-values of 0.1, 2.5, 5, and 7.5 m. (A) 0.1 m S-value. (B) 2.5 m S-value. (C) 5.0 m S-value. (D) 7.5 m S-value. Contour intervals 0.3, 2, 15, 250 respectively.
Figure C-15. Well 7 resistivity contour maps labeled and scaled according to S-values. These data were from the second survey using an 8 m x 28 m grid and S-values of 0.1, 2.5, 5, and 7.5 m. (A) 0.1 m S-value. (B) 2.5 m S-value. (C) 5.0 m S-value. (D) 7.5 m S-value (D2) Enlargement of anomaly north of Well 7. Contour intervals 0.3, 2, 15, 250 respectively.
Figure C-15 continued.
Figure C-16. Well 8 resistivity contour maps labeled and scaled according to S-values. These data were from the second survey using an 8 m x 28 m grid and S-values of 0.1, 2.5, 5, and 7.5 m. (A) 0.1 m S-value. (A2) Enlargement of anomaly near well with 0.1 m S-value (B) 2.5 m S-value. (C) 5.0 m S-value. (D) 7.5 m S-value. Contour intervals 0.3, 2, 15, 250 respectively.
Figure C-16 continued.
Figure C-17. Well 9 resistivity contour maps labeled and scaled according to S-values. These data were from the second survey using an 8 m x 28 m grid and S-values of 0.1, 2.5, 5, and 7.5 m. (A) 0.1 m S-value. (A2) Enlargement of anomaly near well with 0.1 m S-value. (B) 2.5 m S-value. (C) 5.0 m S-value. (D) 7.5 m S-value. Contour intervals 0.3, 2, 15, 250 respectively.
Figure C-17 continued.
Figure C-18. Contoured resistivity data for Well 3. (A) Measured apparent resistivity pseudo-section (B) Calculated apparent pseudo-section. (C) Inversion Model Resistivity Section. The well is located at approximately 14 m, denoted by a rectangle in each Figure. Resistivity highs in the depth section are located at 16.3 m, 19.5 m, 22.7 m, 25.9 m and 29 m along the surface.
Figure C-19. Contoured resistivity data for Well 6. (A) Measured apparent resistivity pseudo-section (B) Calculated apparent pseudo-section. (C) Inversion Model Resistivity Section. The well is located at approximately 14 m, denoted by a rectangle in each Figure. Resistivity highs in the depth section are located at -6.65, 6.15, 9.25, 12.6 and 15.8 m.
Figure C-20. Contoured resistivity data for Well 7. (A) Measured apparent resistivity pseudo-section (B) Calculated apparent pseudo-section. (C) Inversion Model Resistivity Section. The well is located at approximately 14 m, denoted by a rectangle in each Figure. Resistivity highs in the depth section are located at 6.72, 13.1, 19.5 and 25.9 m.
Figure C-21. Contoured resistivity data for Well 8. (A) Measured apparent resistivity pseudo-section (B) Calculated apparent pseudo-section. (C) Inversion Model Resistivity Section. The well is located at approximately 14 m, denoted by a rectangle in each Figure. Resistivity highs in the depth section are located between 6.88 and 16.5 m.
Figure C-22. Contoured resistivity data for Well 9. (A) Measured apparent resistivity pseudo-section (B) Calculated apparent pseudo-section. (C) Inversion Model Resistivity Section. The well is located at approximately 14 m, denoted by a rectangle in each Figure. Resistivity highs in the depth section are located at -1.9, 6.06, 10.9, 14.1, 15.7 and 17.3 m.