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Jason A. Patton

Arkansas Tech University, jpatton@atu.edu

Michael G. Davis

Arkansas Tech University, mdavis@atu.edu

Kenyon J. Gowing

Arkansas Tech University

Hunter B. Vickers

Arkansas Tech University

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Optimum Magnetometer Transect Spacing to Locate Legacy Oil and Gas Wells: Preliminary Results

J.A. Patton, M.G. Davis, K.J. Gowing, and H.B. Vickers

Department of Physical Sciences, Arkansas Tech University, Russellville, AR 72801

Correspondence: jpatton@atu.edu

Running Title: Magnetometer Transect Spacing to Locate Legacy Oil and Gas Wells

Abstract

The purpose of this project was to examine the optimum transect spacing to locate legacy oil and gas wells using an Overhauser magnetometer. Widely known to be a potential environmental hazard, legacy oil and gas wells may act as a conduit for methane and/or deeper subsurface fluids (naturally occurring brines, injected waste fluids, or injected CO₂) to the surface or shallow subsurface. Many plugged wells have all surface equipment removed leaving no visible trace at the surface and thus making the environmental assessment of these wells difficult. Using a magnetometer along a set of predefined transects, magnetic anomalies from the metal casing can be detected. In order to assess large numbers of wells, understanding the typical anomaly size is critical to maximize the transect spacing and therefore minimize magnetometer field work time. Here we briefly review the wide range of transect spacings reported in the literature and show the results of five wells with an initial survey grid at two meter spacing. Although there is significant variation in the anomaly size (X, Y, and Z), transect spacing of 20 m was sufficient to identify all buried wells using the method described herein. The anomalies associated with four of the wells ranged from approximately 1000-4000 nanoteslas (nT), while one well anomaly exhibited more than 10,000 nT above background.

Introduction

Legacy wells (defined as any oil or gas well that is at the end of its production life cycle regardless of its current plugged status) resulting from historic oil and gas production have the potential to cause environmental harm through two primary mechanisms: contamination of surface and/or groundwater and release of methane to the atmosphere (Boothroyd *et al.* 2016; Chilingar and Endres 2005). This situation arises when either the well was never properly plugged or

when the state-mandated plugging system fails due to poor construction or old age and allows the migration of deeper fluids and/or gases to the shallow subsurface.

When modern wells are plugged, cement is usually pumped into the well to isolate the production zone (perforated interval) and the shallow fresh water zone. In older wells, standard plugging procedures may not have existed, so the methods utilized varied greatly. As an example, in Pennsylvania, until the year 1955, an oil or gas well was required to be permanently plugged with a “well seasoned, round wooden plug” (Dilmore *et al.* 2015). Recent studies from other states show that failure rates in older wells range from 1.9% to 75% (Davies *et al.* 2014) with older wells being particularly susceptible to plugging failures, even when plugging procedures were followed properly.

As an example of the possible scope of the problem in the Arkoma Basin of Arkansas (an area essentially equivalent to the Arkansas River Valley geographic region), there are approximately 5230 wells that were drilled before 1967 (defined here as older than 50 years)(AOGC 2018). If wells in this area have the same magnitude of failure rates as other areas, then a conservative estimate of 262 wells (5% failure rate of 5230 wells) in the Arkoma Basin may currently be releasing contaminants to the atmosphere or groundwater.

Most of these wells no longer have any surface expression – the pipe is cut off below the land surface and is buried during the plugging procedure. Before these wells can be assessed for risk, their location must be accurately known. Many older wells throughout the country do not have exact locations associated with them and were only required to submit location information equivalent to an area of approximately 16 hectares (40 acres). To determine if older wells are a risk to the environment, their exact location must be known before any environmental assessment can be performed.

The use of magnetics in finding oil and gas wells has a rich history (Frischknecht *et al.* 1983; Aller 1984;

Table 1. General information for wells in this study. Note that the latitude and longitude listed here are approximate locations only. Data obtained from AOGC (2018).

Columns Only: Data columns from HCSG (2013):										
Well Name and Number		Permit	Location			Latitude	Longitude	Year Drilled	Year Plugged	
			Section,	Township, Range						
Ozark Highlands Unit 11-20 1-23		44836	23	11N	20W	35.59442	-93.08168	2011	2012	
Ozark Highlands Unit 11-21 1-23		44835	23	11N	21W	35.58397	-93.18634	2012	2013	
Silex Federal 1-4		34225	4	10N	21W	35.54996	-93.22791	1990	1990	
Pilot Mountain 1		25547	18	11N	21W	35.60672	-93.27351	1979	1979	
Pilot Mountain ES 13114 1		23519	6	11N	21W	35.63615	-93.26085	1977	1977	

Frischknecht *et al.* 1985; Hammack and Veloski 2016; Hammack *et al.* 2016). In general, to perform a ground based magnetic survey, a series of transects is created at a predefined spacing. The magnetometer is carried along the transects, while the earth's magnetic field is constantly measured. Any large metallic objects – including buried objects – will create a magnetic anomaly that is detected by the sensor. The size of the anomaly produced by the object is proportional to the mass, geometry, orientation, and distance of the buried object to the magnetometer (Aller 1984). In addition, both Frischknecht *et al.* (1983) and Jordan and Hare (2002) noted that corrosion of well casings may affect the size of the anomaly, but neither estimated the influence of degradation on the anomalous signal.

Although this technique has been used for both aerial and ground surveys, justification for the transect spacing chosen is commonly absent from most reports (e.g. Xia 2002; Hammack and Veloski 2016; Hammack *et al.* 2016) with transect spacing for ground surveys ranging between 2 m (Hammack and Veloski 2016), 3 m (Martinek 1988), 10 m (Hammack and Veloski 2007), 15.2 m (Frischknecht *et al.* 1983), 30.5 m (Xia 2002) or even increasing as distance from the suspected well location increases (Frischknecht *et al.* 1983; Jachens *et al.* 1986). Jordan and Hare (2002) stated “between-line station spacing is based on the survey goals and size of anomalies expected” (p 7-10) and later noted that transect spacing should be no more than 6-9 m, while Martinek (1988) stated that while 6 m may be sufficient to detect an anomaly, 3 m spacing was needed to ensure the anomaly was a buried well casing. The wide variation in transect spacing reported in these studies makes it difficult to determine what the maximum spacing can be at any one location where a well is suspected to be located. This study investigated the maximum transect width for ground-based magnetometer surveys and presents data from five natural gas wells in the Arkoma Basin of Arkansas.

Methods

Five wells of varying age were chosen to collect field magnetometer data (see Table 1 for general description of each well). For each well location, a grid was set-up with north-south oriented transects with a 2 m nominal spacing between each transect. Although the exact location of each well was not known, the grid was centered over the estimated location derived from well records obtained from the Arkansas Oil and Gas Commission (AOGC 2018). The two most recently drilled wells (permit 44836 and 44835) were located on large, open, accessible well pads. The remaining wells were all located on well pads with significant vegetative overgrowth, making locating the transect spacing less regular.

The magnetic data were collected using a GEM System GSM-19W Overhauser Magnetometer with integrated GPS. The data were collected by setting the magnetometer to take readings every two seconds while the operator walked the transects. Diurnal corrections were not made to the field data due to the expected relative magnitude difference between typical diurnal variations and well casing anomalies (Hammack and Veloski 2016) and the short duration of field data collection (<30 minutes at each site).

After field collection of the data was complete, the data were downloaded for further analysis. The data were imported into ArcGIS 10.2 (ESRI) and Microsoft Excel for mapping and data analysis purposes, respectively. In ArcGIS, the data were gridded using the IDW interpolation technique with a 1 m grid size. No reduction to the pole transformation or other transformations were performed because the intent of this study was to maximize transect spacing.

To differentiate between probable well casings and non-target metallic debris, we used two criteria: the presence of a monopole signature and anomaly amplitude threshold value of 50 nT above background.

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Several authors (Hammack and Veloski 2016; Jordan and Hare 2002) have noted that well casing anomalies typically exhibit a monopole form, due to the orientation of the well casing relative to the earth's magnetic field (Breiner 1973). In addition, Breiner (1973) noted that most small metallic objects have magnetic anomalies well below 50 nT, while other authors have shown that most well casings have anomalies that are more than 1000 nT (Jordan and Hare 2002). The 50 nT anomaly contour was plotted over the monopole signature to be used as a basis for estimating the maximum transect size needed to detect the well casing.

Results

Significant variation was found in the amplitude of the magnetic anomaly from the five wells surveyed (Table 2). Anomalies ranged from 1021 nT to 10,343 nT. Magnetic surveying at one well location (Permit 25547) was impeded by the presence of dense vegetation and a small pond, therefore results from that location are incomplete. Figure 1 show the results of the interpolation of the field data and identification of the 50 nT anomaly boundary. Figure 2 shows a north-south oriented profile through the highest magnetic reading at each well location. Although wider spacing may be able to capture most wells, the smallest anomaly found suggests that a 20 m spacing would identify the 50 nT threshold for each of these wells and is therefore appropriate for further testing and refinement.

Table 2. Magnetic values measured at each well location. Note that the survey for Permit 25547 was not completed. Background values were collected at each site during field work.

Permit	Max Value	Min Value	Back-ground	Anomaly Amplitude
44836	53066	50418	50652	2414
44835	51859	50612	50651	1208
34225	51719	50685	50698	1021
25547	54907	50473	50561	(4346)*
23519	60835	50296	50492	10343

Discussion

Several interesting features should be noted regarding these findings. First, the amplitude of the anomaly of Permit 23519 was unexpected. Amplitudes

commonly range from 2000 – 5000+ nT (Jordan and Hare 2002). Permit 23519 had an anomaly amplitude of more than 10,000 nT over background, which was at least four times greater than the other wells in the study with similar construction. Interestingly, Permit 23519 is also the oldest well in our survey, having been drilled and plugged in 1977 (Table 2), and presumably may be somewhat degraded compared to the newer wells we examined. Although both Frischknecht *et al.* (1983) and Jordan and Hare (2002) noted that corrosion of well casings may affect the size of the anomaly, it is assumed well corrosion would decrease the amplitude, not increase the anomaly size as observed here.

The minor amplitude variation found in the others wells, ranging between 1021 and 2414 nT, may simply be related to transect location. Further analysis of points near the well location show that the gradient of the magnetic field was sufficient to cause a change of more than 1000 nT over a range of about one meter. The wells with lower values (e.g. Permit 34225) may not have had a transect directly over the top of the well, while the higher value wells may have. In an attempt to further explain the variation between all wells, a search of the plugging and completion data for each well was performed and is shown in Table 3. No noticeable correlation exists between pipe size or pipe length and the total anomaly size, similar to what was found in Frischknecht *et al.* (1983). What is not known about each well is the total burial depth. Only one well (Permit 34225) had information about how far below the surface the pipe was cut before burial. Plugging records throughout the area commonly state the burial depth to between 1 and 2 m. This depth may affect the total magnetic anomaly size in that a well with a shallow casing would produce a greater anomaly. Corrosion, transect location, burial depth, and pipe construction details may all have contributed to variations in anomaly amplitude.

Table 3. Type and amount of pipe left in each well location.

Permit	Conductor		Surface Casing	
	Width (cm)	Length (m)	Width (cm)	Length (m)
44836	40.64	12.5	24.45	319.1
44835	40.64	12.5	24.45	366.7
34225	-	-	21.91	155.8
25547	29.85	9.1	21.91	91.4
23519	29.85	12.8	21.91	196.3

Figure 1. Magnetic Data from All Well Locations Along Nominal 2 m Spacing. Permit number is shown in corner. Dashed line shows 50 nT anomaly boundary. Wells 44836 and 44835 were located in areas with well-defined pads, whereas wells 34225 and 23519 were located in areas of heavy vegetation.

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Figure 2. Magnetic Profiles of Well Locations. Note that each profile is centered around highest reading. Negative distance values are north of the high, positive distance values are south of the high.

A 20 m grid spacing was sufficient to identify all well locations using the methods described herein and as shown by the size of the 50 nT contour on Figure 1. When considering that most wells without detailed locations have general location data down to the Quarter Quarter Section of the Public Land Survey System, a 20 m spacing would allow surveying an area of this size in only a few hours.

Conclusion

As finding the exact location of these wells becomes more important in the future so that an environmental assessment can be performed, the maximum transect size that will find all wells, including the smallest signatures, will be critical. A transect spacing of 20 m was sufficient to accurately identify all of the well locations in this study, but more research is needed into variations in anomaly size so that future studies do not inadvertently miss wells with small anomaly signatures.

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