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Utilizing A Magnometer To Locate Abandoned Oil Wells In Butler County, Kansas

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UTILIZING A MAGNETOMETER TO LOCATE ABANDONED
OIL WELLS IN BUTLER
COUNTY, KANSAS

being

A Thesis Presented to the Graduate Faculty
of the Fort Hays State University in
Partial Fulfillment of the requirements for
the Degree of Master of Science

by

Christopher D. Neeley
B.S., Fort Hays State University

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GRADUATE COMMITTEE APPROVAL

The Graduate Committee of Christopher D. Neeley hereby approves his thesis as meeting partial fulfillment of the requirement for the Degree of Master of Science.

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Date_____________________

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ABSTRACT

Two ground-based magnetometer surveys were conducted on the American Legion Brownfields Targeted Assessment site in El Dorado, Kansas during November 2011, in an attempt to locate two oil and gas wells that were abandoned prior to 1939. The search areas were delineated by Kansas Corporation Commission staff, and prior to the magnetometer surveys, investigated with ground penetrating radar and a metal detector in an unsuccessful attempt to locate casing material or backfilled drilling cellars.

The magnetometer surveys yielded several anomalies that were dismissed as cultural noise after the results were compared with field observations. Two anomalies in survey area #1 were isolated from known cultural features and occurred in the same location as four anomalies that were detected by the ground penetrating radar. The magnetic anomalies were morphologically irregular; had intensities of 80 nanoteslas and 112 nanoteslas, and depths of 1.5 meters and 2 meters respectively. Survey area #2 has a positive magnetic gradient that increases in the direction of a known plugged well outside of the search area, and a circular anomalous low of 145 nanoteslas, adjacent to a vertical steel pipe, which is approximately 5 meters outside of the study grid.

Further investigation is required to further the conclusions of this work. The anomalies within survey #1 are primary targets for excavation, which will allow the identity of the objects causing the anomalies to be determined. The areas adjacent to the magnetic gradient and anomalous low in survey #2 should be surveyed to determine if the magnetic character within the grid is related to the cultural features outside of the search area.
ACKNOWLEDGMENTS

The completion of this thesis was only accomplished with the assistance of many individuals. My graduate committee, Dr. Thomas Schafer, Dr. Hendratta Ali, and Mr. Case Morris; chaired by Dr. Kenneth R. Neuhauser, was absolutely invaluable as a source of insight and direction, and much of the credit is due to them for their commitment. Dr. John Heinrichs is due thanks for encouraging me to analyze every possible source for error in this research. As a result of his fierce attention to detail, I feel that this thesis is more complete.

The environmental concern that forms the basis of this project was presented to me as a possible thesis by Jeffery Klock and David Bollenback of the Kansas Corporation Commission. In addition to providing the inspiration, a wealth of previous research, and answering my questions, they provided their assistance, along with my fellow graduate student, Adam Staab, in the field while I conducted the magnetometer surveys in El Dorado, Kansas.

Thanks must also be given to my wife, Andrea, and to my parents, for their support and understanding through the years. Without them, I would not have made it this far, and of course, to Rowan.
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INTRODUCTION

Location

Crude oil and brine resulting from oil production during the early 20th century continues to be a significant concern on the former site of the American Legion golf course in El Dorado, Kansas in the SW ¼, Section 3, T26S, R5E (Fig. 1) (Geotechnical Services, Inc., 2009).

Objective

The objective of this study was to investigate two areas within the former golf course that are the suspected locations of two abandoned oil wells, and to determine if casing material, related ferrous items, or the cellars that were once beneath the drilling floor of a cable tool drilling rig can be detected. Previous studies have shown that the use of a magnetometer to locate ferrous materials below grade, including well casings, is a well-tested technique (Baer et al., 1995; Martinek, 1988; Xia, 2002; Neuhauser, personal communication, 2013; Rebar et al., 2005). The success of this survey could allow the
Kansas Corporation Commission (KCC) to mitigate any environmental hazard associated with the wells.

Geology and Hydrology

The city of El Dorado and all but a small portion of eastern Butler County are within the Flint Hills uplands physiographic region in Eastern Kansas (Aber, 1991). The Flint Hills are formed by the cropping out of Permian strata in a band stretching from Northeastern Kansas to the Oklahoma border in South Central Kansas and beyond (Merriam, 1963). The strata underlying the study area is that of the Permian Chase Group (Fig. 2); though definitive identification of the bedrock at the formation or member level has not occurred previously during work specific to the site, or the present research.

![Figure 2—The Stratigraphic Succession of the Chase Group. (after Zeller, 1968).](image)
The Fort Riley Member is a light gray or tan thinly bedded limestone with thin, shaly beds in the basal and middle portions, and is noted for a conspicuous outcrop pattern and a massive “rim rock” bed in the middle portion of the member. The thickness of the member ranges from 30 to 45 feet (Zeller, 1968). A previous report states (Geotechnical Services Incorporated, 2009), that the Geologic Map of Butler County, by Aber (1994) (Fig. 3) shows the bedrock beneath the survey areas is that of the Fort Riley Limestone Member of the Barneston Formation.

Figure 3—The Geologic Map of Butler County taken from Aber (1994). Doyle Shale = Pbd; Barneston Limestone Formation = Pbf. The cross hatching = city of El Dorado.
However, the geologic map of Butler County, as compiled by James S. Aber (1994), actually identifies the underlying formation as undifferentiated Doyle Shale, which in descending order is made up of the Gage Shale, the Towanda Limestone, and the Holmesville Shale Members, which together have a thickness of roughly 70 feet (Zeller, 1968).

The map included in “Geology of the El Dorado [sic] oil and gas field”, by Fath (1921), shows the American Legion’s former property is divided by Constant Creek with the Doyle Shale being the bedrock unit on the east half and the Fort Riley Limestone Member on the west (Fig. 4). The presence of a sinkhole west of Constant Creek could arguably be viewed as evidence that supports the geologic interpretation provided by Fath, because sinkholes are numerous within the Fort Riley Limestone throughout Butler County (Aber, 1991).

An extensive soil sampling program was undertaken by Terracon Consultants, Inc., in 2011, to establish the thickness of the soil mantle, and the elevation of the top of the bedrock. Samples were taken and a probe was driven to bedrock at 79 locations. The upper surface of the bedrock ranged in depth from 0.61m (2ft) to 4.8m (15.75ft) below ground surface. The soils overlaying the bedrock are generally considered to be nearly level, or gently sloping Dwight-Labette, which are widespread throughout the uplands of Butler County. The surface layers are silty loam or silty clay loam, and the subsoils are silty clay (Penner et al., 1975).
The data resulting from the Terracon survey was contoured to show the elevation of the bedrock surface. By drawing a line that crosses down gradient contour lines at right angles, the direction of drainage can be approximated and measured. As expected, the theoretical groundwater gradient dips toward a perennial stream, Constant Creek, which has bisected the property by incising a shallow valley that runs generally northwest to southeast.

Figure 4—The Map of the Eldorado [sic] Oil and Gas Field Butler County, Kansas; from Fath (1921). This excerpt shows areal geology and the structure of the Fort Riley Limestone (contour interval 10 feet; mean sea level datum). The SW ¼ of section 3 is outlined in red. Cd = Doyle shale; Cdt = Doyle Shale containing Towanda Limestone; Cfr = Fort Riley Limestone; ⬇ = Dry hole drilled into the “600ft sand zone”; ⬆ = Dry hole drilled into the Stapleton zone.
Historical Background of Study Area

Until the property was purchased by the American Legion in 1927, it was used principally for agriculture. The American Legion constructed a sand golf course around 1937. The process for constructing the sand greens required soaking the sand greens with waste oil multiple times each year (Taylor, 1931). In 1958, the sand greens were replaced with grass. The construction of the grass course led to extensive anthropogenic reworking of soils and other improvements to the site including: construction of buildings, concrete pathways, dirt construction, and additional trees being planted.

The discovery well for the El Dorado oil and gas field, Stapleton #1, was drilled in 1915 near El Dorado, Kansas, though exploration and production in the area had begun closer to the turn of the century. By 1918, the field was producing more than any other in the United States (Fath, 1921). The large amount of oil and gas held in reserve contributed to a singular effort to develop the field. Beginning in 1909 or 1910, with the city of El Dorado’s attempt to produce gas for municipal use by drilling on what was then the farm of A. J. Holderman, which later became the American Legion Golf Course, there have been 18 wells drilled, and properly recorded, in section 3. The Kansas Geological Survey’s (KGS) Interactive Oil and Gas Map, displays three wells on the American Legion Brownfields Targeted Assessment (BTA) site in the SW ¼ of section 3, T26S, R5E (Killion, 2013).

The wells listed are one plugged and abandoned oil well, and two cathodic protection wells. However, three maps of the area spanning 20 years show that five wells were drilled prior to 1939 in the SW ¼ of section 3; three of which are on the American
Legion’s former property (Figs. 4, 5, & 6). Two of these wells are displayed as dry and abandoned, and the third as a plugged and abandoned oil well. These five wells are not recorded in the “Master List of Oil and Gas Wells in Kansas” compiled and maintained by the Kansas Geological Survey (2013) or the records of the Kansas Geological Society. As such, the disposition of these wells is unknown, but it is justifiably assumed that the abandonment was not carried out in an environmentally sound manner.

Figure 5—1933 Cities Service Map Showing Wells drilled on the Holderman and Kaufman leases (Geotechnical Services Inc., 2009); the former American Legion Golf Course is outlined with red. The two arrows point to the wells that were targeted by the study areas.
The contamination at this site has been repeatedly brought to the attention of regulatory agencies. Since the early 1940s, the Kansas Department of Health and Environment (KDHE) have received numerous reports of pollution at the site. In June 1941 a letter sent to the State Board of Health (now KDHE) by F. J. Leasure stated, “The local Post of the American Legion owns and operates a golf course immediately west of the city of El Dorado. A small stream flows through the course and empties into the Walnut River about a mile and a half from the southern boundary of the land used for the

Figure 6—1939 Map Showing Well Development in the Survey Area (Geotechnical Services Inc., 2009)
golf course. A heavy rain causes this stream to overflow, and each time it overflows oil, oil refuse and salt are brought down the stream. Some of it is spread over the golf course, and of course a large quantity of such refuse is carried into the Walnut River.” In 1976 oil runoff severely impacted the north pond on the course, causing a fish kill, which prompted the United States Coast Guard (USCG) and the Environmental Protection Agency (EPA) to take remedial action (KDHE, 2009).

The target of the EPA and USCG efforts was a containment reservoir and former skimming structure that was constructed around a sinkhole that is present in the southern portion of the property, but not within the study area.

A mitigation and remediation plan was designed to take advantage of the existing sinkhole and the enclosure for the skimming operation. An oil separator was constructed adjacent to the uppermost pond on the property that would allow the oil and water to naturally separate over time. The structure was connected to the pond by pipes that would draw off only the water and leave the floating oil behind. The separator was also connected to the sinkhole through an underground aqueduct lined with limestone blocks. The wall around the sinkhole was left intact to prevent any accumulated oil from escaping over the top of the sinkhole during heavy rainfall events. Additional studies of the area were planned to locate the original source or sources of the oil. The long-term remediation of the problem was also part of the three phase project. Due to cost constraints, the construction of the separator was the only portion of the plan ever implemented. Within 10 years it had filled with sediment and was ultimately destroyed by fire. Attempts to rebuild an improved version of the separation system did not receive real consideration (Terracon Consultants Inc., 2011).
PREVIOUS WORK

The KCC conducted a review of the literature documenting the land use of the survey location. The maps that show the wells which are unaccounted for are not accurate enough to indicate exact locations, but instead gave the locations of general areas that conformed to conventions of well placement within the El Dorado oil and gas field within the appropriate period of time the oil and gas development occurred. This information was used by the KCC to focus further investigations on the most probable areas.

These target areas were traversed with a metal detector by KCC employee Jeff Klock in an attempt to locate casing material. While this method was successful at other locations, it was unsuccessful at this area. The failure of the metal detector led the workers to hypothesize that the casings had been removed entirely or removed to a depth below the metal detector’s capabilities. However, the previous success of this method was the result of the search area being greatly constrained by water emanating from the well and flowing to the surface (J. Klock, personal communication, October, 2011).

The drilling methods of the period would have required cellars to be dug into the shallow bedrock directly below the drilling derrick to accommodate the drill string and the casing. The cellars that would have been dug were likely 2.44m by 2.44m (8 feet by 8 feet) (Bollenback, 2011) or 2.44m by 3.04m (8 feet by 10 feet) and as much as 6.1m (20 feet) deep (Paine et al., 1913). It was suggested by the KCC that ground penetrating radar (GPR) could locate these cellars and by extension greatly constrain the location of the well bores.
In 2011, a search was conducted by Ground Penetrating Radar Systems, Inc. using a SIR-3000 operating system with a 400 MHz antenna. The equipment is capable of scanning to a maximum soil depth of 1.5m to 1.8m (5-6 feet). A line spacing of .61m to .9m (2 feet to 3 feet) was used. This configuration is capable of showing underground graves, utilities, and voids, in addition to other structures below grade. The success of the survey depended on the ability of the GPR to determine the bedrock-soil contact and detect any gaps in the bedrock. During the survey event the location of numerous anomalies were recorded. Nine “disturbances” and four subsurface “obstructions” were detected, three large disturbances were excavated, and 15 additional points were probed with a hand auger in an unsuccessful attempt to directly encounter well casings or the cellars cut into the bedrock (Bollenback, 2011).
METHODS

A magnetometer was chosen for its ability to detect subsurface well casings in situations similar to this study. Because a high-precision GPS was not available to mark anomalies as they were discovered, and immediate excavation was not an option, a gridded survey was performed. This would allow the positions of anomalies to be provided to the KCC even after much time had elapsed.

An overlay was performed to integrate two types of geophysical surveys, and to place the results over satellite imagery to provide a frame of reference. This allows the viewing of results of the two surveys in relation to each other and visible surface features.

Grid Construction

Survey grids were constructed to ensure that the entire target locations were methodically searched. The geospatial positions of these grids must be accurately and precisely known and recorded. Construction of the grid must be repeatable to ensure that future workers will be able to accurately identify the location of any anomalies on the surface of the earth. The survey lines were aligned with magnetic north and the UTM coordinate of the “lower left” corner was recorded. The phrase “lower left” is used by Geometrics to refer to the southwest corner of the survey area. This location is also referred to as (0, 0) or the origin. The length and width of each survey was measured and recorded in detailed field notes.

Two locations on the property were identified from maps and well spacing conventions as favorable areas to conduct the geophysical surveys, and therefore studied. The position and extent of the grids were determined by workers from the KCC. The
first and northern most survey location was a rectangular area 50m by 60m. This survey location was selected in hopes of locating the formerly producing oil well in the extreme northwest corner of the American Legion BTA site. The second grid was located approximately 100m south of the first area and was a 40m square adjacent to, but not overlapping a known well location that has been previously located and plugged just to the northeast of the survey grid. This known well was not considered as a possible scientific control, because the hole has been cased, and the wellhead is above grade. The target wells are below grade, and the presence, composition, and disposition of the casings are unknown.

Although a line spacing of 1-2 meters would allow for more resolution and aid in identifying the causative objects, the survey design must take into consideration the size of the area to be surveyed, the target characteristics, obstacles in the area, time constraints, and diurnal variation (Martinek, 1988). As a compromise between maximizing coverage area, detectability and resolution, and minimizing diurnal variation, and the time required to conduct the survey, a line spacing of 10m was selected.

Equipment

The magnetometer used to conduct the survey is a Geometrics G-858 self-oscillating split-beam automatic hemisphere switching cesium magnetometer. It is lightweight, portable, and features an integrated user interface which stores data. In favorable conditions it is possible for a single operator to conduct a survey. The G-858 is capable of 0.05 nT precision when operating at the default 0.1 second cycle rate and higher precision when the cycle rate is decreased. The unit is tolerant to all but the most
extreme magnetic gradients, and will operate in temperatures ranging from -25°C to 50°C (Geometrics Inc., 1995).

Distance measurements taken during grid construction were made with 50m tape measures with mm gradations. The tape measures used during the field work are accurate with less than 20 N (4.5 lbs.) of tension applied to them. However, high wind speeds during the day of the study almost certainly caused more than 4.5 lbs. of tension, and therefore some degree of error due to stretching. This error is likely not significant, as the excavation event will encompass an area larger than the absolute size of the target thus negating any errors related to the measuring process.

The alignment of the grid was carried out with a Brunton pocket transit. The transit has a level of precision that is acceptable for this work (1/2° azimuth) (Brunton, 2007). The Brunton was positioned in the southwest corner and a field assistant stretched a measuring tape toward the north. By aligning the north arrow and the field assistant, the western boundary and first survey line was aligned with magnetic north. This process was repeated for each of the lines in the survey areas. This process was also negatively affected by the high winds that were buffeting the workers during the entire process. The winds made it difficult to hold the compass level and still, and so some error is undoubtedly present. Additionally, the declination was incorrectly set for a location further west of the agonic line. The study area was off 2° east. The error attributable to the wind is not quantifiable, but is not likely to be significant. The error due to improper declination adjustments could be significant for anomalies as they near the farthest extent of the survey areas, because the magnitude of the error is dependent on the distance from the origin. A basic set of mathematical operations using the Pythagorean Theorem and
the law of sines, was used to determine the severity of the error, and to correct the position of the anomaly if needed.

The UTM coordinates for the southwest corner were determined with a handheld Garmin GPS unit. When using a geometrics magnetometer, this grid point must be recorded. The precision of the GPS is listed in its user’s manual as less than 15m (Garmin, 2002). This could be enough to induce significant error into the results. To augment the GPS, which could have produced error, detailed field notes were taken that included measurements taken with the tape measures from landmarks near the study grid to a point on the grid. These measurements were typically less than 5m from the landmarks to the point and were not subject to any appreciable error, thus providing a degree of certainty to the grid placement.

Data Manipulation

The user interface for the G-858 magnetometer has a memory capacity of five .bin files. This means that after collecting 5 trials the data stored on the console typically has to be transferred to a computer before any further trials can take place. If the main battery is disconnected, as it is during travel to and from the field site, an internal battery maintains the stored data in the memory until the transfer takes place. However, due to the internal battery failing, a field portable data transfer and storage solution had to be created to preserve the data. Fortunately, the method used to overcome the problem resulted in expanded capabilities.

To carry out data transfer on location an Xplore ruggedized tablet was chosen for its portability and field worthiness. Because the console for the magnetometer links to
desktop computers using a serial port and the tablet computer does not have a serial port, a serial-to-USB adapter was used to facilitate the data transfer. Geometrics’ program MagMap200 was installed on the computer to import the .bin files from the magnetometer console. The data can now be transferred, viewed, vetted, and saved on site rather than requiring the surveyor to return to a desktop computer to complete these processes. This also allows the operator to perform as many trials as they see fit rather than dividing the five bins between multiple surveys.

After the initial data transfer and viewing with the software installed on the xplore tablet computer, the data was converted from .bin to .dat format using MagMap2000 (GEOMETRICS). Surfer 8 (Golden Software) was then used to contour the .dat files using the minimum curvature interpolation method. The contour maps generated in Surfer were then able to be adjusted to create a final product that clearly displayed the essential data.

The magnetic contour map was used to identify the locations of anomalous readings, and using functionalities built into Surfer, north-south boundary line files (.bln) were created through the centers of the anomalies. These boundary line files were opened in Grapher (Golden Software) to create magnetic profiles of the anomalous zones. The magnetic profiles were then used to determine the depth to the top of the object. Manual methods of depth estimation such as those outlined in Peters’ 1949 paper, the straight slope method, and the half-width method, are simple techniques that can be applied quickly to the generated profile, and are usually correct within 30 percent (Milsom, 2003).
ArcMap (ESRI) was used to geospatially overlay an aerial photograph with the contoured magnetic data and the results from the GPR survey, in the form of GPS points, to compare the data types and determine the spatial relationships between them. This also allows the final position of the survey grid to be cross checked for accuracy by utilizing the measure tool within ArcMap to ensure that the placement on the photograph is in agreement with the control points in the field notes.

The overlaying of the data was accomplished using satellite imagery available within ArcMap and the contour maps that were exported from Surfer as shapefiles. During the initial projection, the contour maps were automatically drawn smaller than their actual size, so a spatial adjustment was performed.

Using built in utilities control points representing the true location of the four corners of each survey grid were projected onto the imagery, and the respective corners of the grids were linked to these control points. ArcMap then redrew the grids in the proper locations, and enlarged them to the appropriate size while maintaining the proper contour geometry.

During the GPR scan carried out by Ground Penetrating Radar Systems Inc., in 2011, a GPS point was taken above each disturbance, each obstruction, and at the center of each of the excavation sites. These points were recorded in an Excel file, which was imported to ArcMap, and displayed as latitude and longitude data before being converted into a shapefile and projected onto the photograph and contour map combination.
RESULTS AND DISCUSSION

Although the GPR and magnetometer surveys did not perfectly overlap, they did to a significant degree. It was the intention to expand on the previous research by having total overlap of the surveys, but this was not achieved for various reasons. The lack of dimensional information, or a survey reference point as it pertains to the size or exact location of the GPR survey grid prevented the magnetometer survey from being the exact size or in the exact location of the GPR survey. Nevertheless, the surveys were complementary. Only 2 of the 16 points recorded during the GPR survey fell outside of the magnetometer grids. Additionally, one “obstruction” and three “disturbances” that were detected during the GPR survey are within two magnetic anomalies seen in survey #1. The three exploration pits were dug along the northern edge of the magnetometer survey #1 area, but do not correspond to any areas of anomalous magnetic values (fig. 7).

A large amount of magnetic variation is present along the western edge of survey #1 (fig. 8). These variations are arranged in a line five meters wide and running the entire length of the 50 meter grid boundary. The magnetic character is a succession of highs and lows with rounded hourglass, circular, elliptical, and rectangular shapes. Two anomalies (A & B) are present outside of the zone of variation, and cannot be readily dismissed as cultural noise. They are present below a grassy area, and do not appear to be a part of any trend as do the anomalies on the west side of the survey. Anomaly A has a rectangular high that is approximately 10 meters in the east-west direction and 5 meters in the north-south direction. Within this rectangle the magnetic values continue to rise, with an elliptical anomaly that increases to 112 nT. This is flanked on the north and south
Figure 7—Survey #1 results and ground penetrating radar survey results over satellite imagery. Note: Location of Holderman #1 is approximate. Map created in ArcMap with ESRI data.

Figure 8—Survey area #1 Magnetic Contours; Blue ellipses within the boxed-in anomalies show primary excavation targets. Map created in Surfer (Golden Software).
by magnetic lows. The depth to the tops of the object causing the anomaly was calculated to be approximately 1.5 meters (fig. 9).

![Magnetic Profile of Anomaly A](image)

Figure 9—Magnetic Profile of Anomaly A; generated in Gr彻her (Golden Software).

Immediately southeast of anomaly A, is anomaly B. It exhibits a reversed dipole configuration, which was also an unexpected result for this search. The high value for this anomaly is 80 nT, and the dipole fills a roughly square area that is 15 meters by 17 meters. The depth to this causative object was calculated to be approximately 2 meters (fig. 10). These depths are technically estimations, but have been used with enough success over the last six decades to be considered venerable. Furthermore, any future excavation event would be undertaken methodically and carefully, and done so in such a manner as to encompass more area than required while digging down very slowly. Therefore, accuracy within 30 percent should be sufficient.
The true positions of anomalies A and B were determined using trigonometry to correct for the declination error, and the distances from the southwest corner and the mapped anomalies were calculated. The true anomaly positions were on average, 1.2 m north and 1.3 m west of the mapped anomaly locations. These changes do not require any wholesale changes to the study, but will be addressed by excavating a marginally larger area than would normally be required.

The southern survey, #2 (figs. 11 & 12), does not have any magnetic anomalies that correspond to anomalies detected during the GPR survey. There is an area with a positive gradient increasing toward the northeast corner of the survey grid, and a strong negative anomaly, of 145 nT in the southwest corner. This low is approximately five meters from a vertical, above-ground steel pipe roughly one meter in length, outside of the survey grid.
Figure 11—Survey #2 photo overlay showing the relationship of the anomalies found during the GPR survey and the magnetometer survey, but for the southern survey site, survey #2. Note: Location of Skelly #2 is approximate. Map created in ArcMap with ESRI data.

Figure 12—Survey Area #2 Magnetic Contours; map prepared in Surfer (Golden Software).
CONCLUSIONS

The geology and soils found within this area do not possess enough magnetic susceptibility to impact the results of this research. Furthermore, the distribution of the types of rocks and soils present is homogenous, so any effects would also be uniformly observed.

Survey #2 is largely free from magnetic anomalies other than those in the southwest and northeast corners. The strong low anomaly in the southwest is directly east of a steel pipe that is protruding from the ground close to the west side of the survey grid. It is likely that this low is paired to a magnetic high just outside of the survey related to the steel pipe, while the presence of American Legion Post 81 #1, roughly 15 meters to the northeast of the southern site could be producing the increasing magnetic gradient seen in the northeast corner. It is not possible to make a definitive statement concerning these variations in the local magnetic field without first extending the survey to include the objects that are suspected to be the sources of the anomalous results. However, since the survey was performed, massive changes to the site have occurred, which may complicate any further investigation.

While many anomalies are present in the magnetic field within both survey areas, most have been excluded as noise by comparing the magnetic contour maps to known cultural features. The western edge of survey #1 is near Haverhill road and its associated vehicular traffic, overhead power lines, irrigation connections, and unspecified utilities, which may include a steel pipeline (field notes, 2011), and therefore, the magnetic variation is likely a result of these non-target features.
The map of survey #1 generated with GIS, shows that not only are there magnetic anomalies in a general area that a well is known to exist, but also shows the ground penetrating radar detected anomalous readings in close enough proximity with them to be viewed as evidence supporting the suspicion that a well may indeed be present below the survey location. Despite the methods used during this research being developed to locate an iron or steel casing string, not a discontinuity in the subsurface, the shapes of the anomalies are approximately square or rectangular, which corresponds closely to the square or rectangular drilling cellars that are present somewhere on the property.

This research does not explicitly show that a well is present. The weight of evidence merely suggests that further investigation is warranted, primarily at the location of the two anomalies in survey #1. These areas should be excavated, keeping in mind the error due to improper declination, to determine if the wells are present. Though the scope of this work has been completed, the success or failure of applying a magnetometer to this problem cannot be determined until the anomalous zones are excavated. This is a decision that will be made by state regulators, who may choose or choose not to act on these results.
LITERATURE CITED


Martinek, B.C., 1988, Ground based magnetometer survey of abandoned wells at the rocky mountain arsenal: A case history. In proceedings volume of the symposium on applications of geophysics to engineering and environmental problems. p. 578-596.


