High-resolution Magnetic and Gradient Survey at Big Chief Mobile Home Park in Hutchinson, Kansas

Jianghai Xia

Abstract

A natural gas explosion on January 17, 2001, destroyed two downtown Hutchinson businesses. A day later another explosion at the Big Chief Mobile Home Park three miles away took the lives of two residents and forced the evacuation of hundreds of people as gas geysers began erupting in the area. The pathways to the land surface at both the explosion sites and the geysers were abandoned brine wells used for solution mining of salt. A high-resolution magnetic and gradient survey was performed at the Big Chief Mobile Home Park in November 2003 in hopes of finding any hidden brine wells. The total survey area was 670,000 ft^2. High-resolution magnetic data and gradient data were acquired at 526,000 locations along lines three feet apart. Monopole-shape magnetic anomalies with high amplitude (> 20,000 nT), a high vertical gradient (> 150 nT/in), and a wide half-width (> 6 ft) were detected at locations of all five known brine wells in the survey area. Survey results did not suggest existence of any other brine wells. Forty-two anomalies were verified. One resident water well was found.

Introduction

On January 17, 2001, a natural gas explosion and fire destroyed two downtown Hutchinson businesses. The next day another explosion occurred at the Big Chief Mobile Home Park three miles away. Two residents died of injuries from the explosion, which forced the evacuation of hundreds of people as gas geysers began erupting in the area. The geysers spewed a mixture of natural gas and saltwater. The pathways to the land surface at both the explosion sites and the geysers were abandoned brine wells used for solution mining of salt (http://www.kgs.ukans.edu/Hydro/Hutch/Background/index.html, Allison, 2001).

The known brine wells in the mobile home park had steel cased pipes. Xia (2001a, 2001b, 2002a) successfully located one buried abandoned brine well by an electro-magnetic method during a testing in 2001. In a noisy urban environment, however, electromagnetic signature recognition and the investigation depth by the electromagnetic method still remain a challenge (Xia, 2002a).

The Kansas Geological Survey has a long history of using gravity and magnetic methods to solve regional geological problems (Yarger, 1983, 1989; Lam and Yarger, 1989; Xia et al., 1992, 1995a, 1995b, 1995c, 1996). Algorithms related to data processing and interpretation were developed (Yarger et al., 1978; Xia and Sprowl, 1991 and 1992, Xia et al., 1993). Although this past research focused on deep (> 700 ft) geology, the fundamentals of anomalies induced by the geomagnetic fields in the near-surface (< 20 ft) materials remain the same.

The length of vertical steel pipes in brine wells in the Hutchinson area normally is 400 – 700 ft. The maximum magnetic signal caused by this amount of pipe can be higher than 15,000 nT on top of the normal geomagnetic field in Hutchinson, Kansas (Appendix A). This huge anomaly shows promise in locating brine wells in the city noise environment. Five abandoned brine wells, five water wells, and one probable gas pipe were located by a high-resolution magnetic method in the summer of 2002 (Xia, 2002c; Xia and Williams, 2003, 2004). We also found that wells could be in the vicinity of only a few feet, which requires that a geophysical method should possess a certain horizontal resolution. The horizontal resolution of the high-resolution magnetic method employed in that phase may not be high enough in some situations (Xia et al., 2003).

To increase the horizontal resolution, a vertical gradient method was proposed to search for wells in the summer of 2003 when a second sensor was employed to acquire data for calculating pseudo-gradient of magnetic fields. The City of Hutchinson designed eight sites with a total area of 1,024,000 ft^2. Magnetic anomalies and gradients from known brine wells were first recorded as signatures to use in identifying anomalies caused by possible buried brine wells. Of forty-seven anomalies verified by excavation with a backhoe, twenty-nine anomalies were due to wells buried at depths from 0 to 8.5 ft: twenty-one 6- to 8-inch wells were abandoned brine wells, seven 1.5- to 3-inch wells were probably (water?) wells, and one 16-inch well was a dewatering well for construction at a depth 3 ft. Two 4-inch wells were found without excavation because they were on the ground surface. Approximate monopole shape anomalies were observed from all these wells after data corrections. However, a wide range of amplitudes of magnetic anomalies from these abandoned brine wells was measured. It was from 7,000 to 28,000 nT, mainly due to the thickness of wells and depths wells were buried. Anomaly amplitudes from 1.5- to 3-inch wells were 4,000 to 8,000 nT and linearly correlated with the buried depth. One 3-in well that caused an anomaly with amplitude of 13,000 nT could be the inner pipe of a brine well. Gradient anomalies were roughly in a range of 100 to 200 nT/in for 1.5- to 3-inch wells and 200 to 300 nT/in for brine wells (Xia et al., 2003, 2004).

Based on the results of the magnetic survey around well C8, where two residents died of injuries from the explosion, the other brine well that was 14 ft north of well C8 was found (Xia et al., 2004). A high-resolution magnetic and gradient survey was performed over the entire Big Chief Mobile Home Park in November of 2003, hoping to find any hidden brine wells.

Methodology

The survey area was 670,000 ft^2. The survey area was divided into 66 grids and normally defined as 100 ft × 100 ft each using a theodolite (left, Figure 1). The accuracy of horizontal location within each grid is higher than ±0.5 ft by rechecking directly with a tape measurement and by checking mis-ties at several locations. A portable cesium gradiometer G858 (right, Figure 1) was used to measure the total component of the geomagnetic field and the vertical gradient of the geomagnetic field. The bottom sensor and the top sensor heights were 16 in and 36 in above the ground surface, respectively, over the entire survey area. Pseudo-vertical gradients of the geomagnetic field are calculated by subtracting readings of the top sensor from readings of the bottom sensor.

Theoretically speaking, the horizontal resolution of the vertical gradient can increase approximately 70% for a monopole source with the vertical magnetization (Figure 2) if the half-width, the horizontal distance between the maximum anomaly (assumed to be over the center of the source) and the point where the value is exactly one-half the maximum anomaly (p. 31, Breiner, 1973), is used. Practically, we may not achieve 70% improvement in the horizontal resolution with pseudo-vertical gradient data. I tested the gradiometer G858 at a well near the Kansas Geological Survey building (Well KGS). Total magnetic data and pseudo-vertical gradient data are shown in Figure 3. It is obvious that the pseudo-vertical gradient data (Figure 3d) possess about 30 – 40% higher horizontal resolution than the total magnetic field (Figure 3b). Figure 3c shows the total magnetic data acquired "2 inches above the ground," which are calculated by downward continuation from data of the bottom sensor. Based on the central profile results (Figure 3e), however, the total magnetic data acquired "2 inches above the ground" possess at least the same resolution as pseudo-vertical gradient data do. This result indicates that keeping the sensor close to the ground is critical to obtain higher resolution data when only one sensor is available.

Magnetic anomalies and gradient signals on the sites of wells C4 and C8 were first acquired to serve as signatures in locating brine wells. Data were acquired along lines spaced 3 ft apart with an average data density of 2.3 measurements/ft. There are 55 sheds with an average size of 64 ft^2 in the Big Chief Mobile Home Park. Data were also acquired at the center of sheds (Table 1).

The normal geomagnetic field in the City of Hutchinson was around 53,500 nT in November 2003 (Appendix A). The normal geomagnetic field was monitored during the survey by checking the Kp Index. The Kp Index is a 3-hourly planetary geomagnetic index of activity generated in Gottingen, Germany, based on the K Index from 12 or 13 stations distributed around the world. The K Index is a 3-hourly quasi-logarithmic local index of geomagnetic activity relative to an assumed quiet-day curve for the recording site. Range is from 0 to 9. The K Index measures the deviation of the most disturbed horizontal component (http://www.maj.com/sun/status.html). The maximum change of the geomagnetic field during the period of the survey was less than 15 nT/hour. Because the time to finish the magnetic survey on each 10,000 ft^2 grid was about 15 minutes and the amplitude of well anomalies were on the order of several thousands nanoteslas, no geomagnetic field correction was necessary.

Each data set that was acquired on an individual grid was processed in the following procedure:

1) Assignment of field geometry.
2) Correction for the sensor locations based on shapes of known anomalies such as anomalies due to brine wells by shifting odd numbered lines by 1.2 ft – 2 ft.

3) Correction for data dropouts, which are readings over the meter scale. A linear interpolation was used to remove the dropouts.
4) Gridding data by a linear Kriging method with a search radius of 9 ft. Measurements were then gridded into 1 ft × 1 ft grids (Surfer®, 1999).
5) Picking of anomalies based on their amplitudes (> 3,000 nT), the half-width (> 1.5 ft), and gradient values (> 100 nT/in). Anomalies would be picked for verification if they met any two of these three conditions. Shapes of picked anomalies should be close to the monopole that is the shape of anomalies due to wells or vertical pipes.
6) Display of high-resolution magnetic data using Surfer® in a color scale to enhance anomalies potentially caused by brine wells.

After the step three, all data were also merged to generate a map covering the entire survey area. A residual magnetic anomaly map was generated by removing the normal earth field.

Magnetic Signals from Known Wells

I acquired high-resolution magnetic data at known wells C4 and C8. The survey area at each site is 40 ft × 40 ft with line spacing of 2 ft. Wellheads are located in about the center of each grid. The monopole anomaly (p. 24, Breiner, 1973) at well C4 is almost perfectly imaged in both total magnetic field (Figure 4a) and pseudo-vertical gradient data (Figure 4b). The maximum anomaly of total magnetic field at well C4 is over 20,000 nT (= 78,000 – 53,500) and the maximum gradient is over 300 nT/in (= 10,000/30). Amplitudes of magnetic field and gradient anomaly at well C8 (Figure 4c and 4d) showed the same as at well C4 but shapes of anomalies may not be easily linked to monopoles. This is due to the other well 14 ft north of well C8. These huge and positive anomalies with a bulls-eye shape in both total magnetic field and gradient data showed promise in effectively recognizing anomalies of abandoned brine wells in the Hutchinson area.

Results of Magnetic Survey at the Big Chief Mobile Home Park

A high-resolution magnetic survey was performed at the Big Chief Mobile Home Park, Hutchinson (Figure 5a). The survey area was 670,000 ft^2. The survey area was divided into 66 grids and normally defined as 100 ft × 100 ft each (Figure 5b). The magnetic data were normally acquired at 100 ft × 100 ft grids with line spacing of 3 ft (Figure 6). High-resolution magnetic data and gradient data were acquired at 526,000 locations. The average density of a high-resolution magnetic survey along a line was 2.3 measurements/ft. Around 43 miles of data were acquired in the 670,000 ft^2 survey area. Figures 7 through 9 show the total field component of magnetic anomaly from the bottom sensor, the top sensor, and the pseudo-vertical gradient of magnetic anomaly (= readings from the bottom sensor - readings from the top sensor), respectively. Appendix B contains all final maps of the high-resolution magnetic survey in the Big Chief Mobile Home Park. Maps are in order of grid numbers. The total field component of magnetic anomaly results from readings from the bottom sensor. The pseudo-vertical gradient of magnetic anomaly is calculated by subtracting readings of the top sensor from the readings of the bottom sensor.

1. Anomalies due to brine wells

A residual magnetic map (Figure 10) was generated to show the amplitude of the known brine wells in the survey area. The residual map was calculated by removing the normal earth field (53,484 nT) from the readings of the bottom sensor. There are five known brine wells (orange dots in Figure 10) in the Big Chief Mobile Home Park. They are C7 (37, 1083) in Grid 16, C12 (368, 478) in Grid 60, C13 (374, 881) in Grid 27, and C8 (375, 1266) and another brine well (376, 1280) 14 ft north of C8 in Grid 35. Magnetic anomalies due to these wells are classic examples of the brine-well signatures in Hutchinson area. It is extremely easy to identify them based on their amplitudes (> 20,000 nT) (Figure 10), vertical gradients (> 150 nT/in, see corresponding maps in Appendix B), the half-width (> 6 ft), and the monopole shapes of both magnetic anomalies and vertical gradients. The pseudo-vertical gradient map of Grid 35 clearly showed two individual anomalies, one located at C8 and a second one 14 ft north of C8.

Only three other anomalies that might fit these criteria were located at (452, 902) in Grid 45, (442, 892) in Grid 46, and (457, 502) in Grid of 62. The first two anomalies were due to the well cases pulled out from C13 (Figure 14) and the last one was due to well cases pulled out from well C12. Readings were normal after these well cases were removed.

2. Anomalies due to sheds

There are 55 sheds with an average size of 64 ft^2 in the Big Chief Mobile Home Park. The purple dots (negative anomalies) in the total field component of magnetic anomaly map (Figure 7 and 8) and green dots (positive gradients) in the pseudo-vertical gradient of magnetic anomaly map (Figure 9) showed locations of these sheds. The instrument readings surrounding sheds were in a range of 40,000 nT to 50,000 nT so that the existence of sheds generally reduced geomagnetic readings 2,000 nT to 15,000 nT, depending on the materials sheds were made of. Sheds were made of seven different materials, so readings inside the sheds were different (Table 1). Thirty-eight sheds were made of type-I metal sheets (Figure 11a). Four sheds (BC45-1, BC64-1, BC60-1, BC55-1) were made of type-II metal sheets (Figure 11b). Two sheds (BC49-1, BC49-2) were made of type-III metal sheets (Figure 11c). Six sheds (BC42-1, BC46-1, BC47-1, BC48-1, BC63-1, BC61-1) were made of concrete (Figure 11d). Two sheds (BC28-2, BC36-1) were made of brick (Figure 11e). Two sheds (BC35-1, BC45-2) were made of wood (Figure 11f). One shed (BC35-3) was made of wood with a metal door and metal beams (Figure 11g).

The geomagnetic fields in the center of sheds of each group (Table 1) were fairly consistent as far as the standard deviation is concerned. For instance, most of sheds (69%) were made of type-I metal sheets with an average reading at the center of the shed of 38,600 nT with a standard deviation of 2,300 nT. To make sure there were no anomalous objects under the sheds, two sheds (BC19-2, BC23-1) were removed and readings of the geomagnetic fields were taken again. The readings were 53,000 nT and 52,500 nT (the normal geomagnetic field is 53,500 nT) at the center of shed BC19-2 and

BC23-1, respectively. This test indicates the effect of sheds made of type-I metal sheets would reduce readings at the center of the sheds around 10,000 nT to 15,000 nT. Because anomalies due to brine wells possess average amplitude of 10,000 nT (with the minimum of 7,000 nT) in Hutchinson area, readings at the center of this group of sheds may indicate the existence of brine wells only if readings were higher than 45,000 nT. The reading closest to 45,000 nT was in shed BC13-2 (44,000 nT).

The average reading at the center of sheds with type-II metal sheets was 45,000 nT. Because the standard deviation was relatively small (2,160 nT), I concluded that the effect of sheds made of type-II metal sheets would reduce readings at the center of the sheds around 8,000 nT. Readings would be over 53,000 nT if there were brine wells under these sheds.

The same readings in both sheds made of type-III metal sheets indicated two possibilities: there are no anomalous objects under both sheds or the same objects were under both sheds. The same interpretation applied to readings at centers of sheds made of bricks or wood.

The reading in shed BC35-3 was extremely low (25,000 nT). This was because the shed was built with a metal door and metal beams.

The average reading in sheds made of concrete was 47,800 nT with a standard deviation of 3,500 nT. A reading over 54,800 nT would be expected if there were a brine well under these sheds. The reading closest to 54,800 nT in this group was in shed BC46-1 (53,000 nT).

3. Other anomalies

Forty-two anomalies (Table 2) were detected based on amplitude (> 3,000 nT), gradient value (> 100 nT/inch), and the half-width (> 1.5 ft). Anomalies were selected for verification if they met any two of these three conditions. Shapes of picked anomalies should be close to the monopole, which is the shape caused by anomalies due to wells or vertical pipes. Locations of anomalies were pinpointed based on their coordinates with assistance of the magnetometer. Verifications were performed by excavation with a backhoe or surface search for anomalous sources. Photos of anomalous sources are available on the CD-ROM included with this report. The forty-two anomalies (Table 2) were classified into seven groups.

A. Vertical pipes/rebar. Eight vertical pipes/rebar were found. One of them was a 5-in water well at a depth of 2 ft (Figure 12). The rest were 1 in to 1.5-in gas pipes, an electric pipe, or a rebar (Figure 13). These pipes were found in Grids 1, 12, 32, 47, and 66.

B. Well casing. There were three anomalies with amplitude over 15,000 nT and a half-width of at least 5 ft in Grids 45, 46, and 62. These were well casings pulled out from wells C12 and C13 (Figure 14). The readings were 52,000 nT after the well casing was removed. The anomalies were due to the well casing.

C. Trailer ties. Five anomalies were identified and verified in Grid 47 and 48 as trailer ties. Two examples are shown in Figure 15. Amplitude and gradients of this kind of anomaly were around 3,000 nT - 5,000 nT and 100 nT/in to 190 nT/in, respectively. Obviously, there were several other similar anomalies in the survey area. For example, anomalies at (176, 646), (186, 639), and (240, 612) in Grid 47 and (176, 522) in Grid 48 were interpreted to be similar tie downs.

D. Power outlets. Eight anomalies were identified and verified in Grids 17, 44, 46, 47, 55, 61, and 66. Amplitude and gradients for this kind of anomaly was around 4,000 nT - 8,000 nT and 50 nT/in to 280 nT/in, respectively, mainly depending on the distance between the magnetometer sensors and the outlets (Figure 16).

E. Light poles. Seven anomalies were identified in Grids 28, 32, 34, 41, 46, and 66 and verified as light poles in front of trailers. Amplitude of this kind of anomaly was pretty consistent and in a range of 10,000 nT – 12,000 nT and the half-width was in a range of 3 ft to 5.5 ft. These were very interesting anomalies (Figure 17) because both amplitude and the half-width were very close to anomalies due to brine wells in Hutchinson area. To be certain that the anomalies were due to these light poles, a pole in Grid 46 was removed and readings returned to around 53,500 nT (the normal earth field).

F. Horizontal pipes. The ends of horizontal pipes may also produce monopole-like anomalies. Three anomalies identified in Grids 24 (Figure 18) and 47 were caused by the ends of horizontal pipes. One anomaly was dug out on the edge of a street and found to be the end of a 6-in corrugated drainage pipe (Grid 24-2). Because the other anomaly (Grid 24-1) possessed almost the same pattern and was located on the other side of the street, it was believed that the anomaly was due to the other end of the pipe. With tighter line spacing and horizontal gradient data, monopole-like anomalies due to ends of horizontal pipes could be recognizable.

G. Other sources. There were nine anomalies were identified in Grids 13, 17, 29, 36, 42, 44, 48, 55, and 57. All anomalous sources were on the ground surface except for one anomaly in Grid 57. Two anomalies in Grid 57 were believed to be a sewer line indicated by green flags (Figure 19). Another anomaly caused by a telephone box possessed amplitude of 12,000 nT and gradient of 300 nT/in.

Contents of Included CD-ROM

The CD-ROM included with this report contains all raw data (.bin) and processed data (.dat). The raw data can only be read and processed by Geometrics software MagMap2000®. The processed data can be read and manipulated by Microsoft Excel® and Golden Software Surfer®. The CD-ROM also contains all photos I took in field, the merged data set of the entire survey area (wholeset.dat), and the digital form of this report.

Conclusions

This high-resolution magnetic survey as well as surveys that were completed in the last three years demonstrated the high-resolution magnetic method and gradient method could successfully locate buried abandoned brine wells. Distinguishable monopole-shape magnetic anomalies with high amplitude (> 20,000 nT), a high vertical gradient (> 150 nT/in), and a wide half-width (> 6 ft) were detected at locations of all five known brine wells in the Big Chief Mobile Home Park, Hutchinson, Kansas. No other anomaly in the Big Chief Mobile Home Park possessed the characteristics similar to those associated with the brine wells that were found. Results of a high-resolution magnetic survey in the Big Chief Mobile Home Park did not suggest existence of any additional hidden brine wells. I verified forty-two anomalies possessing much lower amplitudes and narrower half-widths. One 5-in resident water well was found. Analysis of readings in sheds showed that the two highest readings at BC13-2 and BC46-1 were still 1,000 nT lower than the minimum amplitude of anomalies due to brine wells in the Hutchinson area.

Acknowledgements

I greatly appreciate Jeffrey Banikowski and William Wright of O'Brien & Gere for their arrangement and assistance in permitting, clearances, and access issues. I would like to thank James Kelley and Ron Wilson of Kansas Geological Survey for their assistance in field data acquisition. I would also like to thank Brett Bennett of Kansas Geological Survey for his assistance in instrument preparation. Finally, I would like to thank Mary Brohammer of Kansas Geological Survey for her efforts in preparation of this report.

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