USING THE ELECTROMAGNETIC METHOD TO LOCATE ABANDONED BRINE WELLS IN HUTCHINSON, KANSAS

Jianghai Xia
Kansas Geological Survey, The University of Kansas, Lawrence, KS

Abstract

Natural gas explosions and fire destroyed two businesses in downtown Hutchinson and two residents of a mobile-home park also died of injuries from explosions. Gas geyser eruptions spewing a mixture of natural gas and saltwater in the area forced the evacuation of hundreds of people. 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 part of the Hutchinson Response Project is to find abandoned brine wells. I proposed to use the eletromagnetic (EM) method to search for these wells. A GEM-2 is an EM instrument that can survey an area quickly and with great detail. Multi-frequency data are acquired simultaneously with a maximum sampling rate of 30 Hz when an instrument operator walks along a survey line. For each frequency, both in-phase and quadrature components of the induced EM field in ppm (parts per million relative to the primary field) were recorded. Three frequencies were chosen for this project: 2,430 Hz, 7,290 Hz, and 18,270 Hz. EM signals from a known well were first recorded to determine what kind of anomaly would be identified as a possible buried well. The signals were then compared with EM reconnaissance results acquired at a designated area.

EM results successfully located one uncapped abandoned brine well 4 inches in diameter and buried at a depth of 5 ft. This survey result indicates the potential investigation depth with a GEM-2 would be as deep as 20 ft in this specific area. This survey also demonstrated the importance of acquiring target signals in interpreting anomalies. Based on these results, EM surveys in Hutchinson will be successful and effective in locating the abandoned brine wells.

Introduction

On January 17, 2001, a natural gas explosion and fire destroyed two downtown Hutchinson businesses. The next day another explosion occurred at a mobile home park 3 miles away. Two residents died of injuries from the explosion and hundreds of people were evacuated as gas geysers spewing a mixture of natural gas and saltwater began to erupt 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 (http://www.kgs.ukans.edu/Hydro/Hutch/Background/index.html; Allison, 2001).

To find these abandoned brine wells is a part of the Hutchinson Response Project (Allison, 2001). Hutchinson City and state officials say there may be more than 160 abandoned brine wells in and around Hutchinson and estimate it will cost around $60,000 to plug each well (*Hutchinson News*, May 9, 2001).

Some known wells in the mobile home park had steel cased pipes. A microgravity survey was not proposed to locate abandoned brine wells because anomalies due to brine wells or salt voids are too weak to be detected by this method. The length of vertical steel pipe normally is 400-700 ft. The predicted maximum gravity signal caused by this pipe is only 4-6 μGal (microgal). The sensitivity of the most advanced gravitymeter is one μGal, so a microgravity survey would not be effective in locating these wells. I also calculated the gravity anomaly caused by a salt cavern with a volume of 100 ft × 100 ft × 100 ft buried at a depth 400 ft, a typical depth of salt voids in Hutchinson area. The maximum anomaly from the cavern is approximately 25 μGal, assuming that the cavern is completely empty. In actuality, the maximum anomaly caused by such a cavern will be much less than 25 μGal because caverns are always filled with water, soil, and/or rocks, making the density contrast considerably smaller. To detect this 25-μGal anomaly, sensitivity of the gravitymeter and accuracy of elevation measurements are critical. The sensitivity of the most advanced gravitymeters available in the market is 1 to 10 μGal. It takes much longer (normally more than 15 minutes/station) to acquire microgravity data than a normal exploration gravity survey in order to achieve the 1-μGal sensitivity level.

Elevation measurements are the other main challenge in the microgravity survey. The error associated with elevation measurements is 5 μGal per inch. In practice, one inch accuracy could be achieved by the most advanced Trimble GPS system.

To confidently identify a gravity anomaly, the maximum anomaly should be at least three times higher than possible errors. Therefore, to see an anomaly with amplitude of less than 25 μGal, the sensitivity of gravitymeter should not be less than 4 μGal (in the range of 1-4 μGal) and the accuracy of elevation measurements should be within one inch. It is very difficult to complete an elevation survey with a one-inch accuracy range. In addition, cultural noise will become a serious impediment to detecting this 25-μGal anomaly in an urban area.

It is expected that 3-D ground penetrating radar (GPR) survey could be useful in locating these wells. The ground is dirt fill, however, and a lot of reflected/diffracted events caused by objects other than the brine wells should be expected. Furthermore, time spent on 3-D GPR data acquisition and processing could be much longer than initially expected.

I proposed to use the electromagnetic (EM) method to search for wells. As an EM instrument the GEM-2 can survey an area quickly and with great detail (Won, 1980). Data can be transferred into a notebook computer and maps generated within a few minutes after completion of the survey. The GEM-2 is a portable, digital, broadband electromagnetic sensor. Multi-frequency data are acquired simultaneously with a maximum sampling rate of 30 Hz when an instrument operator walks along a survey line. For each frequency, both in-phase and quadrature components of the induced EM field in ppm (parts per million relative to the primary field) were recorded. The measured in-phase and/or quadrature responses can be used to calculate apparent conductivity and apparent magnetic susceptibility based on the homogeneous half-space assumption by Won et al. (1996 and 1997). Apparent conductivity and apparent magnetic susceptibility are parameters that in general are related to targeted electrical and magnetic properties. Calculation of apparent conductivity and apparent magnetic susceptibility is a method of normalization of the EM data; it makes data analysis and interpretation easier for both geophysicists and other scientists. If the earth were truly homogeneous, the apparent conductivity would be the same at all frequencies and equal the true earth conductivity data (Huang and Won, 2001). In the real world, conductivity measurements are "bulk" or apparent conductivity.

Quadrature data are proportional to the ground conductivity in the low to middle induction numbers but are inversely proportional to the conductivity at middle to high induction numbers. Thus, a moderate conductor may produce a strong quadrature anomaly, whereas a good conductor may produce a weak anomaly or no anomaly. In either case, in-phase data must be used for further analysis (Huang and Won, 2001). An anomaly visible on conductivity maps should also be visible on in-phase and/or quadrature data. The investigation depth is dependent on the frequency of the instrument used in the survey, conductivity and magnetic susceptibility of a target, and surrounding materials. There is no exact relation between instrument frequencies and the investigation depth. A skin depth concept (Won, 1980) may be used to obtain rough estimates of the investigation depth in a specific survey area.

An EM survey was conducted in the open field on the southwest corner of 11th and Chemical Streets (Figure 1). Four anomalies were identified and reported (Xia, 2001a). Anomaly four was caused by an abandoned brine well, 4 inches in diameter and buried at a depth of 5 ft. These four anomalies will be discussed in the following section.

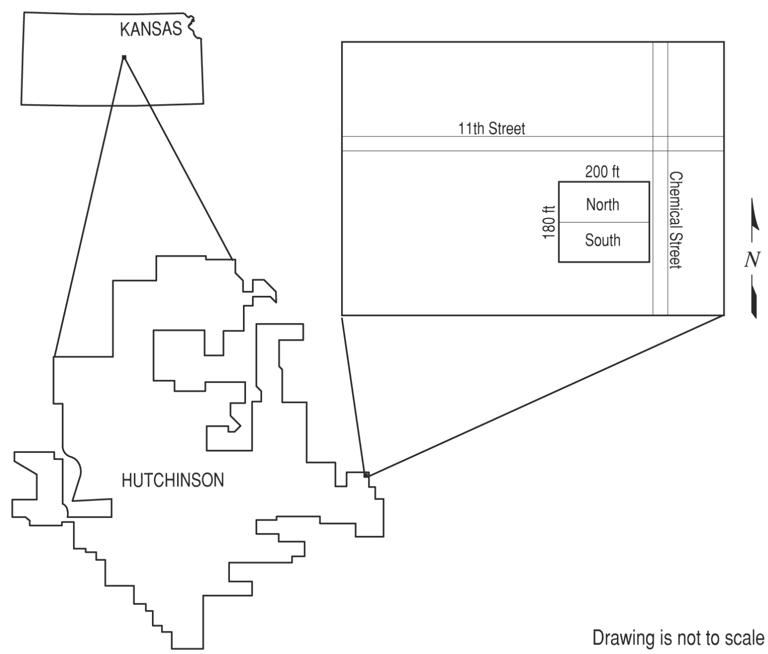


Figure 1. Site map of EM survey at Hutchinson, Kansas.

EM Survey Results

Three frequencies were chosen for this project: 2,430 Hz, 7,290 Hz, and 18,270 Hz. For each frequency, both in-phase and quadrature components of the induced EM field in ppm were recorded. EM signals from a known well were first recorded to determine the anomaly produced by an actual buried well. The signals then were compared with EM reconnaissance results acquired in an assigned area. Signals from abandoned wells are dependent on a physical size of wells, buried depth, surrounding materials, and most importantly, calibration of an individual instrument, so the information from a known well was essential for properly interpreting anomalies.

EM Signals from Well 8C

Well 8C costs two people their lives in the mobile-home park. I acquired GEM-2 data on an area 18 ft by 18 ft along lines with 2 ft spacing (Figure 2). Well 8C is located at point (19, 17). The signals from the well are all elongated ovals in both in-phase and quadrature components (Figures 3a-3f). An anomaly in the southeast corner is caused by rebar in the driveway. The amplitude of signals from this well at 2,430 Hz is much stronger than amplitudes of signals at the other two frequencies (Table 1).

I expected to see a bulls-eye shaped anomaly from the well. The anomaly shown in Figure 3 is in an oval shape elongated in an east-west direction. I walked along an east-west line with the GEM-2 oriented in the same direction. The sample point is about 2 ft away from the receiver coil. Data recorded along each line were linearly interpolated based on the starting point and the ending point when generating Figures 3a-3f. Therefore, I believe that the oval-like anomaly caused by well 8C, rather than a bulls-eye anomaly, is due to the way I acquired data and the 6 ft distance between the transmitter and receiver coils of this GEM-2. The 6 ft distance between a transmitter coil and a receiver coil of a GEM-2 is also a criterion of the horizontal location of an anomalous object. Based on the results from well 8C, I would conclude that half the distance between a transmitter coil and receiver coil (3 ft) of a GEM-2 might be an estimated accuracy of the horizontal location of an anomalous object. The oval effect due to the 6 ft coil distance and the way of walking along lines will be reduced when lines are longer than the testing grid used at well 8C. Thus, bulls-eye anomalies are my main objectives in locating abandoned brine wells.

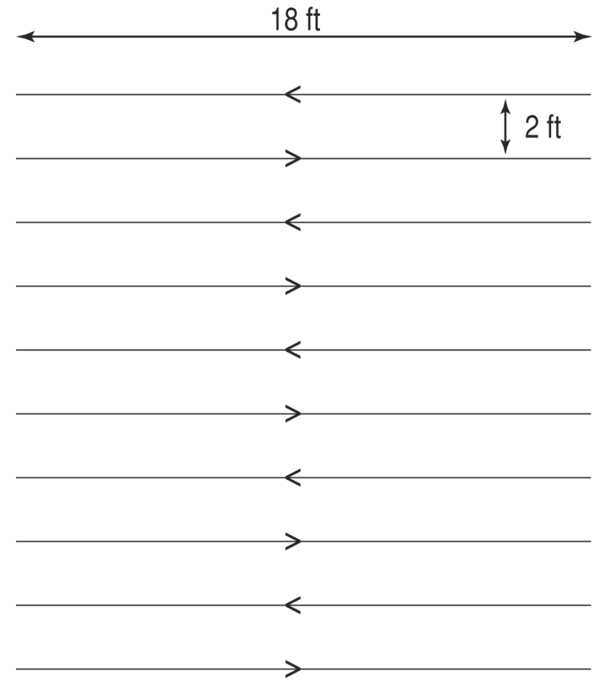


Figure 2. EM survey lines. Arrows indicate the walking direction.

When using the signals to compare data (both in phase and quadrature) from an assigned area, two other characters may be changed. The depth of a well header affects the size of a bulls-eye and amplitude of signals. The deeper the well, the broader (in horizontal dimensions) the bulls-eye and the lower the amplitude will be. Abandoned wells were normally buried 3-5 ft under the ground. The signals from well 8C are from a well header on the ground. For a specific frequency, thus, the bulls-eye anomalies from buried wells should be broader than the bulls-eye (Figure 3) from well 8C with a normally lower amplitude.

Different signals may be acquired at the same site using different GEM-2 instruments due to calibration of the instrument. Thus, it is important to obtain signature readings from a known object.

EM Survey Results on the Southwest Corner of 11th and Chemical Streets

A 200 ft by 180 ft grid was surveyed on the southwest corner of 11th and Chemical Streets (Figure 1). Due to a data-storage limitation on the GEM-2, the EM survey was split into two parts: south (from 0 to 93 ft) and north (from 93 ft to 180 ft). The EM survey was performed by walking along lines, with 3 ft between lines. (The survey was done as illustrated in Figure 2, except for the 3 ft line spacing.) Total survey length was 12,000 ft. It took two persons 5 hours to lay out the grid and finish the EM survey. Data density is 1.2 measurements/ft^2. Figures 4a-4f present the south part of the GEM-2 results at this site. Figures 5a-5c only show a portion of the north part of the GEM-2 results. See Xia (2001a and 2001b) for complete survey results and a discussion of anomalies identified from EM data.

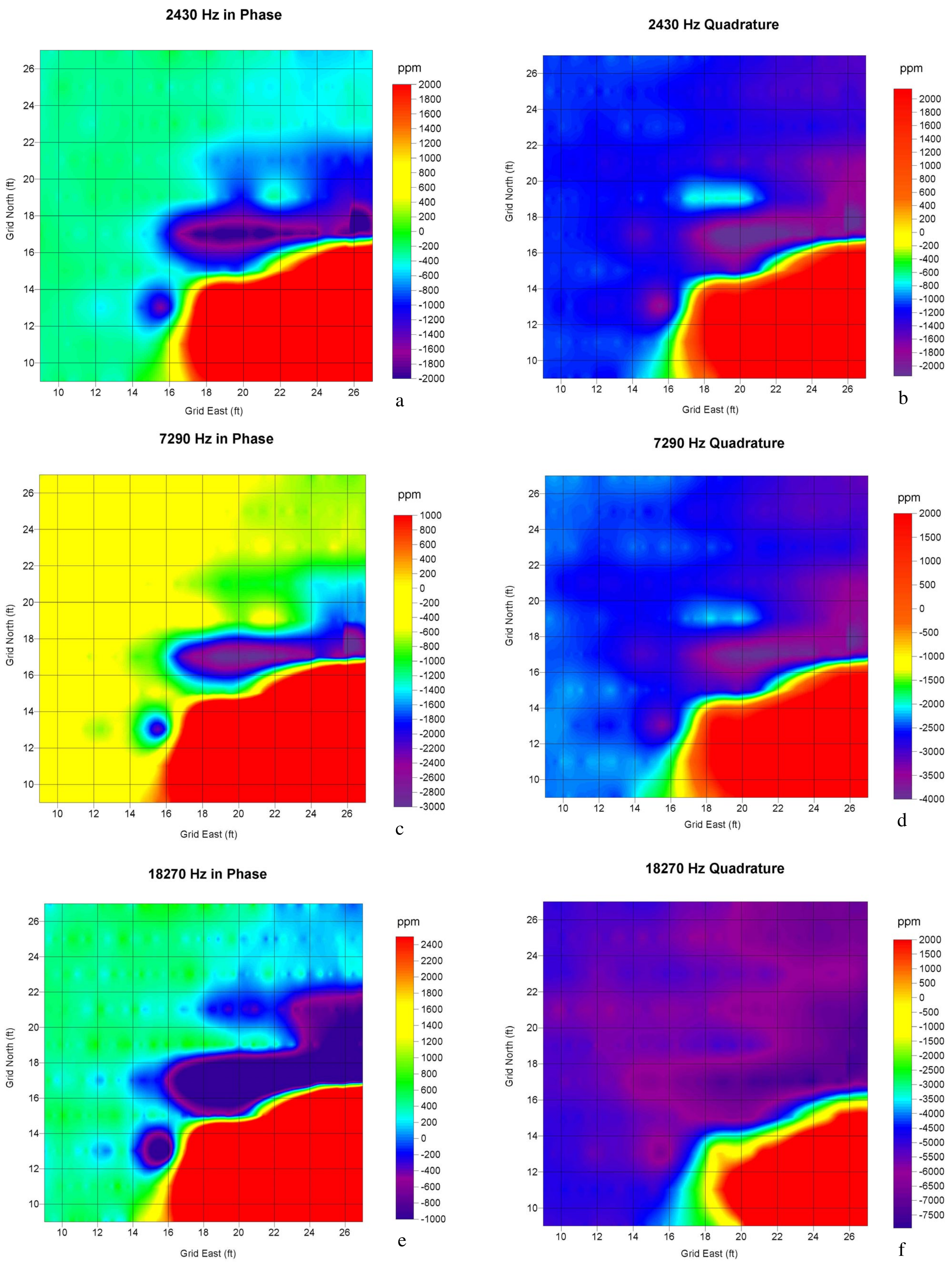
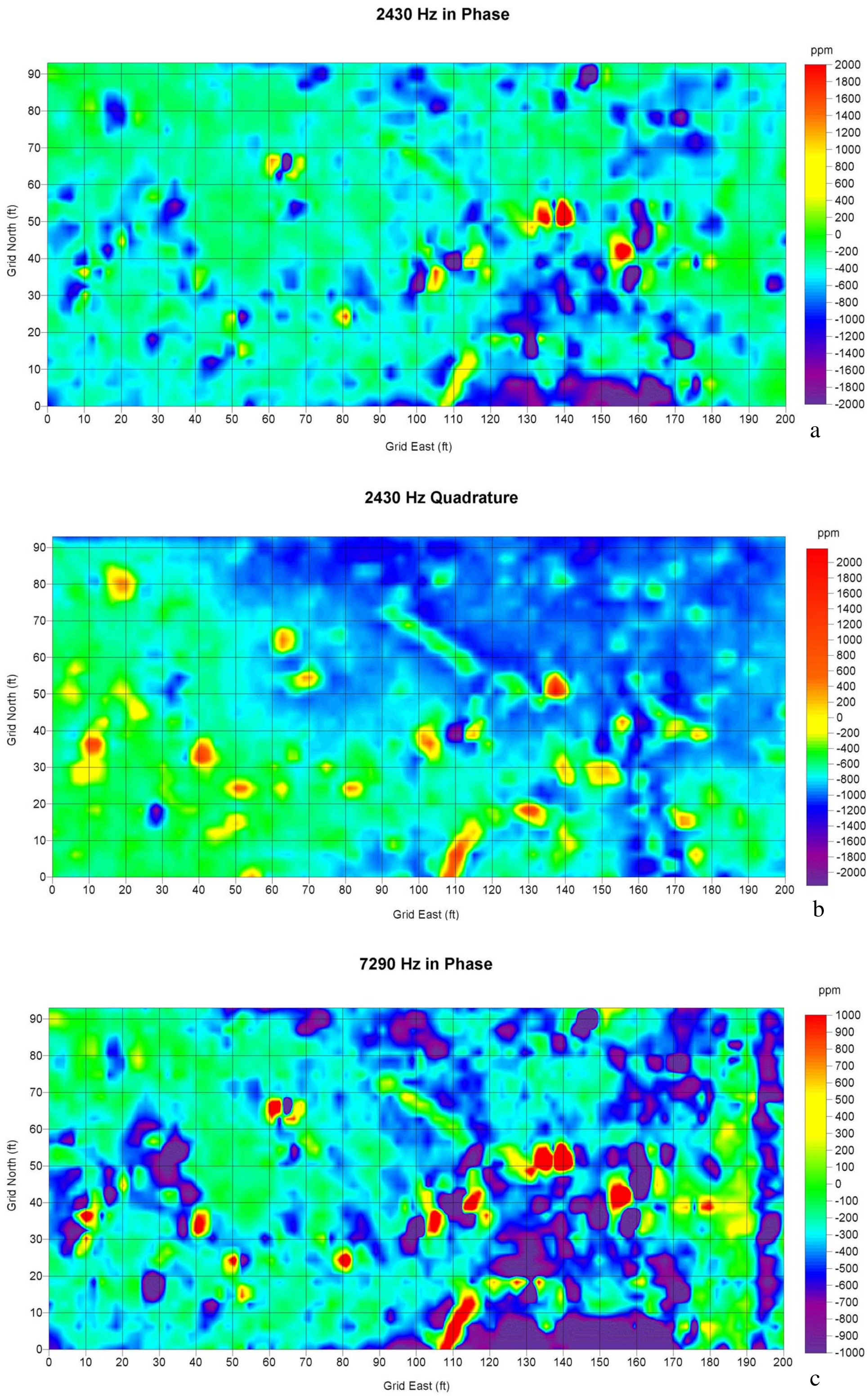
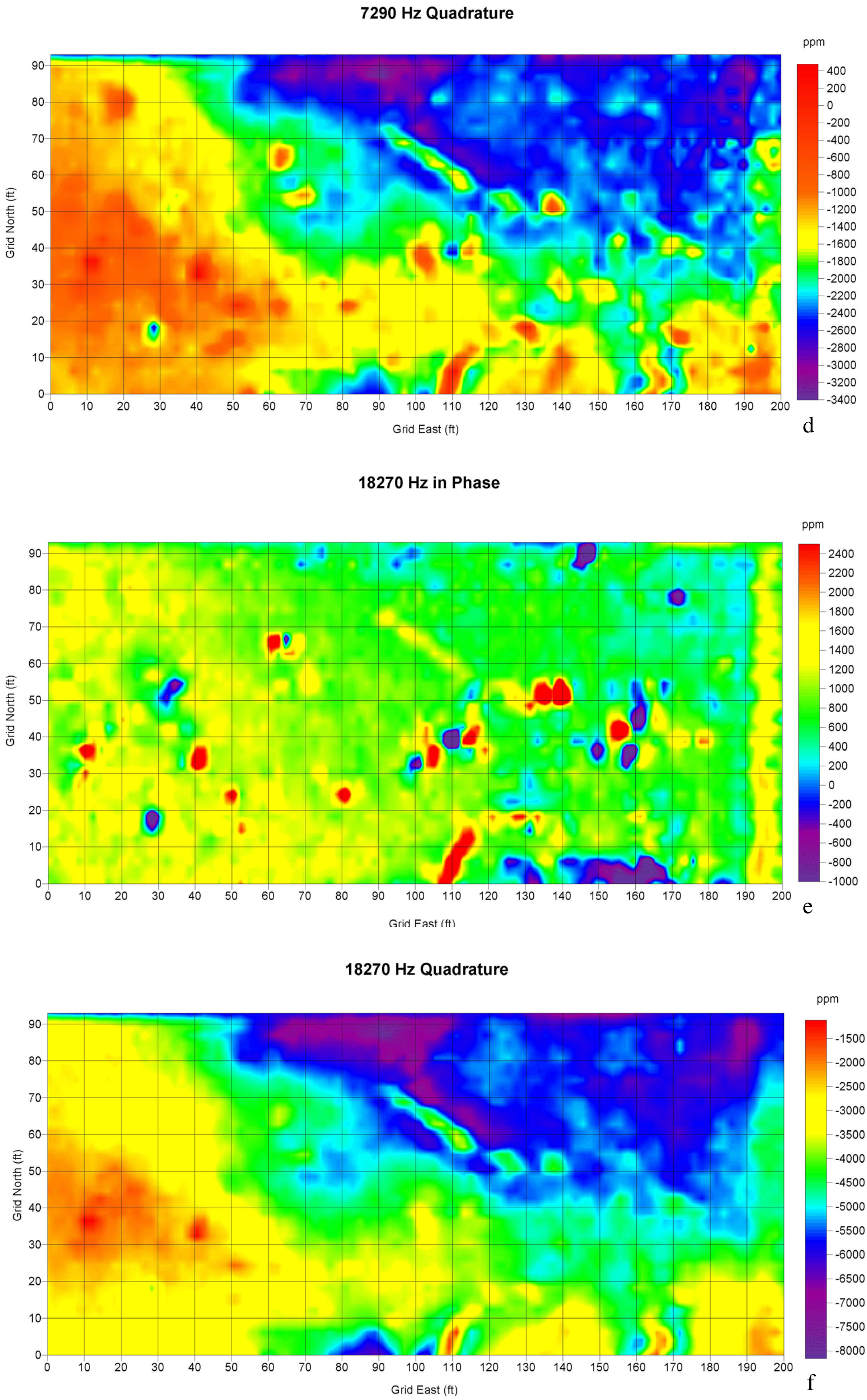


Figure 3. EM signals acquired by a GEM-2 from Well 8C.



Figures 4a-4c. The south portion of GEM-2 results: 2,430 Hz in phase and quadrature, 7,290 Hz in phase.



Figures 4d-4f. The south portion of GEM-2 results: 7,290 Hz quadrature, 18,270 Hz in phase and quadrature.

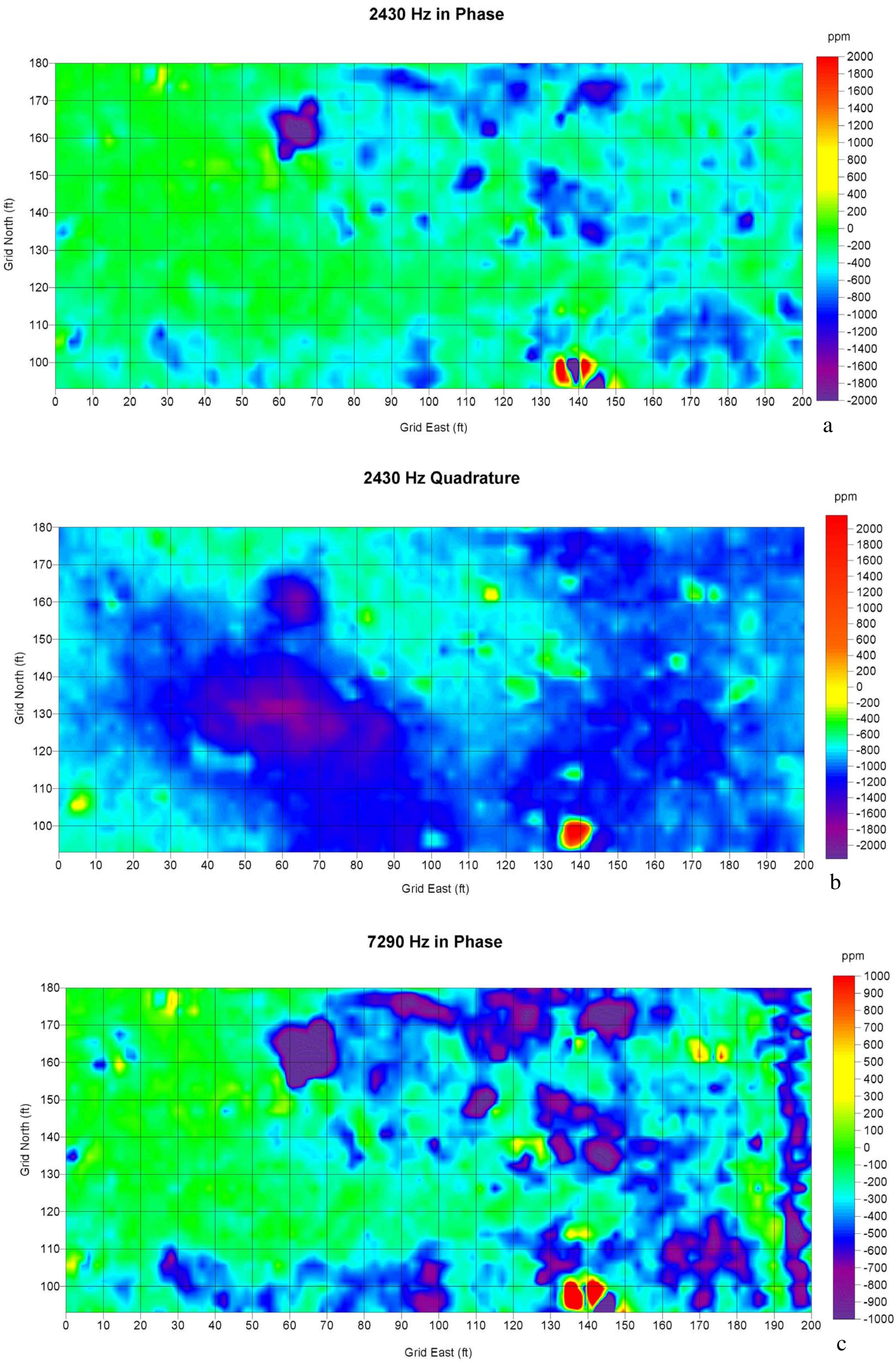


Figure 5. The north portion of GEM-2 results: 2,430 Hz in phase and quadrature, 7,290 Hz in phase.

Table 1. Amplitudes (in ppm) of EM signals from well 8C.

2,430 Hz (I)	2,430 Hz (Q)	7,290 Hz (I)	7,290 Hz (Q)	18,270 Hz (I)	18,270 Hz (Q)
1,700	1,200	2,500	1,700	2,700	2,000

Verification of Anomalies

Abandoned Brine Well Unearthed

The anomaly located at (110, 40) was not identified during the March trip (Xia, 2001a). This anomaly showed a negative bulls-eye on all components except for the 18,270 Hz quadrature component (Figures 4a-4f). Due to the target depth, it is expected that this anomaly might disappear in higher frequency components. The 2,430 Hz results showed the highest amplitude in three frequencies (Table 2). Comparing Table 2 with Table 1, Xia (2001a) interpreted that this anomaly to be caused by a buried well.

A backhoe was on site during a follow-up trip to Hutchinson in May. An uncapped abandoned brine well was unearthed beneath the point (110, 40) (Figure 6). It is 4 inches in diameter and buried at a depth of 5 ft. Sandy soils, clay, and gravel surround the abandoned well.

Table 2. Amplitudes (in ppm) of EM signals from anomaly 1 at point (110, 40).

2,430 Hz (I)	2,430 Hz (Q)	7,290 Hz (I)	7,290 Hz (Q)	18,270 Hz (I)	18,270 Hz (Q)
2,800	1,400	3,600	700	3,600	N/A

To review Table 2, strong in-phase anomalies are shown in all three frequencies. A relatively strong quadrature anomaly is shown in the 2,430 Hz frequency results. This indicates that, based on the skin depth concept (Won, 1980), the investigation depth of a GEM-2 for a 4-inch diameter well could be as deep as 20-30 ft in the Hutchinson area if frequencies around 1,000 Hz are used.

Figure 6. The abandoned brine well was unearthed. Observers' legs serve as a scale (left). This well is located at point (110, 40). A close-up photo is on the right.

Other Anomalies

A backhoe was immediately called to dig up three anomalies immediately after data acquisition in March. Anomaly two was identified at point (65, 161) (Table 3). No bulls-eyes were shown on quadrature components with 7,290 Hz and 18,270 Hz. For the lower frequency (2,430 Hz) signals (Figure 5b), however, a broader and negative bulls-eye anomaly with lower amplitude clearly appeared. This anomaly also appeared on in-phase results with all three frequencies (Figure 8a, 8c, and 8e). This anomaly could have been caused by a buried well but turned out to be a junk steel pipe (Figure 7).

The third anomaly was identified at point (137, 99). This anomaly showed a high-low-high pattern in in-phase components (Figures 5a and 5c) and a positive bulls-eye shape in quadrature components of three frequencies (Figure 8b). The source for this anomaly was believed to be metal junk, not a brine well. I did not see what was recovered at this spot but was told a piece of metal junk was found.

Figure 7. Anomaly two at point (65, 161) was caused by a junk steel pipe. A 3-ft stick serves as a scale.

Table 3. Amplitudes (in ppm) of EM signals from anomaly 2 at point (65, 161).

2430 Hz (I)	2430 Hz (Q)	7290 Hz (I)	7290 Hz (Q)	18270 Hz (I)	18270 Hz (Q)
2900	900	3500	N/A	3600	N/A

The fourth anomaly was identified at point (137, 53). This anomaly showed the same pattern as the third anomaly. This anomaly showed a high-low-high pattern in in-phase components (Figures 4a, 4c, and 4e) and a positive bulls-eye shape in quadrature components of three frequencies (Figures 4b, 4d, and 4f). The source for this anomaly was also believed to be metal junk and not a brine well. After digging, a 1.5 ft by 1.5 ft piece of metal sheet was found at depth of 2 ft (Xia, 2001a).

Figures 4c, 4e, and 5c also indicate a linear anomaly along a line (x = 195) in the 7,290 Hz and 18,270 Hz results. This anomaly was caused by a gas pipe line.

EM signals from well 8C are necessary to distinguish anomalies caused by brine wells from EM survey results. There are several other 2,430 Hz in-phase anomalies similar to that from well 8C (Figure 4a). They can be found, for example, at locations (65, 68), (147, 90), (172, 15), and (172, 78). However, there is no similarity between quadrature anomalies (Figure 4b) at these locations and at well 8C. Because of EM signals from well 8C, elimination of anomalies caused by junk became much easier. The in-phase anomaly is similar to a magnetic anomaly with a vertical magnetization. From this point of view, the EM method provides one more data set (a quadrature component) or one more direction to distinguish an anomaly caused by a buried well from anomalies caused by junk.

Conclusions

An uncapped abandoned brine well 4 inches in diameter buried 5 ft deep in Hutchinson was found by the electromagnetic method. The EM anomalies obtained by a GEM-2 suggests that the investigation depth of a GEM-2 in the Hutchinson area may be as deep as 20 ft. EM anomalies also indicated that getting a signature from a known well is essential in identifying anomalies that could be caused by an abandoned well. Results of this survey were successful and effective in locating abandoned brine wells.

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