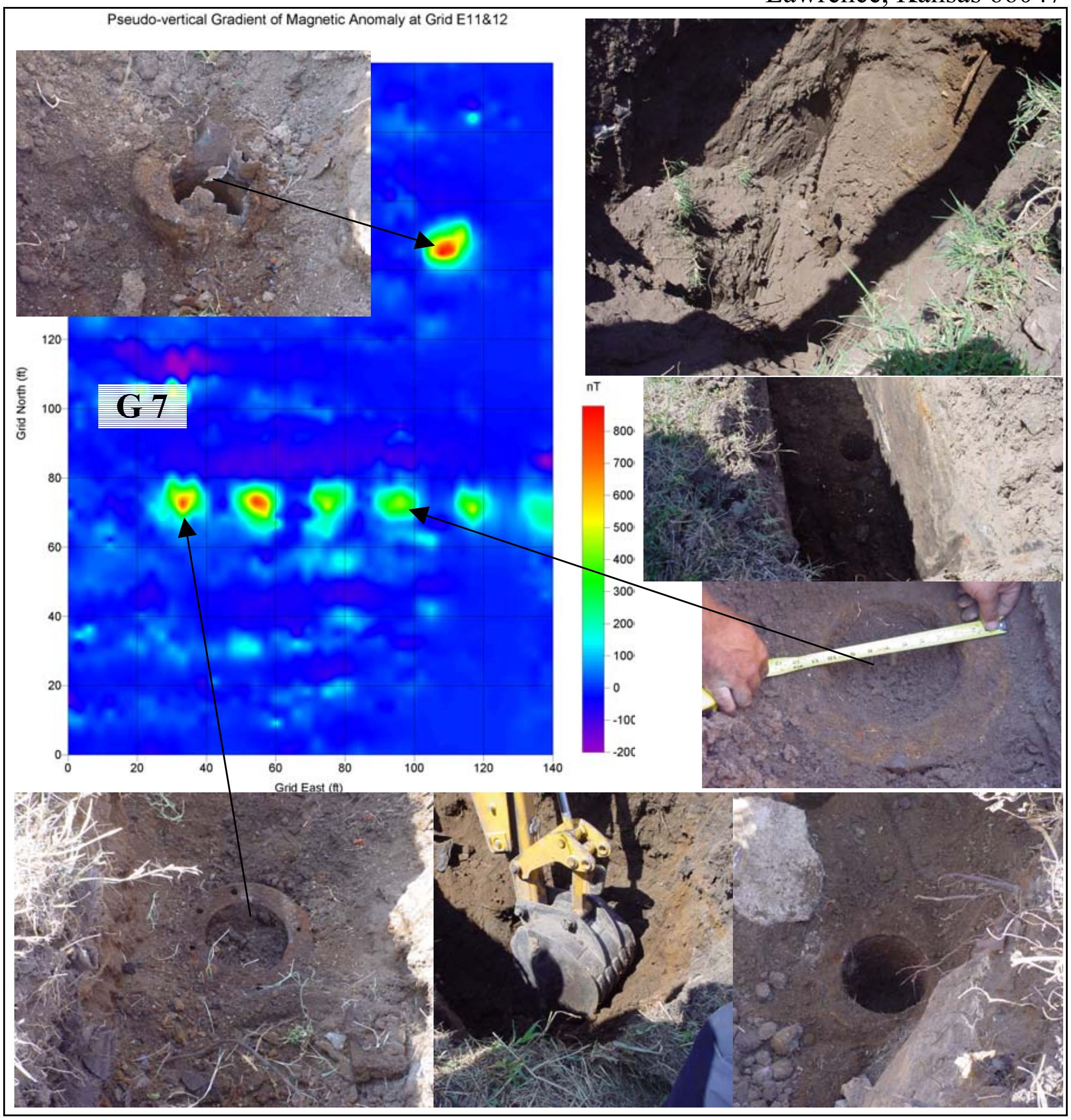
Applications of the High-resolution Magnetic Method and the Gradient Method in Locating Abandoned Brine Wells in Hutchinson, Kansas

Jianghai Xia, Chao Chen, Sihao Xia, and David Laflen

Kansas Geological Survey
1930 Constant Avenue
Lawrence, Kansas 66047



Report to
Dennis Clennan, City of Hutchinson, P.O. Box 1567, Hutchinson, KS 67504-1567

Open-file Report No. 2003-48 October 2003

Applications of the High-resolution Magnetic Method and the Gradient Method in Locating Abandoned Brine Wells in Hutchinson, Kansas

by

Jianghai Xia*
Chao Chen+
Sihao Xia++
and
Dave Laflen*

*Kansas Geological Survey
1930 Constant Avenue
Lawrence, KS 66047

+China University of Geosciences

++The University of Kansas

Report to

Dennis Clennan
City of Hutchinson
P. O. Box 1567
Hutchinson, KS 67504-1567

October 2003

KGS Open-file Report No. 2003-48

Applications of the High-resolution Magnetic Method and the Gradient Method in Locating Abandoned Brine Wells in Hutchinson, Kansas

Abstract

A natural gas explosion on January 17, 2001, destroyed two downtown Hutchinson businesses. Another explosion occurred a day after at a mobile home park 3 miles away. Two residents died of injuries from that explosion, which forced the evacuation of hundreds of people as gas geysers began erupting in the area. The geysers, following pathways to the land surface at both the explosion sites, were discovered to be abandoned brine wells once used for solution mining of salt. To find these abandoned brine wells is a part of the Hutchinson Response Project. After successfully locating one abandoned brine well by an electromagnetic method during a testing phase in 2001 and five abandoned brine wells by a high-resolution magnetic method during phase two in 2002, a high-resolution magnetic method was again proposed to search for wells in 2003 when a second sensor was employed to acquire data for calculating the pseudo-gradient of magnetic fields. The City of Hutchinson designated eight sites with a total area of 1,024,000 ft^2 for investigation in 2003. These sites were divided into grids with an average size of 10,000 ft^2. Survey-line spacing was 3 ft with a data density of 2.3 measurements/ft.

Magnetic anomalies and gradients from known brine wells were first recorded to help determine what buried brine wells might look like on magnetic data. Of forty-seven verified anomalies 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 a 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—7,000 to 28,000 nT—from these abandoned brine wells was measured, which is mainly due to the thickness of wells and depths of buried wells. Anomaly amplitudes from the 1.5- to 3-inch wells are 4,000 to 8,000 nT that are linearly correlated with the buried depth. One 3-inch well that caused an anomaly with amplitude of 13,000 nT could be an inner pipe of a brine well. Gradient anomalies are 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.

As indicated by the potential-field theory, gradient data possess higher horizontal resolution than magnetic field itself. Gradient data provide valuable assistance in determining horizontal locations for excavation of anomaly sources. In practice, however, improvement in horizontal resolution is limited by survey line spacing. If only one sensor is used in a survey, a rapid decrease in the horizontal resolution results when the sensor height increases from 14 to 44 inches, indicating that it is critical to maintain sensor height as close to the ground as possible in hunting buried wells that are close to each

other. It also suggests that downward continuation is useful to increase the horizontal resolution in well hunting.

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 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).

To find these abandoned brine wells is a part of the Hutchinson Response Project. Some known wells in the mobile home park had steel cased pipes. Xia (2001a, 2001b, 2002) successfully located one abandoned brine well by an electromagnetic method during the testing phase in 2001. However, electromagnetic signature recognition and the investigation depth by the electromagnetic method still remains a challenge (Xia, 2002a).

The length of vertical steel pipe of brine wells in Hutchinson area is normally 400 – 700 ft. The maximum magnetic signal caused by this pipe can be higher than 15,000 nT on the top of the normal geomagnetic field in Hutchinson, Kansas (Appendix A). This huge anomaly shows promise in locating brine wells in the noisy city environment. Five abandoned brine wells, five water wells, and one probable gas pipe were located by a high-resolution magnetic method during phase two in 2002 (Xia, 2002c; Xia and Williams, 2003). During this phase, we found that wells were sometimes located only a few feet apart, which requires a geophysical method that possesses 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 2003 when the second sensor was employed to acquire data for calculating pseudo-gradient of magnetic fields. The City of Hutchinson designated eight sites with a total area of 1,024,000 ft^2 (Table 1), which was divided into grids with an average size of 10,000 ft^2 each. Of thirty-one found wells, twenty-one 6- to 9-inch wells are abandoned brine wells, seven 1.5- to 3-inch wells are probably water wells, one 16-inch well is a dewatering well for construction, and two 4-inch wells are found on the ground surface and probably water wells.

Methodology

The survey areas were usually defined as 100 ft × 100 ft grids using a theodolite (shown at left in Figure 1). The accuracy of horizontal location within each grid is less than ±0.5 ft by rechecking directly with a tape measurement. A portable cesium gradiometer G858 (at the right in Figure 1) was used to measure the total field component of the geomagnetic field and the vertical gradient of the geomagnetic field. The bottom sensor high point and the top sensor high point are 14 in and 44 in from the ground surface, respectively. Pseudo-vertical gradients of the geomagnetic field are calculated by subtracting readings of the top sensor from readings of the bottom sensor. Magnetic anomalies on the sites of wells C4 and C8 were first acquired to serve as signatures in locating brine wells.

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, is used. Practically, we may not achieve 70% improvement in the horizontal resolution with pseudo-vertical gradient data. We tested the gradiometer G585 at a well near the Kansas Geological Survey building (Well KGS). Total field component of 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 field component of magnetic data (Figure 3b). Figure 3c shows the total field component of magnetic anomalies 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 field component of magnetic anomalies acquired "2 inches above the ground" possesses 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 if only one sensor is available.

The normal geomagnetic field in the City of Hutchinson was around 53,500 nT in May 2003 (Appendix A). The maximum change of the geomagnetic field in the quiet period ($Kp < 4$) is less than 15 nT/hour. 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 and ranges from 0 to 9. The K index measures the deviation of the most disturbed horizontal component (http://www.maj.com/sun/status.html). It took about 15 minutes to complete the magnetic survey on each 10,000 ft^2 grid, and the amplitude of well anomalies were on the order of several thousands nanoteslas. Because we completed the survey individually grid by grid during the quiet period of the geomagnetic field, no geomagnetic field correction is necessary.

Measurements were first assigned field geometry and then corrected for the sensor locations based on shapes of known anomalies by shifting odd numbered lines by 1.2 ft – 2 ft. Finally measurements were corrected by adjusting for data dropouts, which are readings over the meter scale. Measurements were then gridded into 1 ft × 1 ft grids by the Kriging method (Surfer®, 1999). Gridded measurements were correlated with anomalies from known wells. Anomalies were picked based on their amplitudes, shapes, or correlation coefficients. Some anomalies were also inverted to find their magnetization and depths to the top of the anomaly source.

High-resolution magnetic data were displayed using Surfer® in a color scale to enhance anomalies potentially caused by brine wells.

Magnetic Signals from Known Wells

We acquired high-resolution magnetic data at well sites 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 field component of magnetic anomalies (Figure 4a) and pseudo-vertical gradient data (Figure 4b). The maximum anomaly of total field component of magnetic anomalies 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 the 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 probably due to unsteady walking speed or sources other than well C4. These huge positive anomalies with a bulls-eye shape in both total field component of magnetic anomalies and gradient data showed promise in effectively recognizing anomalies of abandoned brine wells in the Hutchinson area.

Magnetic Survey in Hutchinson

A high-resolution magnetic survey was performed at the eight sites chosen by the City of Hutchinson after review of the historical literature on salt mining in the Hutchinson area (Figure 5). The magnetic data were normally acquired in 100 ft × 100 ft grids with line spacing of 3 ft (Figure 6). The density of a high-resolution magnetic survey along a line is 2.3 measurements/ft. The total survey lineage acquired in the 1,024,000 ft^2 survey area was around 70 miles.

Based on magnetic signatures acquired from the known wells, we determined the anomaly picking criteria: 1. Approximate monopole: both in magnetic and gradient, a weak negative anomaly in north may be associated with monopole for gradient data; 2. Amplitude larger than 4000 nT for magnetic anomaly and 100 nT/in for pseudo-vertical gradient; 3. Half-width: 3 to 12 ft for magnetic anomaly.

Sixty-four anomalies were identified (Table 2). Of forty-seven verified anomalies 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 9-inch wells were abandoned brine wells, seven 1.5- to 3-inch wells were probably water wells, and one 16-inch well was a construction dewatering well at a depth 3 ft. The sources of the rest of the seventeen anomalies were a known brine well, two 4-inch wells on the ground surface, two well-like anomalies next to constructions, some dipoles and 3-D body anomaly that are not due to wells, and some metal junk on the ground surface. Appendix B contains all final maps of the high-resolution magnetic surveys at the eight sites.

1. Findings at Concrete Enterprises, Inc.

The survey at Concrete Enterprises, Inc. covered 540,000 ft^2. Seventeen brine wells, one dewatering well, and one 3-inch well that is suspected to be the inner pipe of a brine well, were found at this location (Figure 7). Total field component of magnetic anomaly and pseudo-vertical gradient anomaly are shown in Figures 8 and 9, respectively. It is clear that pseudo-vertical gradient data possess the higher horizontal resolution.

The first interesting anomaly group is called "G 7" in grids 11&12 (Figure 10). Group "G 7" consists of seven giant individual anomalies. They are nearly perfect bulls-eyes anomalies both in magnetic and gradient data. They may be associated with a unique salt mining method. Gradient data (bottom, Figure 10) provide sharper images of seven individual monopole objects than does magnetic data (top, Figure 10). The peak of each monopole anomaly is the center of an anomalous source. Excavation by a backhoe at "G 7" reveals seven brine wells (Figure 11) from a depth of 26 inches (well E11&12-1) to 101 inches (well E11&12-7). All seven wells are 8-inch wells. From well E11&12-2 to well E11&12-7 is almost a straight line and they are 20 feet apart. Magnetic anomaly amplitudes for the two wells are in a range of 7,000 nT (E11&12-7) to 20,000 nT (E11&12-1). Vertical gradients change from 130 nT/in to 300 nT/in. This is mainly due to depth variation of wellheads. The anomaly at (30, 105) is due to a 0.75-inch pipe on the ground surface.

The other interesting anomaly group is "G 5" in grid E16&17 that consists of five perfect bulls-eyes in both magnetic and gradient data (Figure 12). Anomalies E16&17-2 and E16&17-5 are 15 ft apart and along a straight line. "G 5" reveals five 8-inch brine wells at almost the same depths (from 45 to 48 inches, Figure 13). Amplitudes of magnetic anomalies of "G 5" vary from 12,000 nT to 23,000 nT even though depths to the top of the wells are pretty much the same. Vertical Gradients change from 200 nT/in to 300 nT/in. The changes in amplitude should be mostly related to the thickness of the well.

One individual anomaly with the maximum of 19,000 nT at (175, 141) of grid E16&17 is also caused by an 8-in brine well at a depth of 16 inches. If the pattern of "G 7" and "G 5" could be applied to E16&17-6, there might be several other wells associated with this well. The search area should be expanded to the east of grid E16&17.

Four individual brine wells were found in the south part of the site (Figure 14). E19-1 is a 6-inch brine well at a depth of 29 inches at the center of a T-intersection of roads. Wells E21-1, E23-1, and E25-1 are located in the working yard of Concrete Enterprises, Inc. E21-1 and E25-1 are 8-inch wells at a depth of 60 inches and 13 inches, respectively. There are two pipes associated with well E21-1. The inner pipe is 3 inches in diameter. This dual-pipe well produces the highest magnetic anomaly (81,900 – 53500 = 28,400) and the highest gradient (> 300 nT/in) in this year's results even though it is one of the deeper wells. Well E23-1 is a 6-inch well at a depth of 30 inches. Due to thickness of the wells, their magnetic anomalies (18,000 nT to 28,000 nT) are relatively higher than the amplitudes of “G 7” and “G 5”. Vertical gradients change from 250 nT/in to 350 nT/in.

A 16-inch dewatering well for construction of a pumping station was found in Grid E1 at a depth of 35 inches (Figure 15). Because it is thinner, shorter (40 – 50 ft), and has a larger diameter (demagnatization) than the brine wells the maximum magnetic anomaly is only 7,000 nT.

A random search was done in some areas of the working yard where it was not possible lay out grids. Well E43-1 was first found by the random search and a small grid was defined around it (Figure 15). Well E43-1 is a 3-inch well at a depth of 32 inches. Based on its relatively high magnetic amplitude (13,000 nT) and its depth, we suspected this well may be the inner pipe of a brine well as shown in Well E21-1 (Figure 14).

There are some anomalies at this site that are due to sources other than wells. Anomaly E14-4 at (126, 133) is due to a 9-inch horizontal pipe at a depth of 48 inches pointing 45º from due north (Figure 16). Other anomalies associated with this elongated anomaly are E14-1 at (78, 86), E14-2 at (87, 95), and E14-3 at (116, 126). All are believed to be caused by the same source as the E14-1. E14-5 (117, 95) is due to a 13-inch horizontal pipe at a depth of 43 inches (not shown in the figure). Anomaly E42-1 at (9, 24) is due to buried railroad track at a depth 13 inches (Figure 16). Anomalies E26-1 and E26-2 are believed to be the same buried railroad. Anomalies E41-1, E41-2, and E41-3 are due to 1.5-inch vertical metal bars at depths of 4 inches, 12 inches, and 18 inches, respectively. Their anomalies are the same as anomalies caused by wells. There is no way to distinguish these anomalies from anomalies due to wells.

Anomaly E37-1 at (88, 46) is on the edge of building so it was not excavated (see Appendix B). Based on its amplitude and shape, it could be due to a well.

2. Findings at Pankratz Implement Co.

The survey at Pankratz Implement Co. covered 184,000 ft^2. Three brine wells and eight probable water wells were found at this location (Figure 17). Total field component of magnetic anomaly and pseudo-vertical gradient anomaly are shown in Figures 18 and 19, respectively. It is clear that pseudo-vertical gradient data possess the higher horizontal resolution.

Three brine wells were located along a railroad (Figure 20). Well P3-1 is an 8-inch brine well at a depth of 12 inches. Well P7-1 is a 9-inch brine well at a depth of 20 inches. Well P9-1 is an 8-inch brine well at depth of 42 inches. Their magnetic anomalies and gradients are nearly perfect monopoles. Amplitudes of the total field component of magnetic anomalies are in a range from 26,000 nT to 28,000 nT. Vertical gradients are in the range 260 nT/in to 300 nT/in.

Two 2-inch (water?) wells were found in grids P4 and P5 (Figure 21). Anomaly amplitudes due to these wells are normally lower than brine wells. Amplitudes of the total field component of magnetic anomalies of P4-1 and P5-3 are 7,000 nT and 4,000 nT, respectively. The maximum gradient of both wells is around 100 nT/in. We distinguished these anomalies from the rest of the anomalies mainly because of their near perfect monopoles. Anomalies P5-1 at (92, 63) and P5-2 at (91, 35) are caused by the railroad.

Two 3-inch (water?) wells were found in Grid P8 (Figure 22). Gradient data successfully revealed two individual anomalies six feet apart. P8-1 at (72, 6) and P8-2 at (78, 5) are due to 3-inch wells at depths of 16 inches and 26 inches, respectively. Amplitudes of the total field component of magnetic anomalies of P8-1 and P8-2 are 5,000 nT and 6,500 nT, respectively. The maximum gradient of both wells is around 100 nT/in.

One 3-inch (water?) well and one 1.5-inch (water?) well were found in Grid P10 (Figure 23). P10-2 possesses the maximum anomaly of 8,000 nT and the maximum vertical gradient of 140 nT/in. P10-3 possesses the maximum anomaly of 5,000 nT and the maximum vertical gradient of 120 nT/in. An anomaly ten feet west of P10-3 was not excavated because of its elongated shape and a small half-width. A dipole at (40, 70) was not excavated because we knew it was due to a metal object with a very limited length. Anomaly P10-1 at (30, 60) is due to a 4-inch horizontal pipe with a broken end at a depth of 27 inches. This kind of anomaly source we also encountered at anomalies E14-4, E14-5, E14-6, E15-2, E32-1, E40-1, and E42-2 at Concrete Enterprises, Inc. The end of horizontal pipes/bars will show the almost the same anomaly shape as a well does. To distinguish this kind of anomaly from anomalies due to wells still remains as a challenge for future study.

Two 4-inch (water?) wells five feet apart were found on the ground surface (Figure 24) in Grid P9. Because the two wells are so close to each other, even gradient data with a line spacing of 3 ft showed a little indication of these wells. We redefined a 30 ft by 30 ft grid with 1-ft line spacing (on the top-left of Figure 24). One survey line transited both wells. Gradient data clearly shows two individual anomalies. This test demonstrated that the horizontal resolution can be limited by line spacing.

3. Findings at Stuckey Lumber & Coachlamp Village

One 8-inch brine well was found at Stuckey Lumber & Coachlamp Village (Figure 25). Total field component of magnetic anomaly and pseudo-vertical gradient anomaly are shown in Figures 26 and 27, respectively.

The anomaly due to this well (L7-1) is a classic example of the brine well signature in Hutchinson area. The amplitude of the total field component of magnetic anomaly is 23,000 nT. The maximum gradient is about 230 nT/in (Figure 28). This well is at a depth of 14 inches. The magnetic survey (Figure 28) at this site correctly indicated the location of a known brine well (V1-1). We observed part of an anomaly (L7-2) at the corner of a shed. This anomaly could be due to a brine well (Figure 28).

4. Survey results on other sites

Figures 29 to 33 show magnetic survey results at other sites. After surveying in 2002 at Union Salt, Inc., Salvation Army Park, Ironhorse Equestrian Center, and Monroe St. & Avenue F, more area was covered this year on these sites in hopes of finding more wells. Neither total field component of magnetic data or pseudo-vertical gradient data suggest any anomalies that could be caused by brine wells. One well-like anomaly at (247, 38) of Grid U8 was excavated (Figure 29) and turned out to be caused by a sewer pipe.

Conclusions

The high-resolution magnetic method and the vertical gradient method were successful in locating abandoned brine wells in Hutchinson, Kansas. Twenty-one brine wells and ten (water?) wells were found during this year's magnetic survey. Approximate monopole shape anomalies were observed from all these wells after data corrections. A wide range of amplitudes of magnetic anomalies (from 7,000 to 28,000 nT) was measured from these abandoned brine wells, due mainly to the thickness of wells and depths of buried wells. Anomaly amplitudes from 1.5- to 3-inch wells are 4,000 to 8,000 nT that are linearly correlated with the buried depth. One 3-inch well that caused an anomaly with amplitude of 13,000 nT could be an inner pipe of a brine well. Gradient anomalies are 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. With anomalies at these levels, the high-resolution magnetic method and the gradient method can surely locate abandoned brine wells in a noise environment like the City of Hutchinson. The gradient data not only possess higher horizontal resolution than magnetic data but also provide other dimensions of data that can be used to identify potential brine well candidates. The resolution improvement is limited, however, by line spacing of survey grids.

Acknowledgements

I greatly appreciate Stephen William and Dennis Clennan of the City of Hutchinson for their literature research on the salt mining history in Hutchinson area in order to assign the survey sites, their assistance in permitting, clearances, and access issues, and providing digital site maps. I would like to thank Michael Cochran and Mary Daily of Kansas Department of Health and Environment for discussion and materials on the salt mining history in Hutchinson. I would like to thank Brett Bennett of Kansas Geological Survey his assistance in instrument preparation. I would also like to thank Reg Jones and his crew at the City of Hutchinson for their help in field operation. Finally, I would like to thank Mary Brohammer for her efforts in preparation of this report.

References

Allison, M.L., 2001, Hutchinson, Kansas: A geologic detective story: Geotimes, v. 46, no. 10, p. 14-18.

Breiner, S., 1973, Application manual for portable magnetometers: Geometrics, Inc.

Surfer®, 1999, User's guide: Golden Software, Inc.

Xia, J., 2001a, Feasibility study on using electromagnetic method to locate abandoned brine wells in Hutchinson, Kansas: Kansas Geological Survey Open-file Report 2001-10.

Xia, J., 2001b, Using electromagnetic method to locate abandoned brine wells in Hutchinson, Kansas: Kansas Geological Survey Open-file Report 2001-17.

Xia, J., 2002a, Results of Electromagnetic Survey in Hutchinson, Kansas in May 2001: Kansas Geological Survey Open-file Report 2002-52, 273 pp.

Xia, J., 2002b, Using electromagnetic methods to locate abandoned brine wells in Hutchinson, Kansas: Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) 2002 Annual Meeting of EEGS, Las Vegas, Nevada, February 10-14, 2002, 11 pp, available on CD.

Xia, J., 2002c, Using the high-resolution magnetic method to locate abandoned brine wells in Hutchinson, Kansas: Kansas Geological Survey Open-file Report 2002-43, 58 pp.

Xia, J., and Williams, S.L., 2003, High-resolution magnetic survey in locating abandoned brine wells in Hutchinson, Kansas: Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) 2003 Annual Meeting of EEGS, April 6-10, 2003, San Antonio, Texas, 12 pp, available on CD.

Xia, J., Chen, C., Xia, S., Laflen, D., and Williams, S.L., 2003, Using High-resolution Magnetic Method and Gradient Method to Locate Abandoned Brine Wells in Hutchinson, Kansas: Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP) Annual Meeting of the Environmental and Engineering Geophysical Society (EEGS), February 22-26, Colorado Springs, Colorado, 2004, 1 pp.

Figure 1. A theodolite (left) was used to define grids for high-resolution magnetic survey. David Laflen (left) is defining grids. A portable cesium gradiometer G858 (right) was used to measure the total component of the geomagnetic field. Jianghai Xia is performing the magnetic survey.

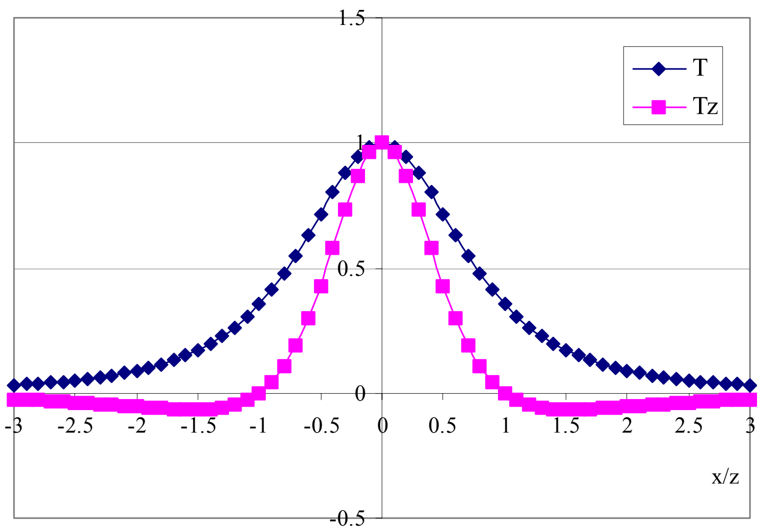
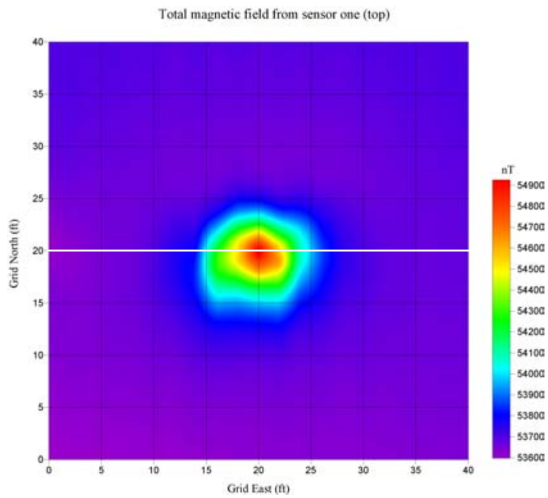
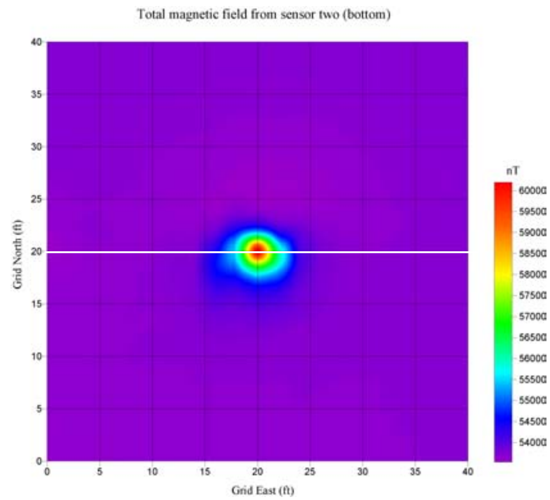


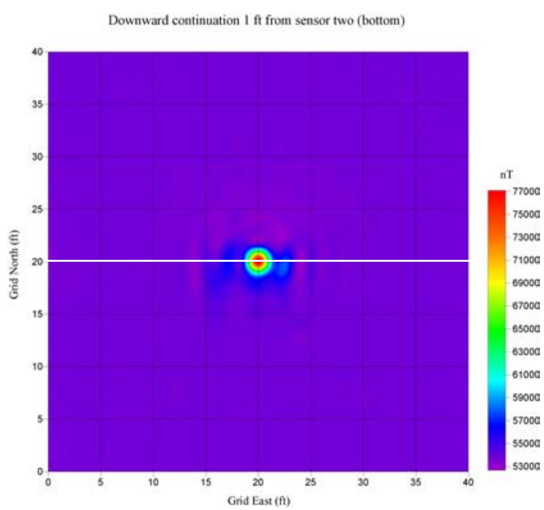
Figure 2. The half width of the total field component of magnetic anomaly (T) of the monopole with the vertical magnetization is ± 0.77 x/z. It is ± 0.45 x/z for the vertical gradient (Tz). The horizontal resolution is theoretically increased with the vertical gradient data by 70% (0.77/0.45 = 1.71)



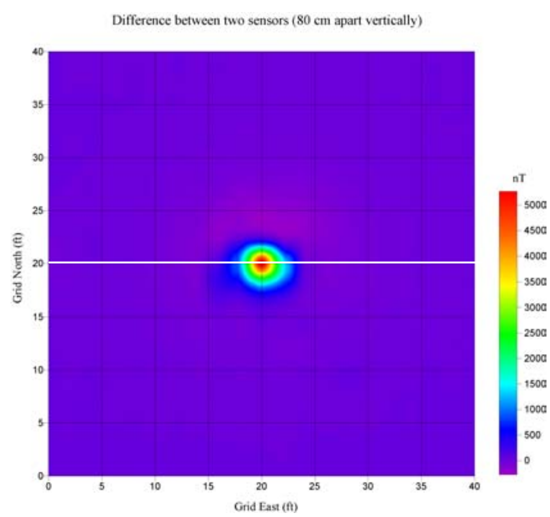
a



b



c



d

Figure 3. Magnetic anomaly of Well KGS. (a) Total field component of magnetic anomaly of the top sensor (44 inches above the ground). (b) Total field component of magnetic anomaly of the bottom sensor (14 inches above the ground). (c) Total field component of magnetic anomaly "2 inches above the ground." (d) Pseudo-vertical gradient (bottom – top). Improvement in the horizontal resolution is obvious when comparing magnetic field (a) with the pseudo-vertical gradient data (d). The downward continuation results (c) also possess higher horizontal resolution. Central profiles indicated by white lines are shown in (e).

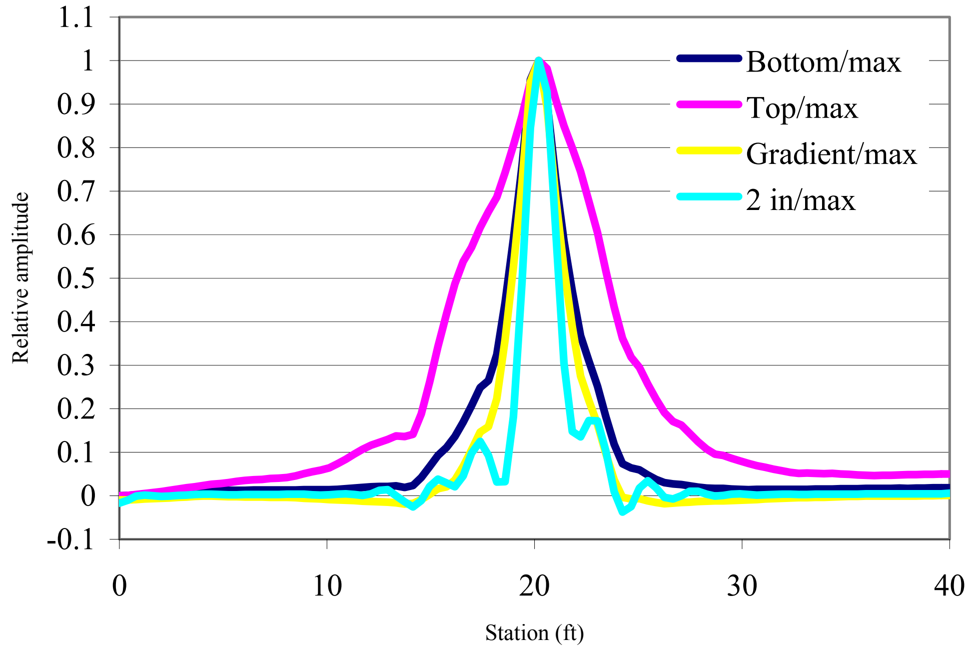


Figure 3e. The central profiles of magnetic data shown in Figure 3a-3d. The narrower anomaly peaks are, the higher the horizontal resolution.

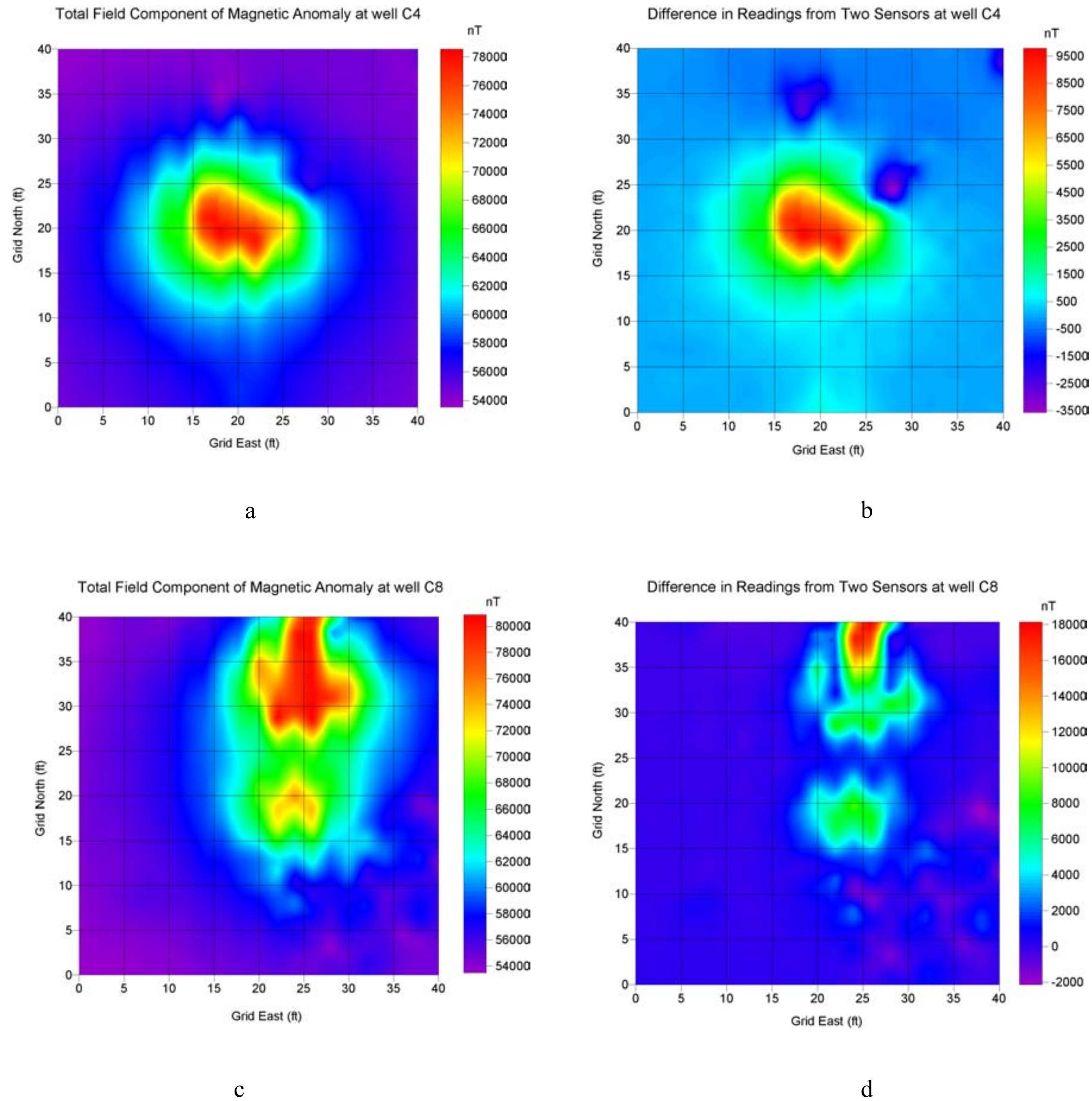


Figure 4. Magnetic signatures at known well sites. The pseudo-vertical gradient data at both sites (b) and (d) possess higher horizontal resolution than their total field component of magnetic anomalies (a) and (c).

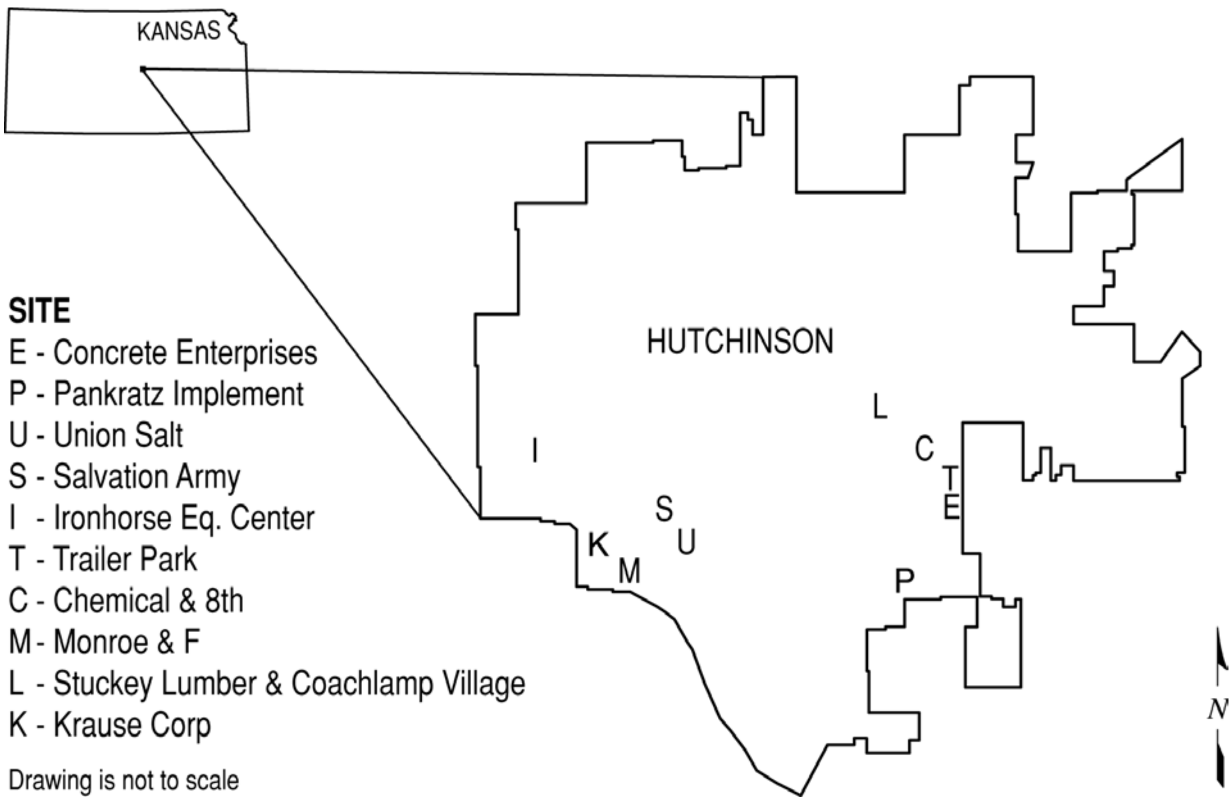


Figure 5. Site map showing the locations of the eight high-resolution magnetic surveys conducted in the City of Hutchinson in 2003 and discussed in this report. Also included are those areas covered by surveys in 2002.

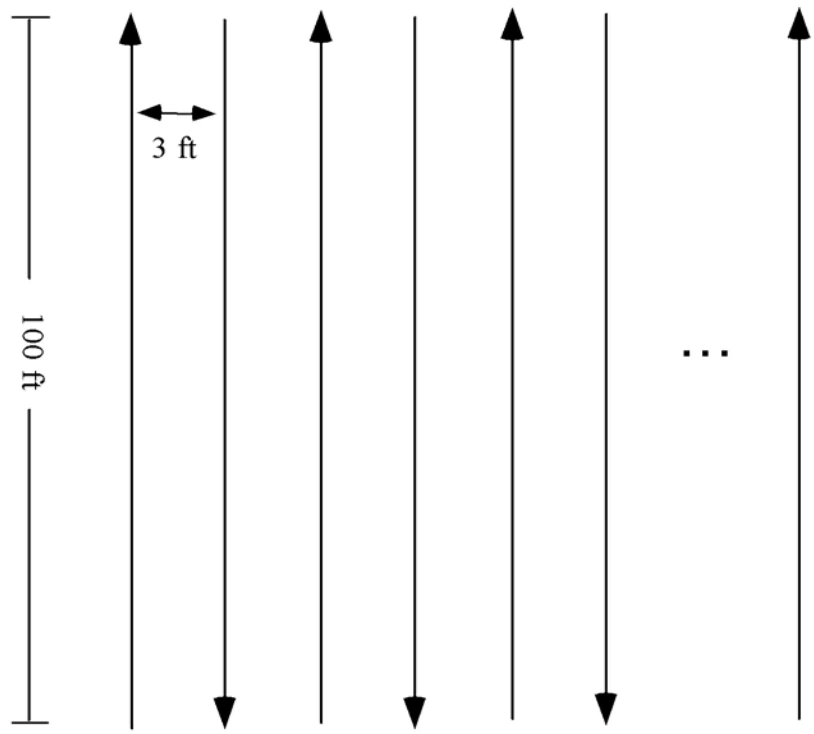


Figure 6. Arrows indicate the walking direction.

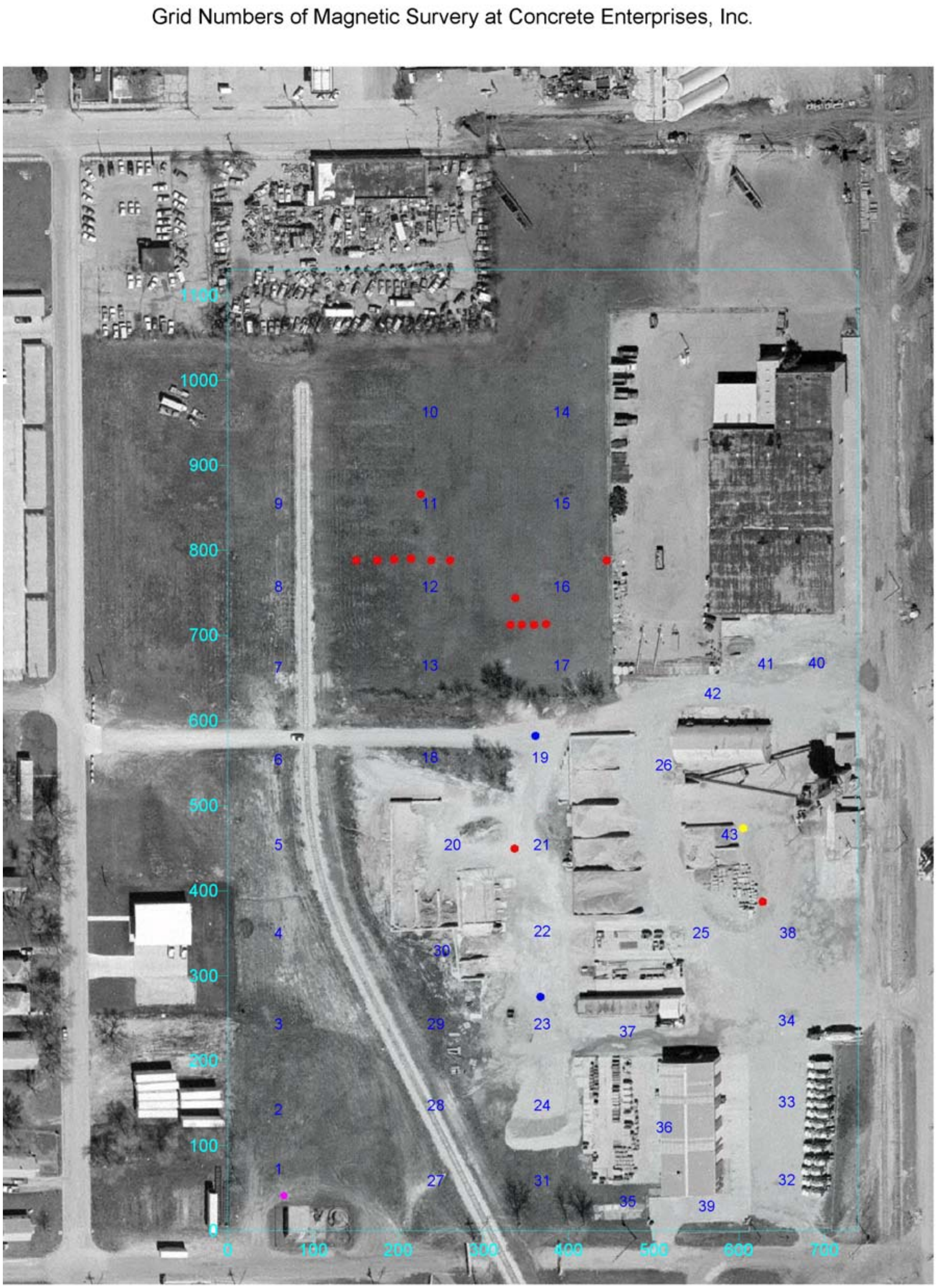


Figure 7. Aerial photo showing Concrete Enterprises, Inc. with survey grids (numbers in blue). The red dots and one blue dot (next to grid number 19) denote the location of brine wells. The one yellow dot (next to grid number 43) indicates a suspected brine well.

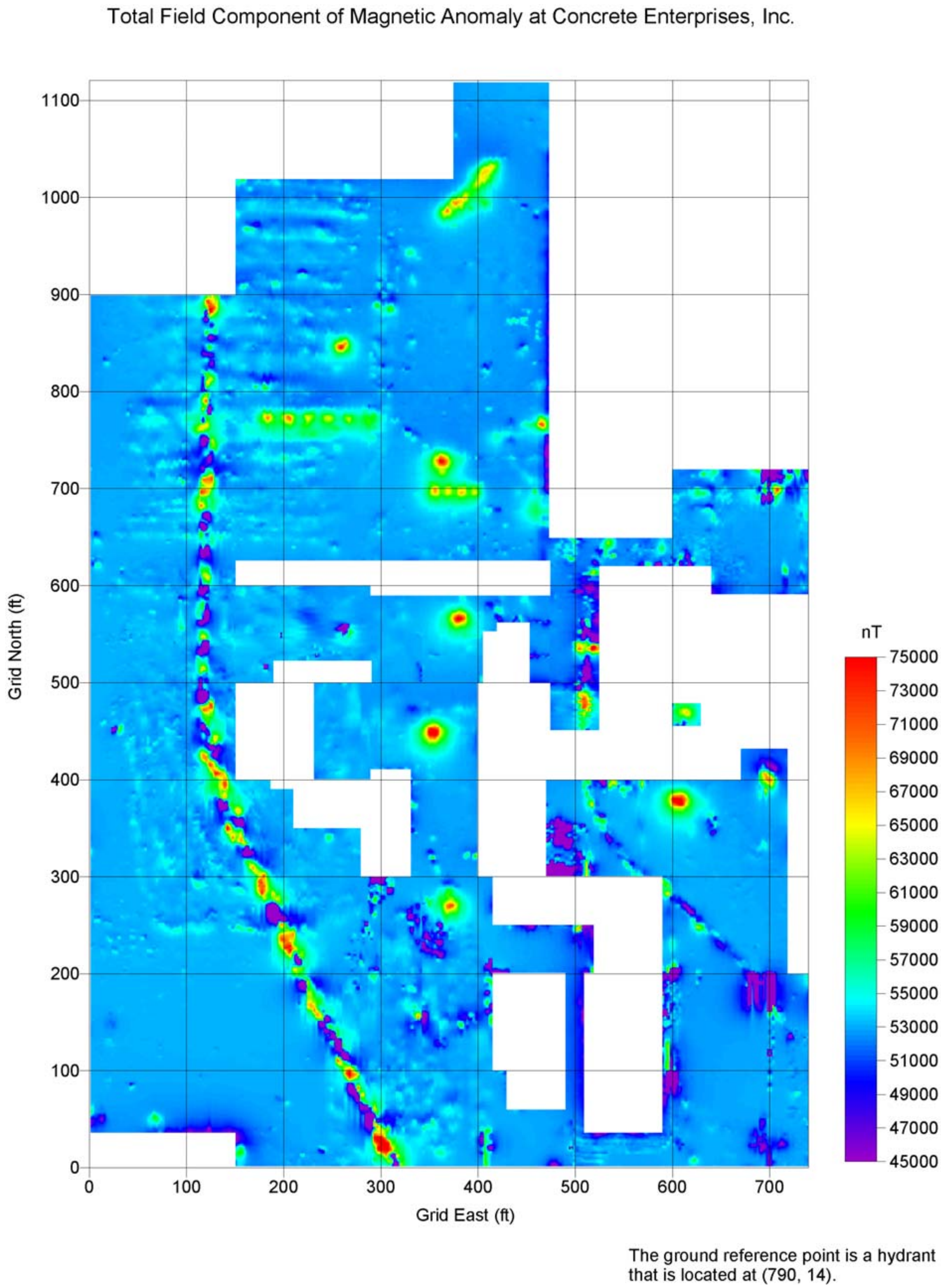


Figure 8. Total field component of magnetic field at Concrete Enterprises, Inc.

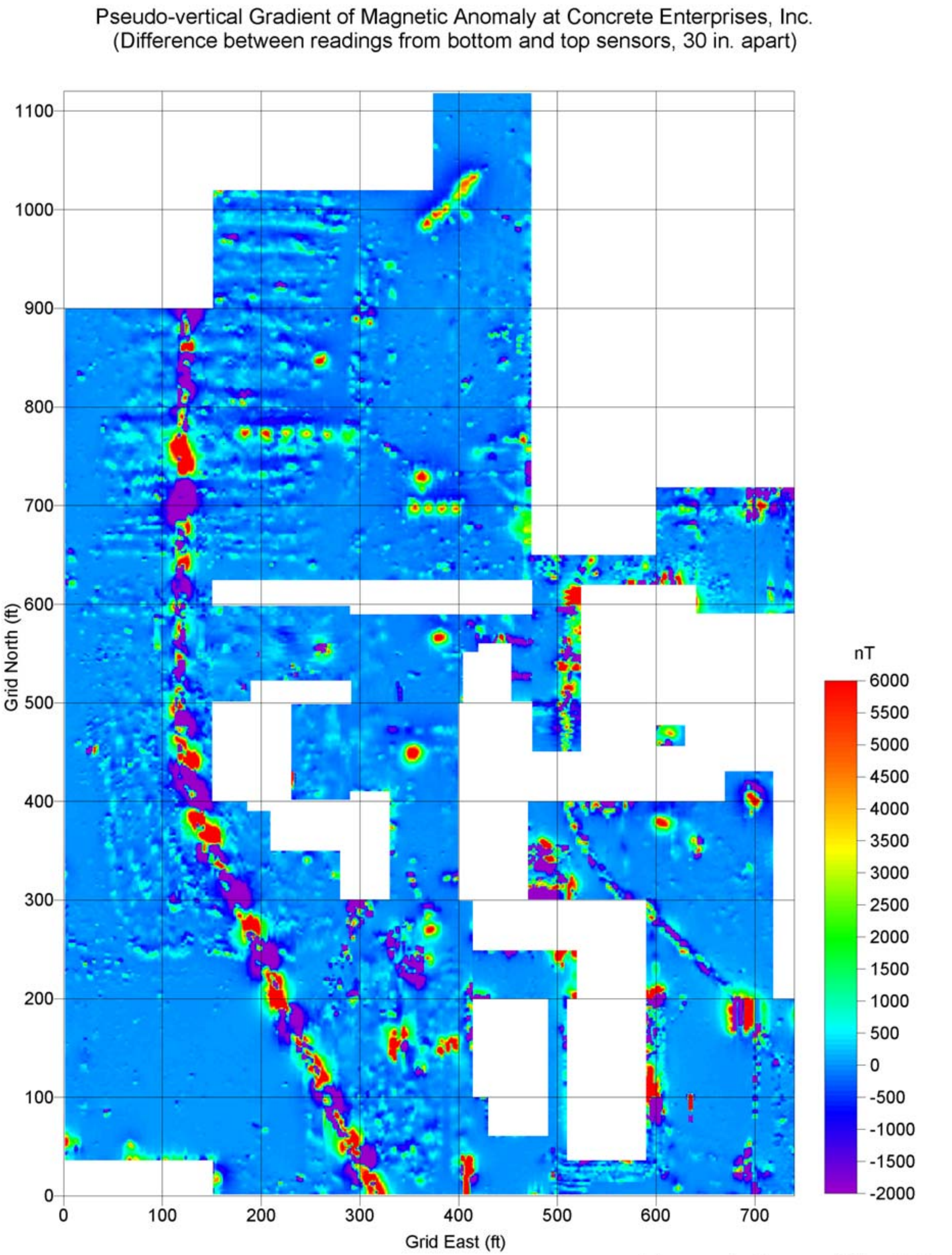
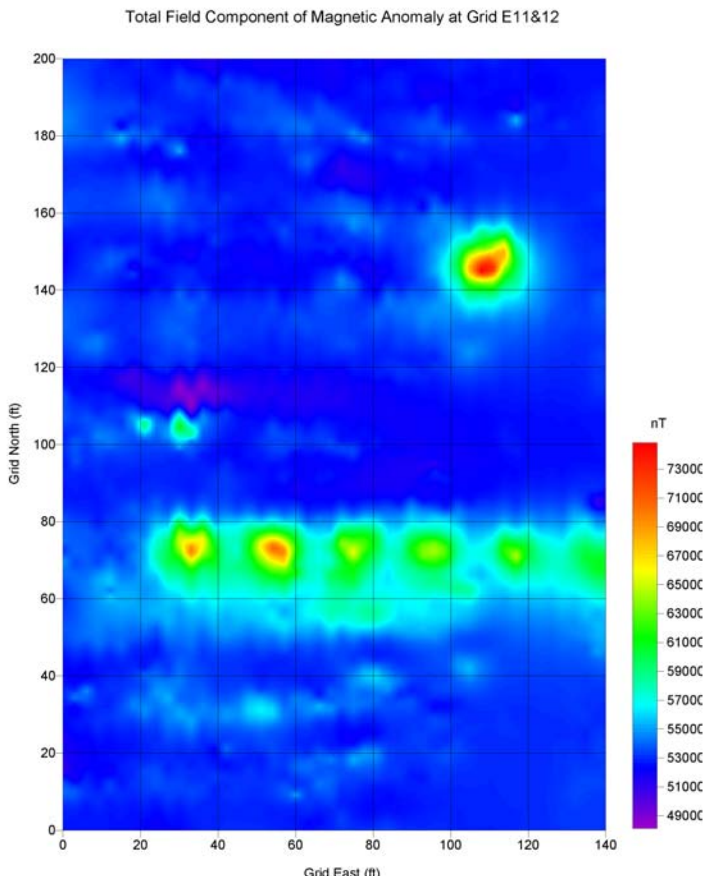


Figure 9. Pseudo-vertical gradient data at Concrete Enterprises, Inc.



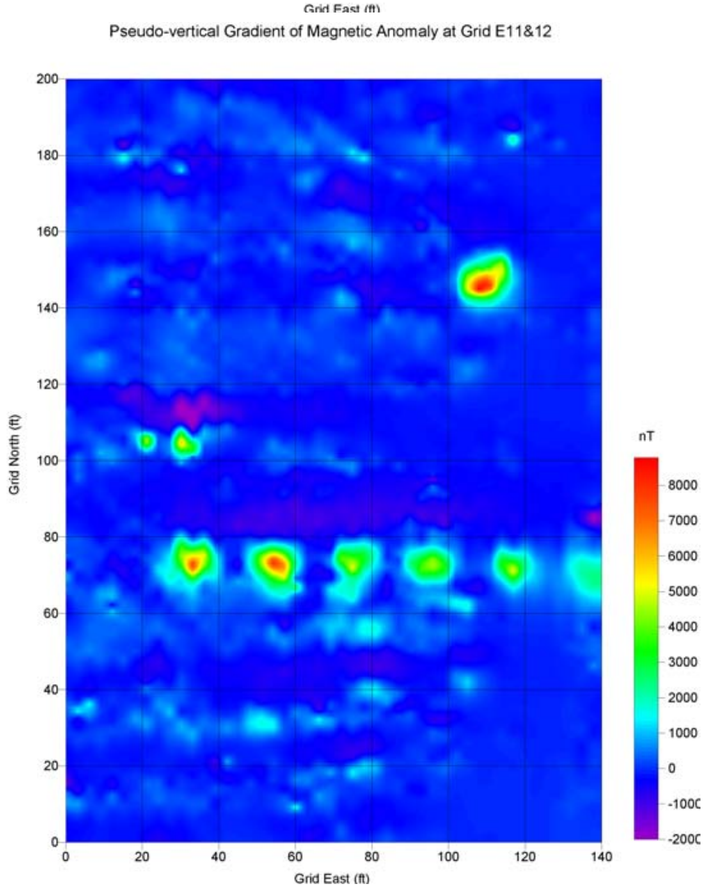
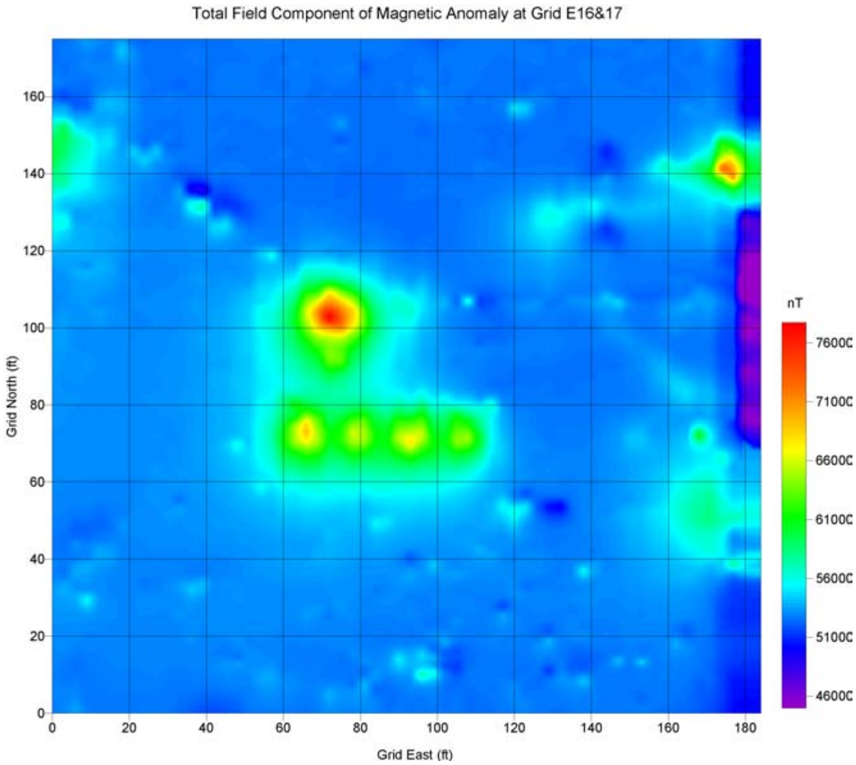


Figure 10. Group "G 7" at Concrete Enterprises, Inc. (top) The total field component of the magnetic anomaly in grid E11&12. (bottom) Pseudo-vertical gradient anomaly in grid E11&12.

Figure 11. Group "G 7" reveals seven 8-inch brine wells from a depth of 24 inches (well 1) to 101 inches (well 7).



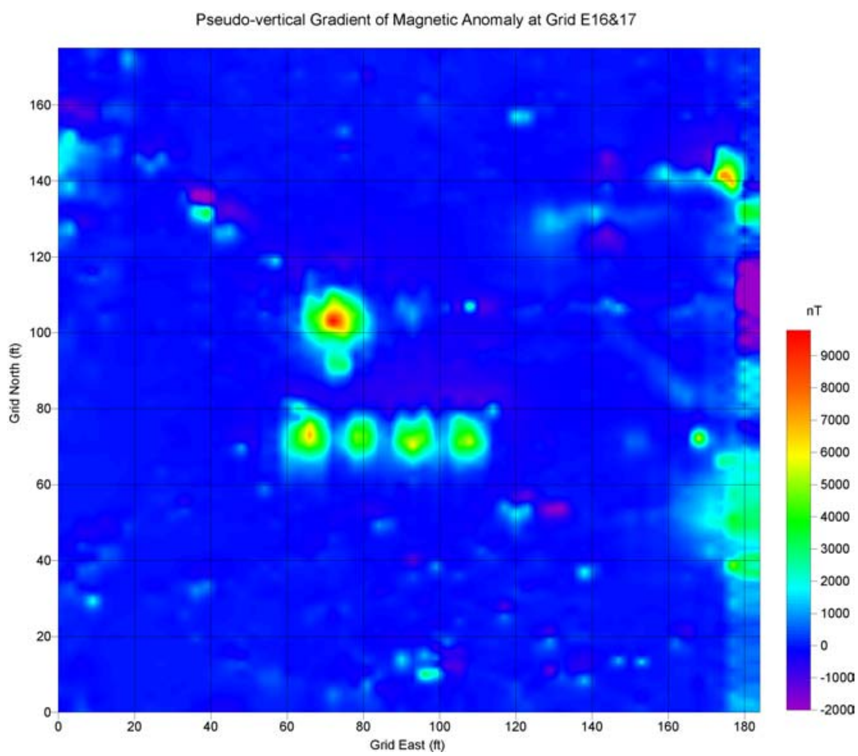


Figure 12. (top) The total field component of the magnetic anomaly in grid E16&17 at Concrete Enterprises, Inc. (bottom) Pseudo-vertical gradient anomaly (bottom) in grid E16&17. This map shows anomaly "G 5" ("Group 5") and one isolated anomaly at (175, 141).

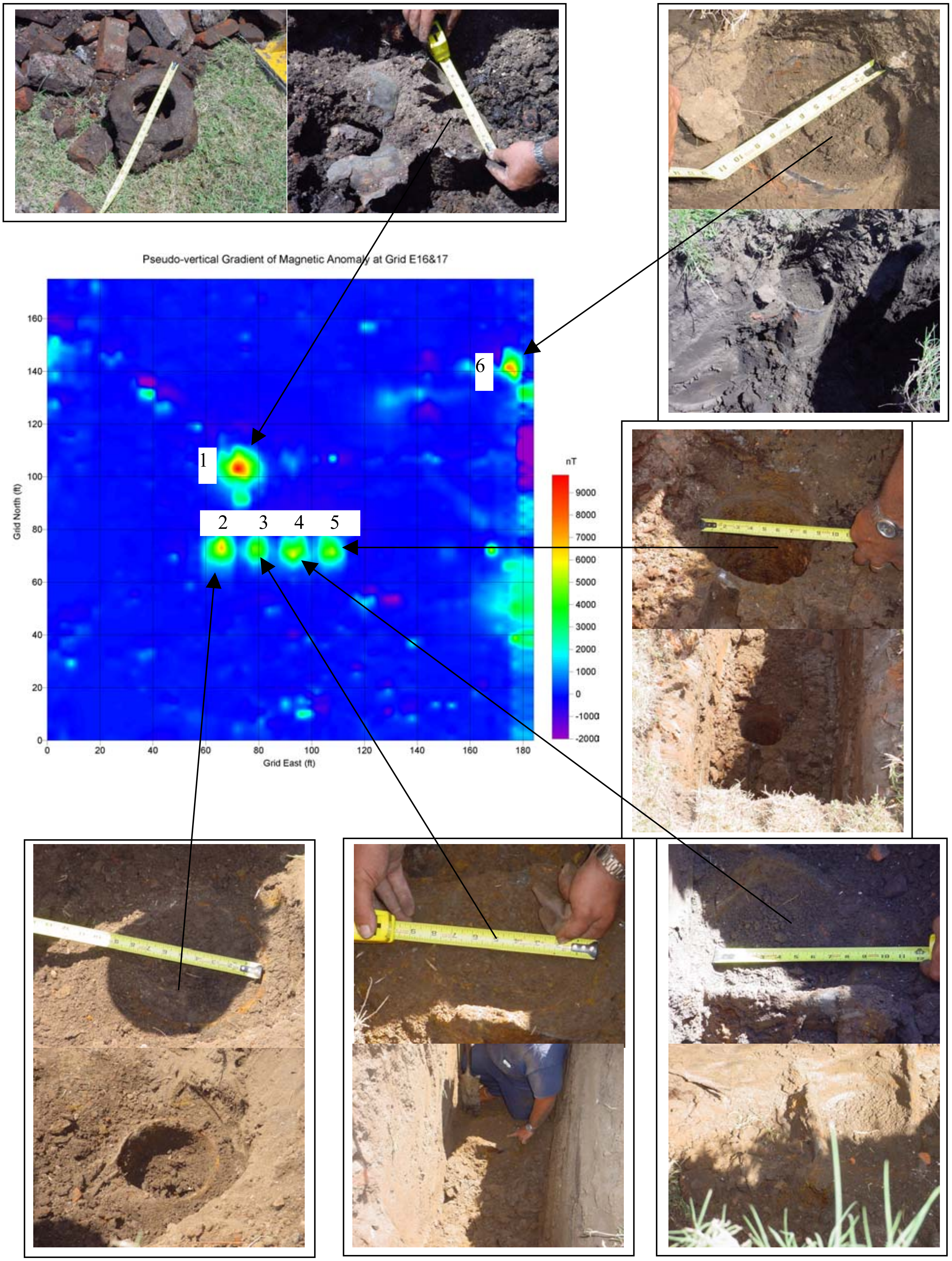


Figure 13. Anomaly group "G 5" reveals five 8-inch brine wells from depths of 45 inches to 48 inches. One individual anomaly (175, 141) is also due to a 8-inch brine well at a depth of 17 in.

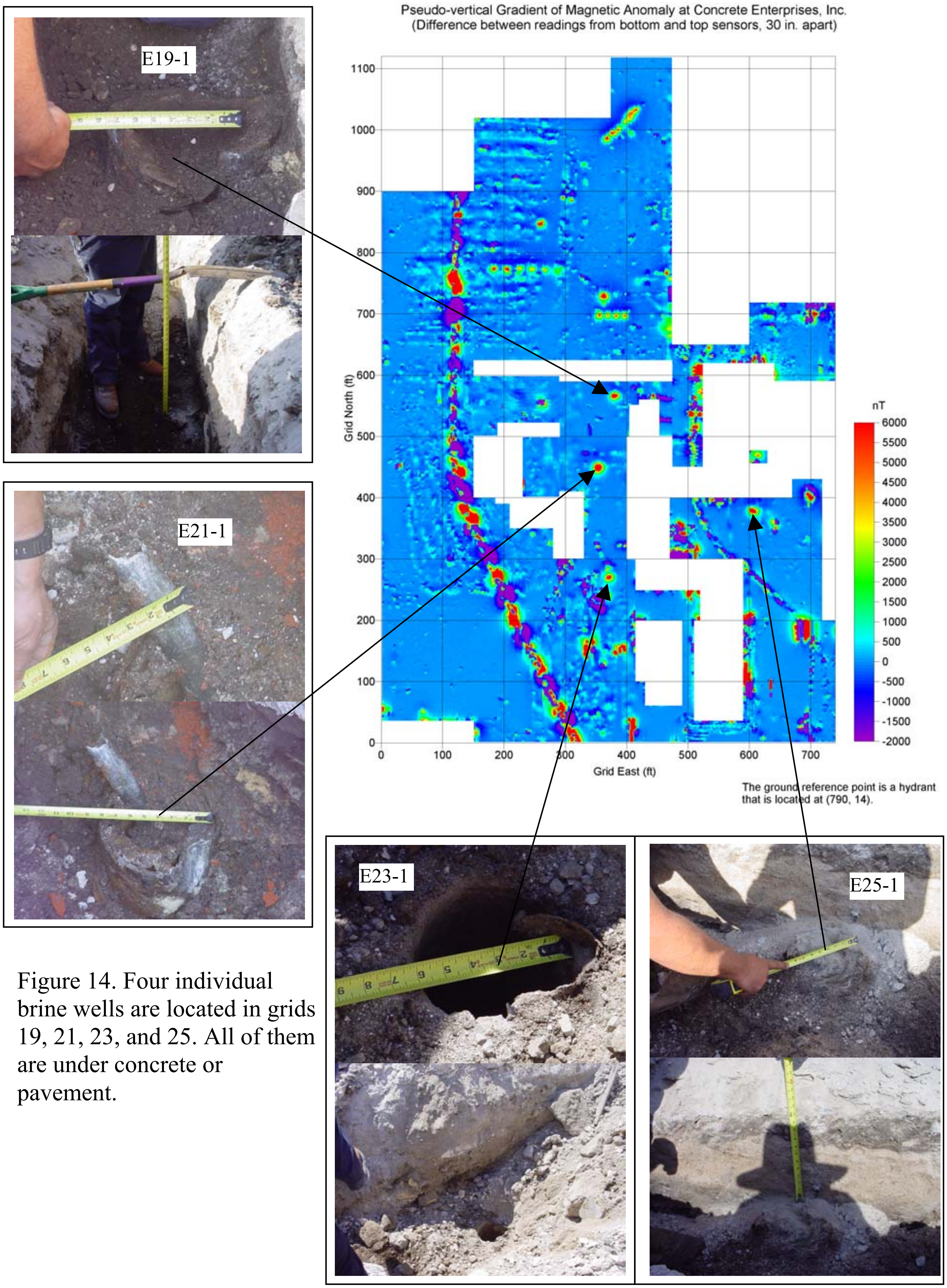


Figure 14. Four individual brine wells are located in grids 19, 21, 23, and 25. All of them are under concrete or pavement.

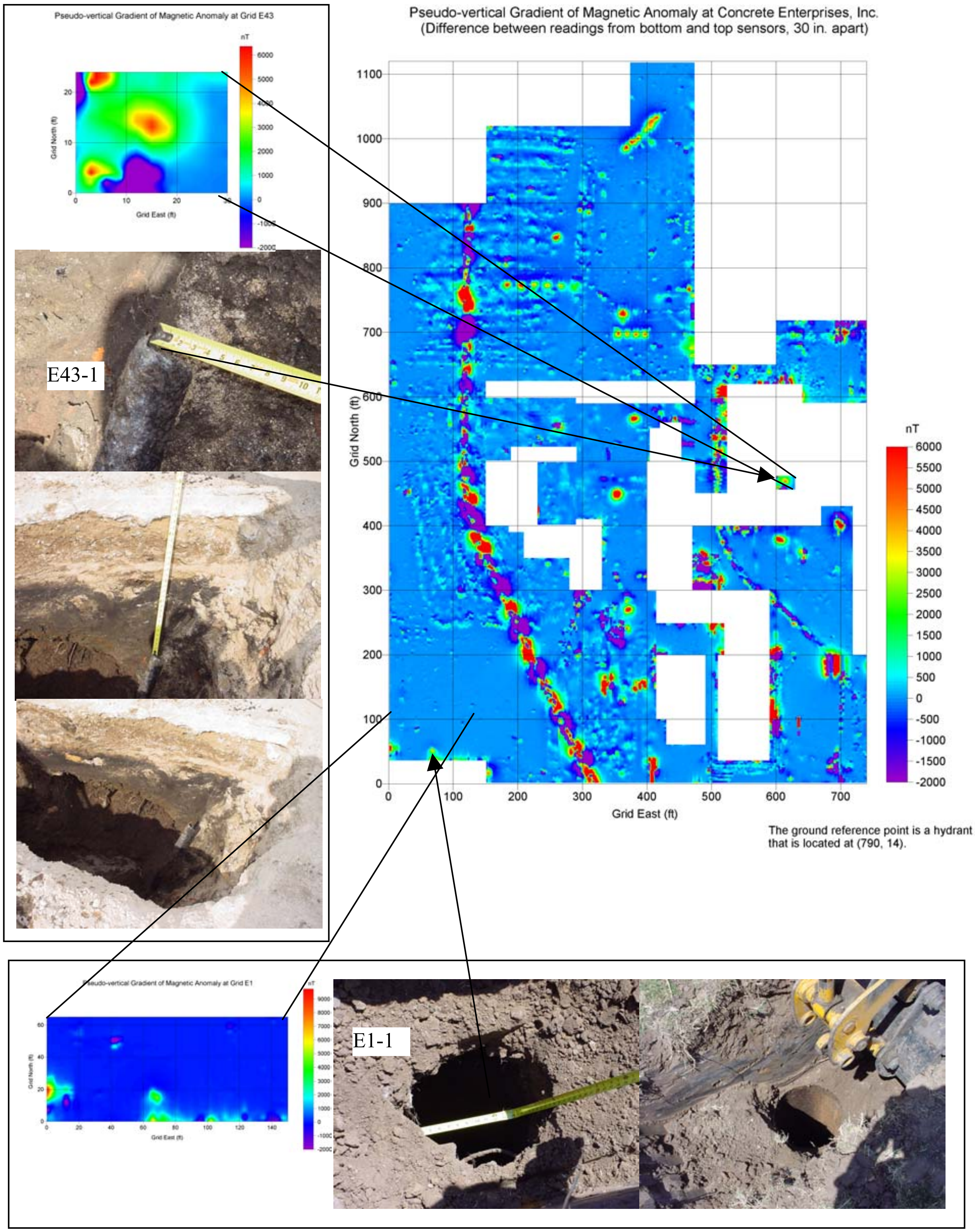


Figure 15. A 16-inch dewatering well for a construction was found in grid E1. A 3-inch well was found in grid E43 by a random search. This second well may be the inner pipe of a brine well, similar to well E21-1, shown in Figure 14. Refer to Appendix B for anomaly details.

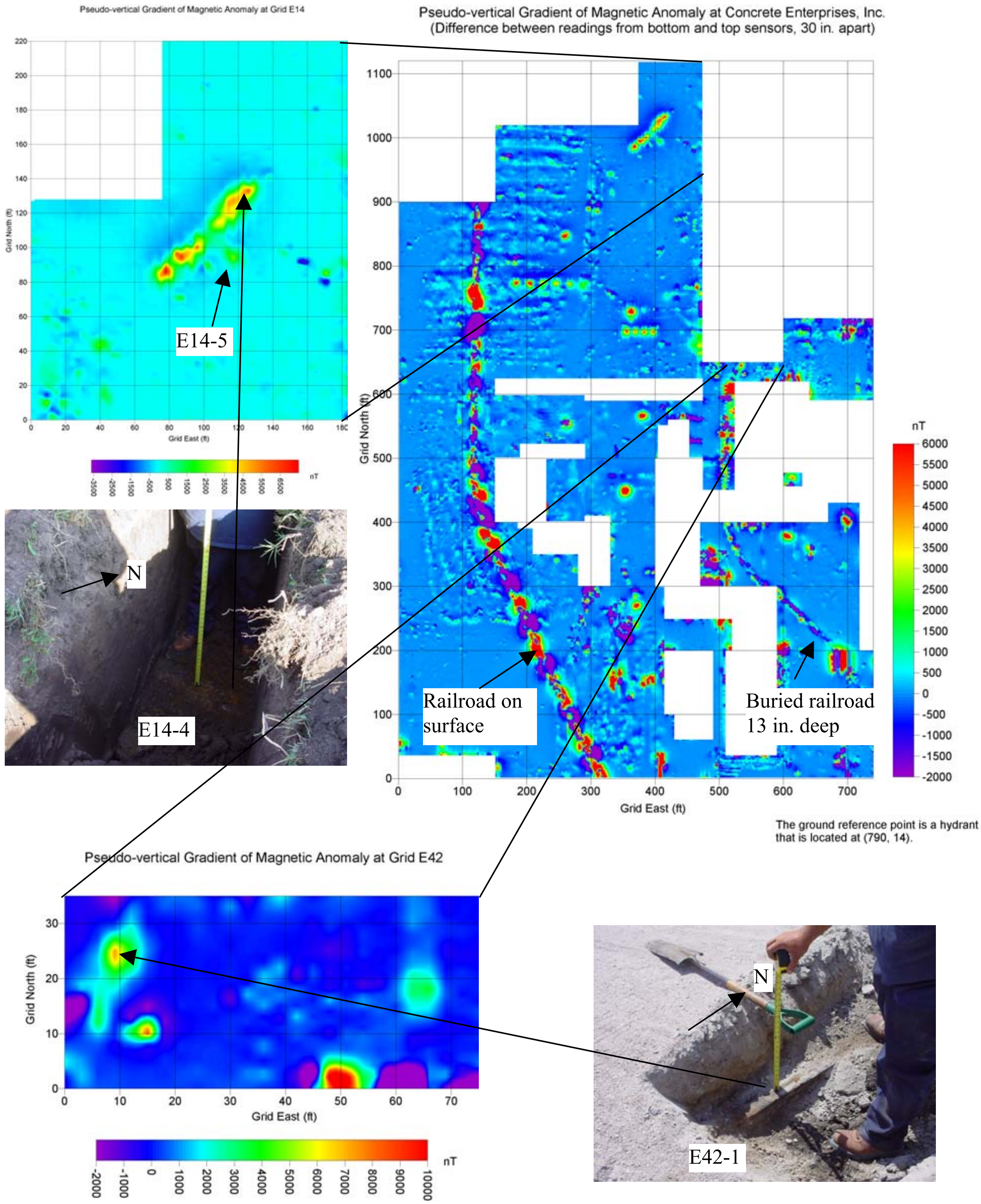


Figure 16. Anomaly E14-4 at (126, 133) is due to a 9-inch horizontal pipe at a depth of 48 inches and pointing 45º from due north. The other anomalies associated with this elongated anomaly are E14-1 (78, 86), E14-2 (87, 95), and E14-3 (116, 126) and are believed to be caused by the same source as E14-1. E14-5 (117, 95) is due to a 13-inch horizontal pipe at a depth of 43 inches (not shown in this figure). Anomaly E42-1 at (9, 24) is due to buried railroad track at a depth 13 inches and anomalies E26-1 and E26-2 are believed to be the same buried railroad.

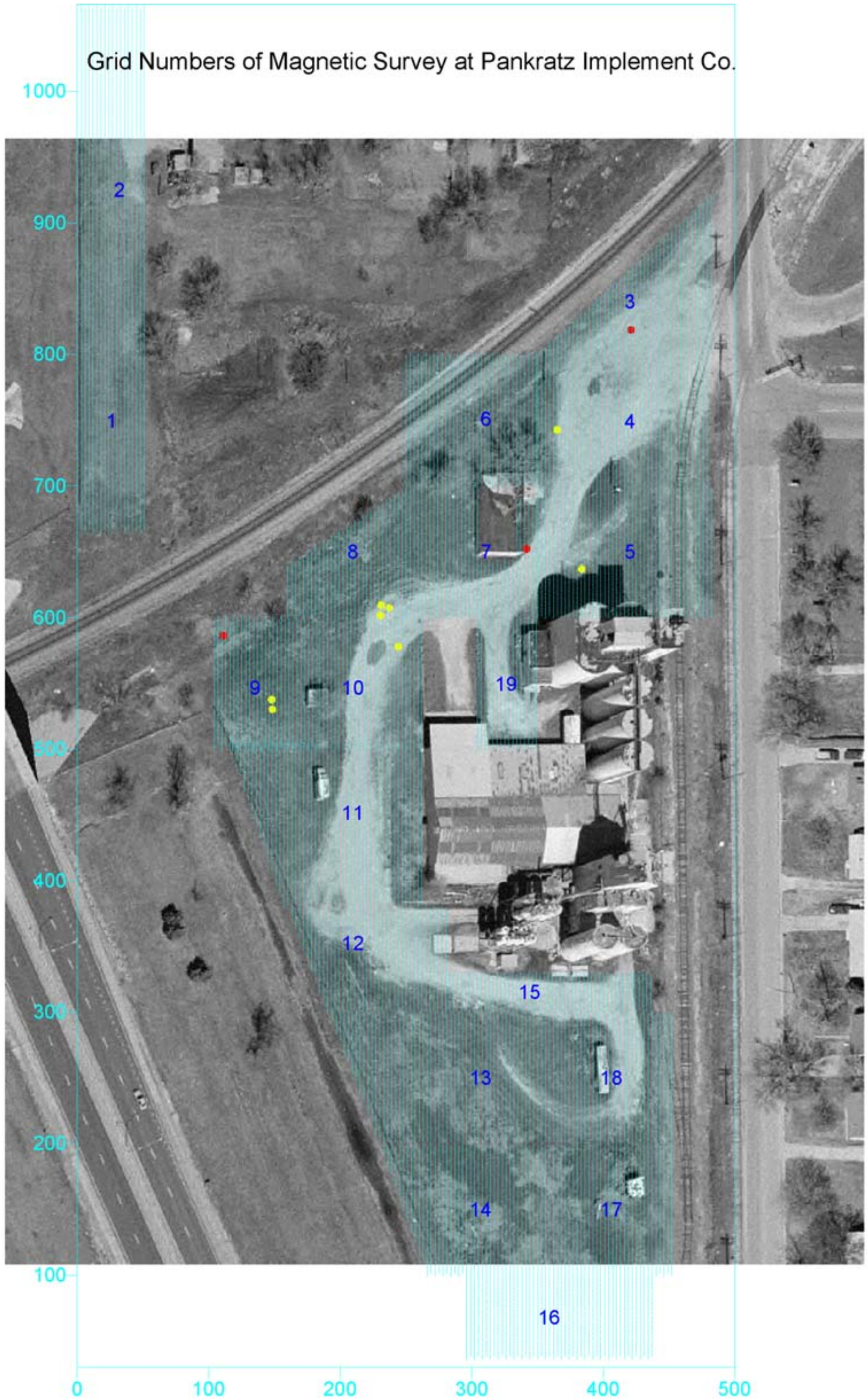


Figure 17. Aerial photo showing Pankratz Implement, Corp. with survey grids (numbers in blue). Red dots denote the location of brine wells. Yellow dots denote water wells.

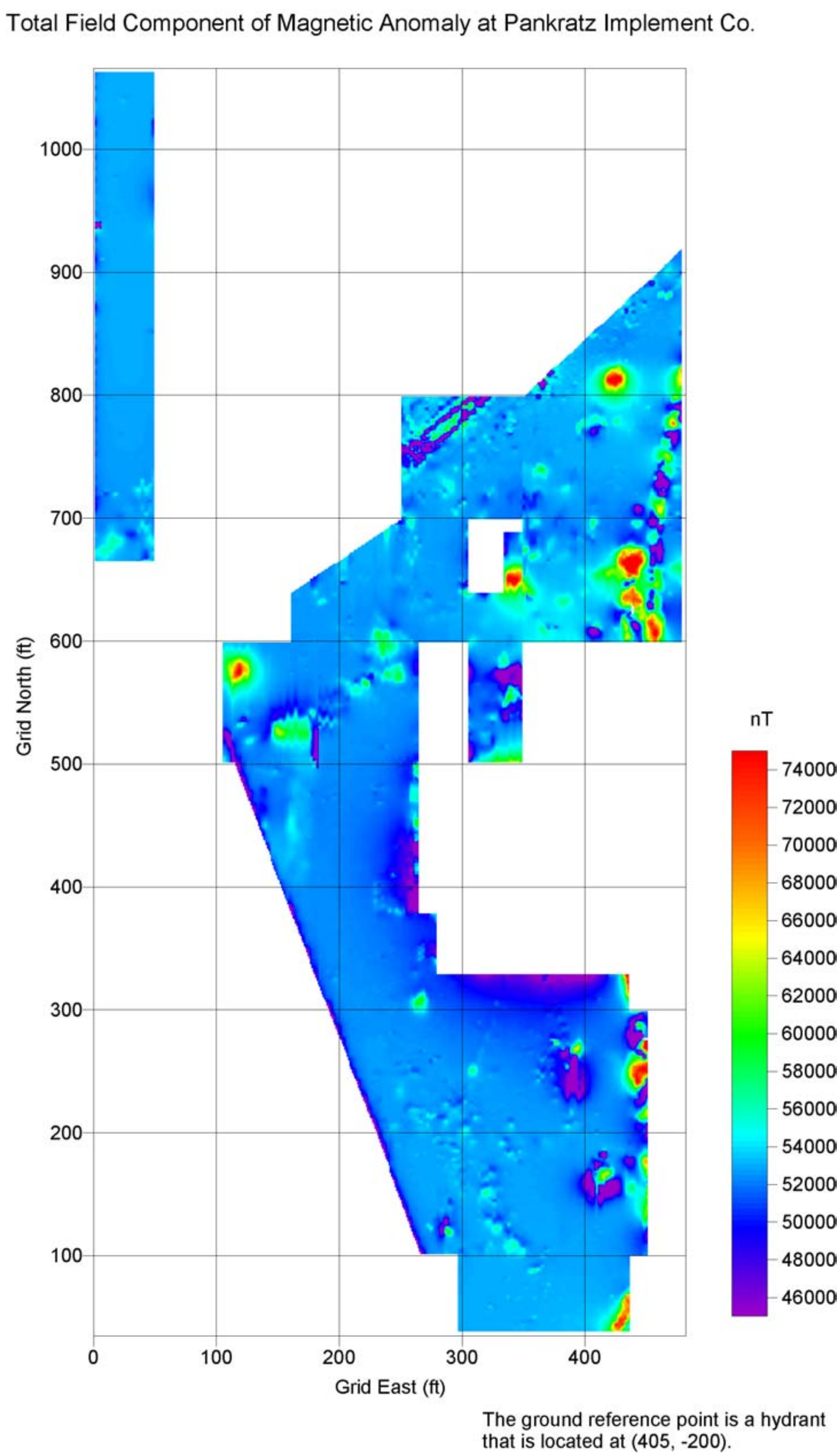


Figure 18. The total field component of the magnetic anomaly at Pankratz Implement Co.

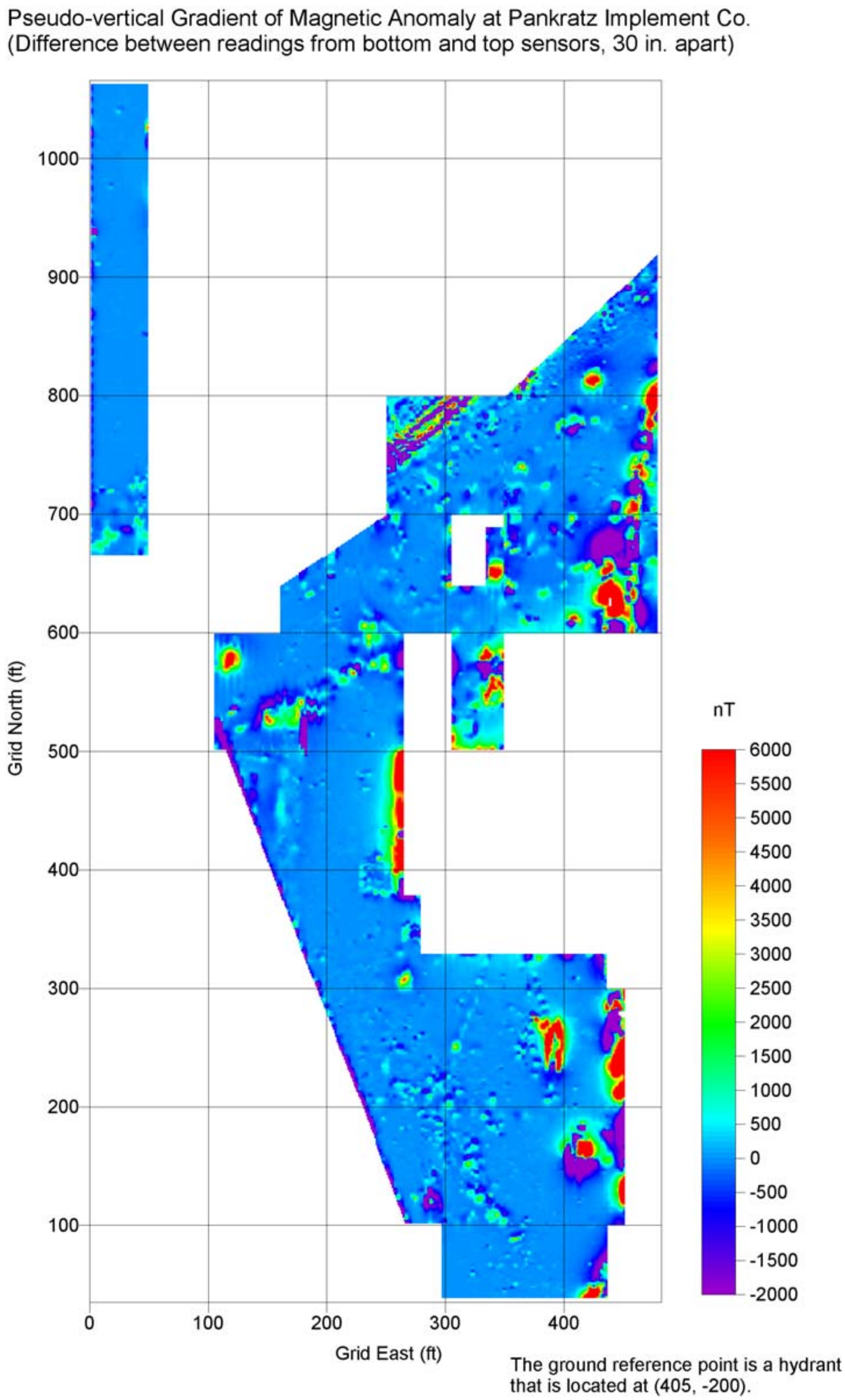


Figure 19. The Pseudo-vertical gradient anomaly at Pankratz Implement Co.

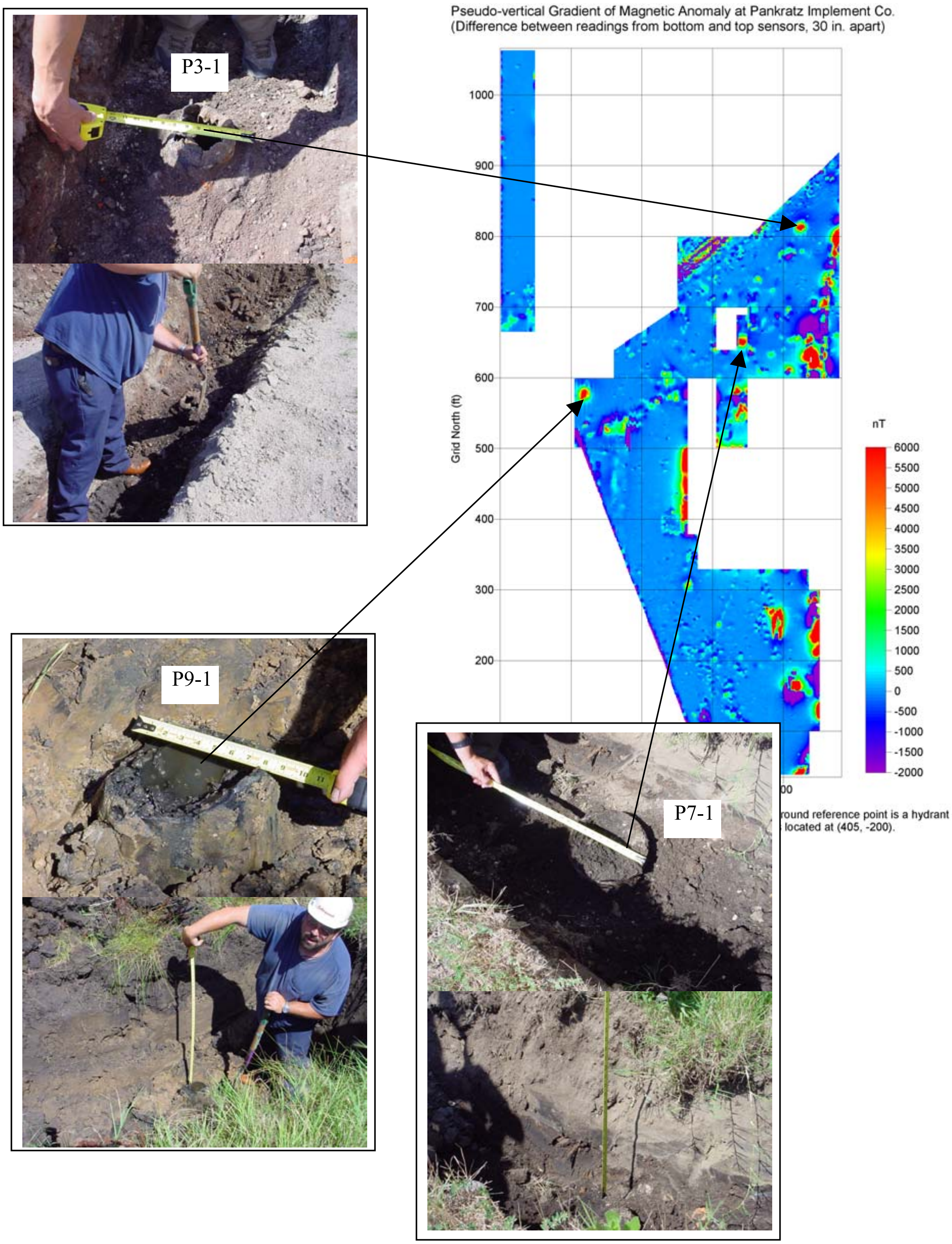


Figure 20. Three brine wells found at Pankratz Implement Co. They are in grids P3, P7, and P9. Jean Hughes of the City of Hutchinson is measuring the depth of Well P9-1.

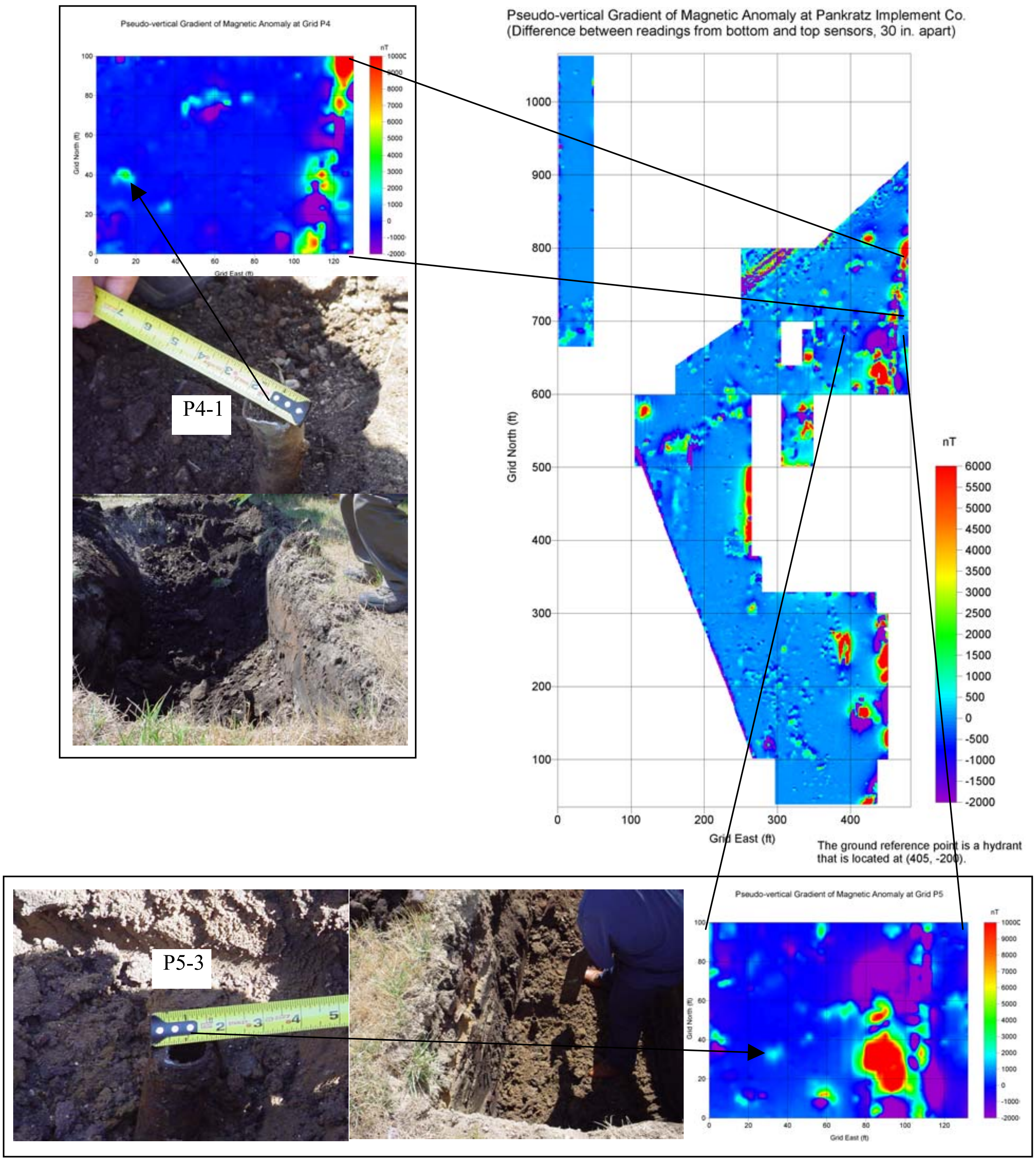


Figure 21. Two 2-inch wells are at depths of 20 inches (P4-1) and 45 inches (P5-3), respectively, at Pankratz Implement Co.

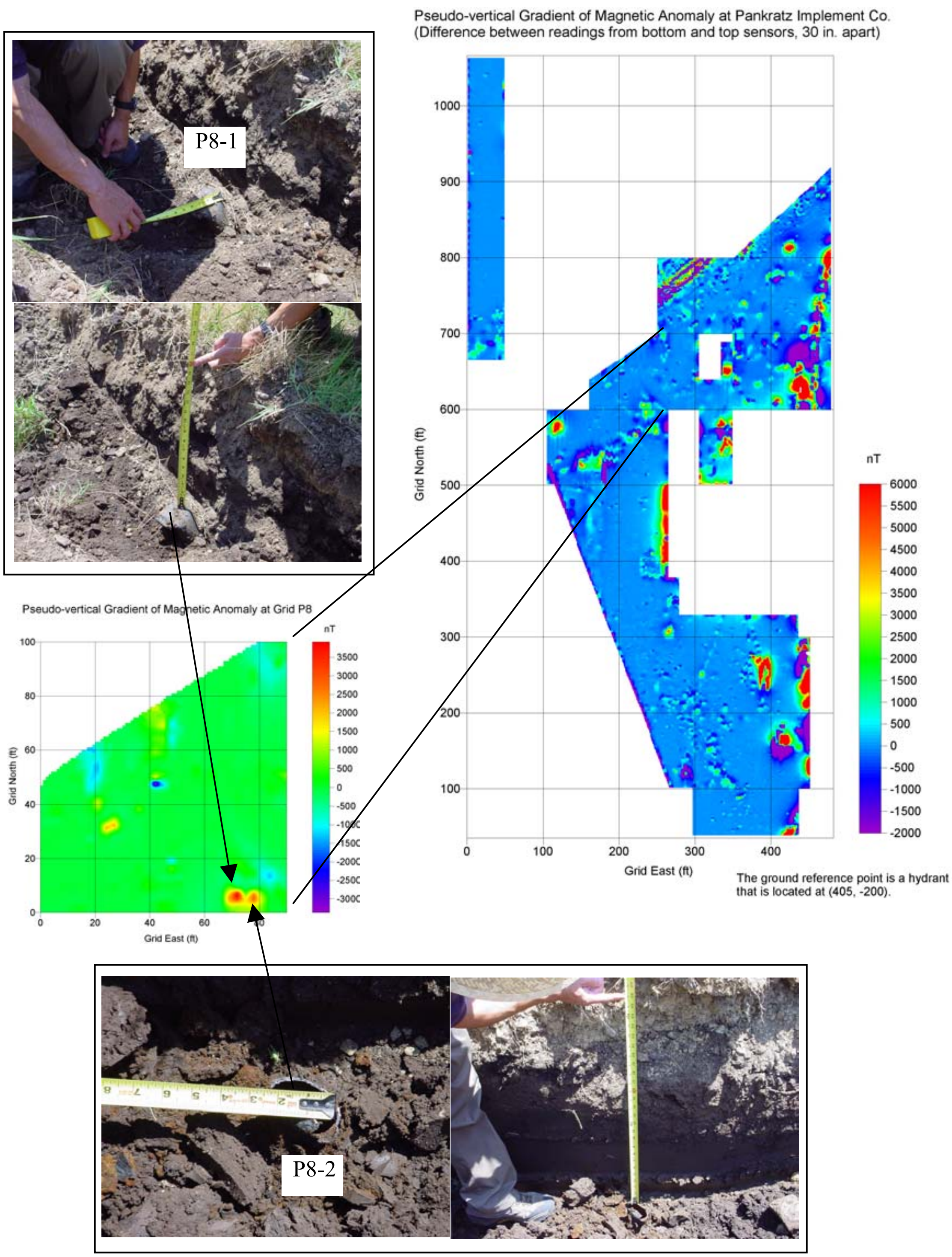


Figure 22. Two 3-inch wells are at depths of 16 inches (P8-1) and 26 inches (P8-2), respectively, at Pankratz Implement Co.

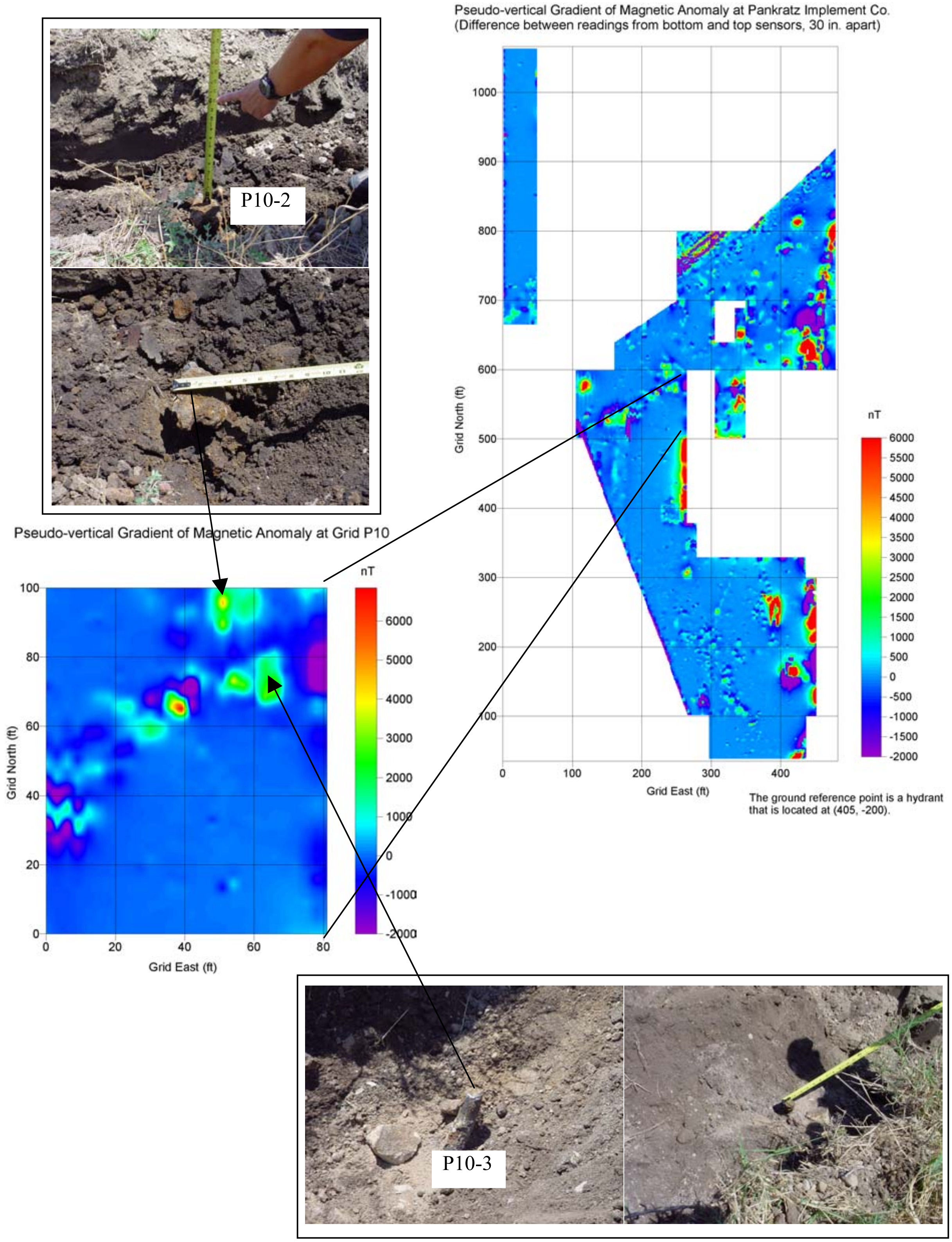


Figure 23. A 3-inch well, P10-2, and a 1.5-in well, P10-3 were located in Grid P10 at depths of 12 inches and 24 inches, respectively, at Pankratz Implement Co.

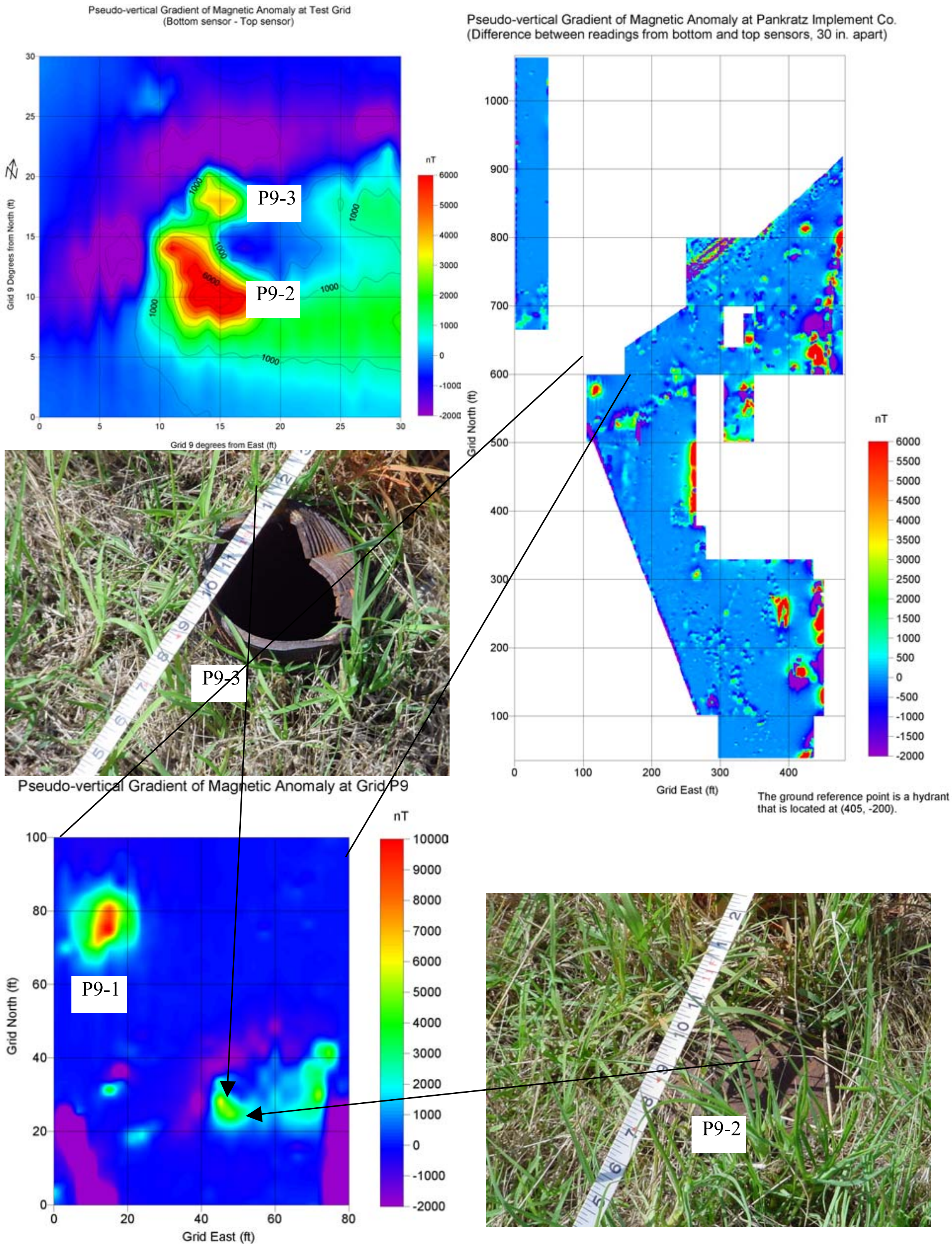


Figure 24.Two 4-in wells were found on the ground surface at Pankratz Implement Co. P9-2 is at (48, 24) and P9-3 is at (45, 28). A 30 ft by 30 ft grid with line spacing of 1 ft was defined to determine the resolving power of the vertical gradient data (the figure in the upper left corner).

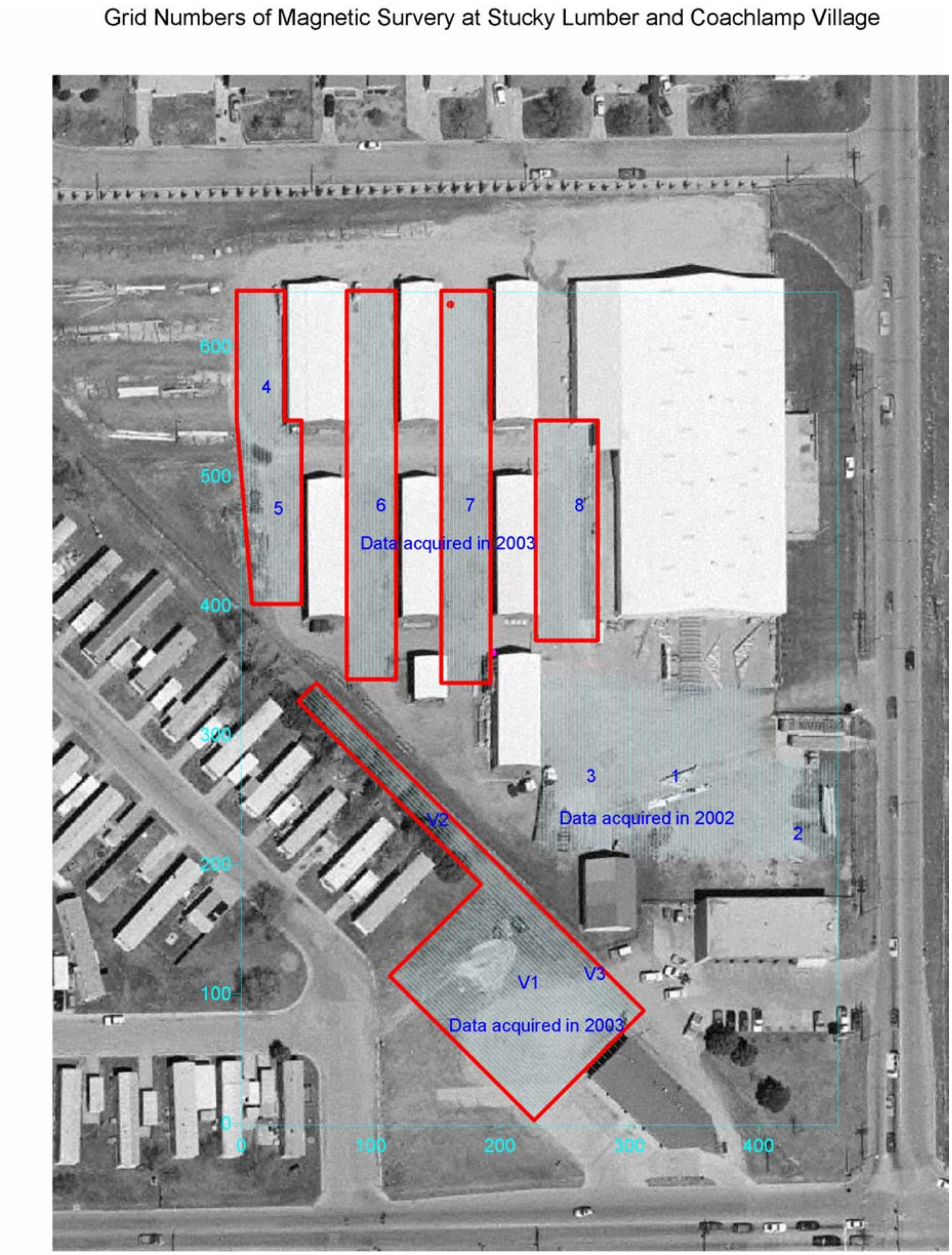


Figure 25. Aerial photo showing Stuckey Lumber & Coachlamp Village with survey grids (numbers in blue). Red dots denote the location of brine wells and suspected brine wells.

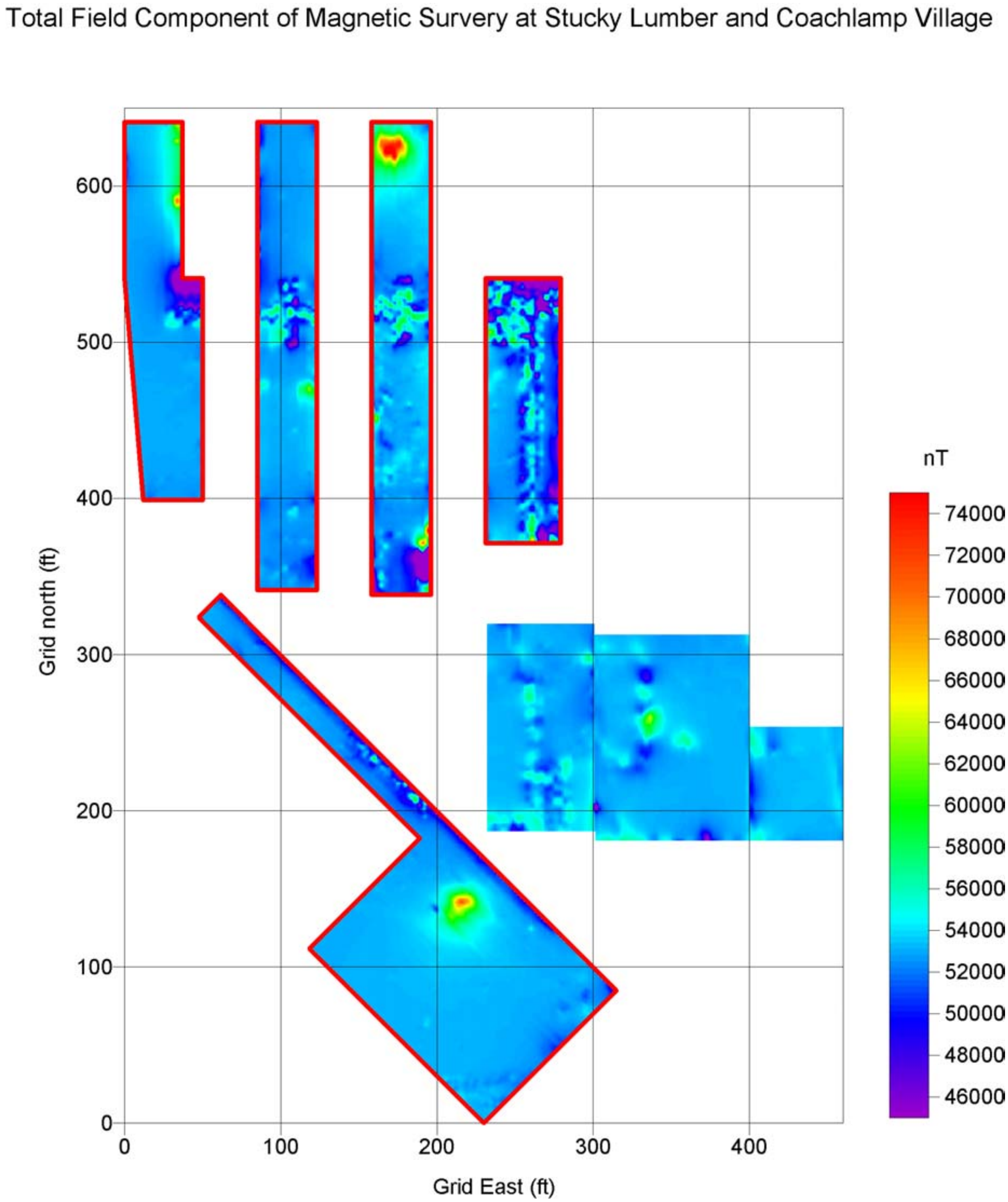


Figure 26. The total field component of the magnetic anomaly at Stuckey Lumber & Coachlamp Village.

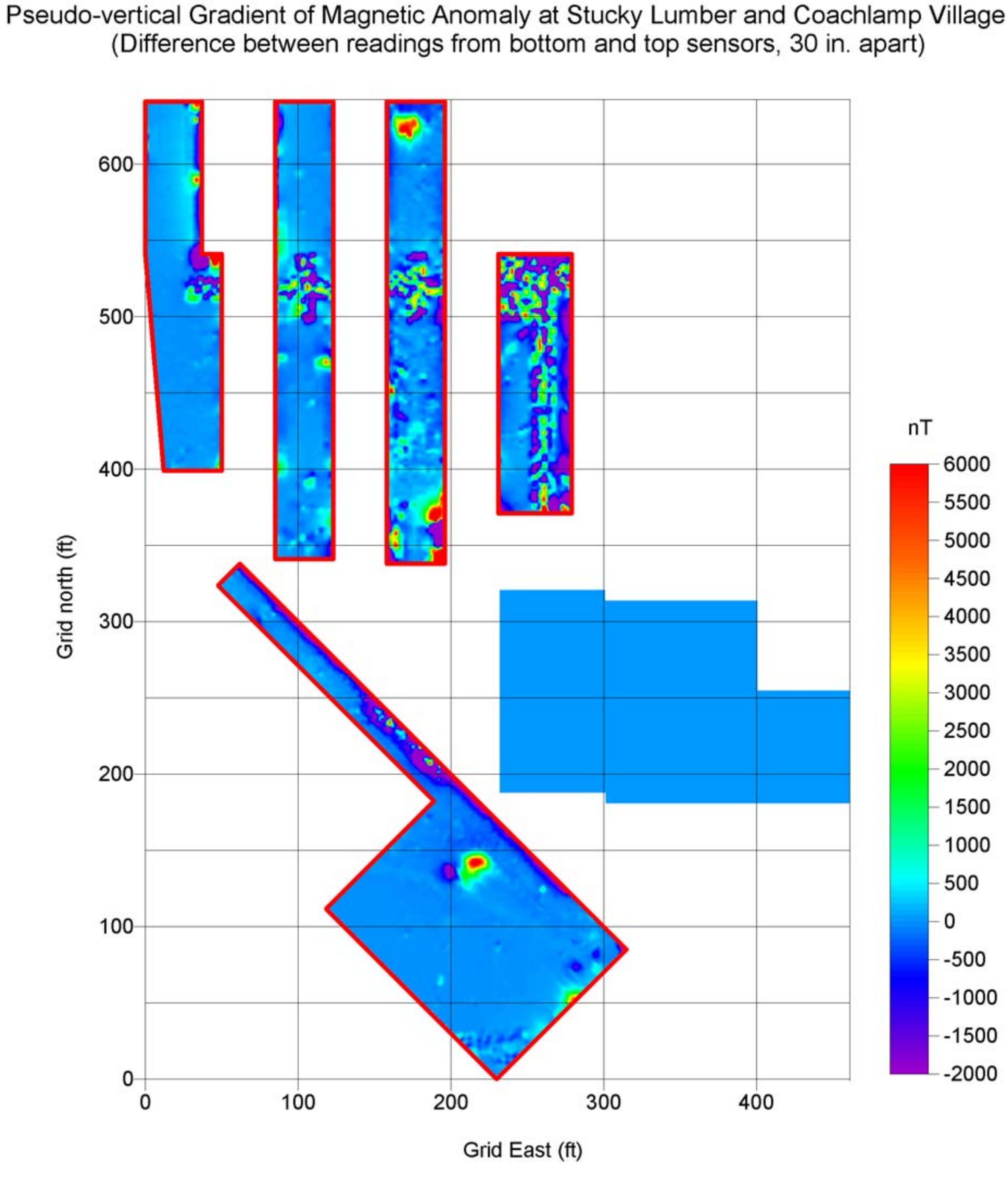


Figure 27. Pseudo-vertical gradient data at Stuckey Lumber & Coachlamp Village.

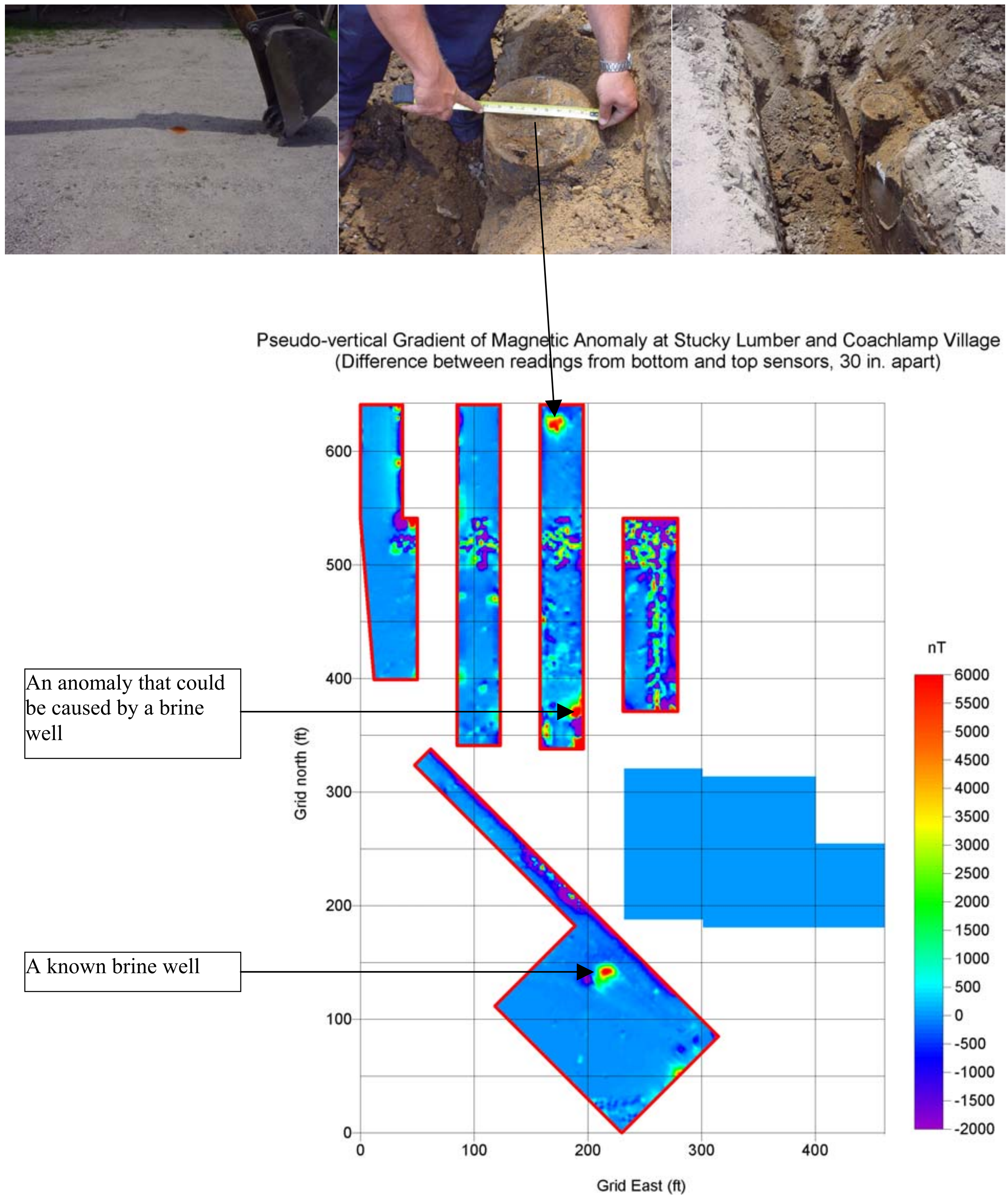
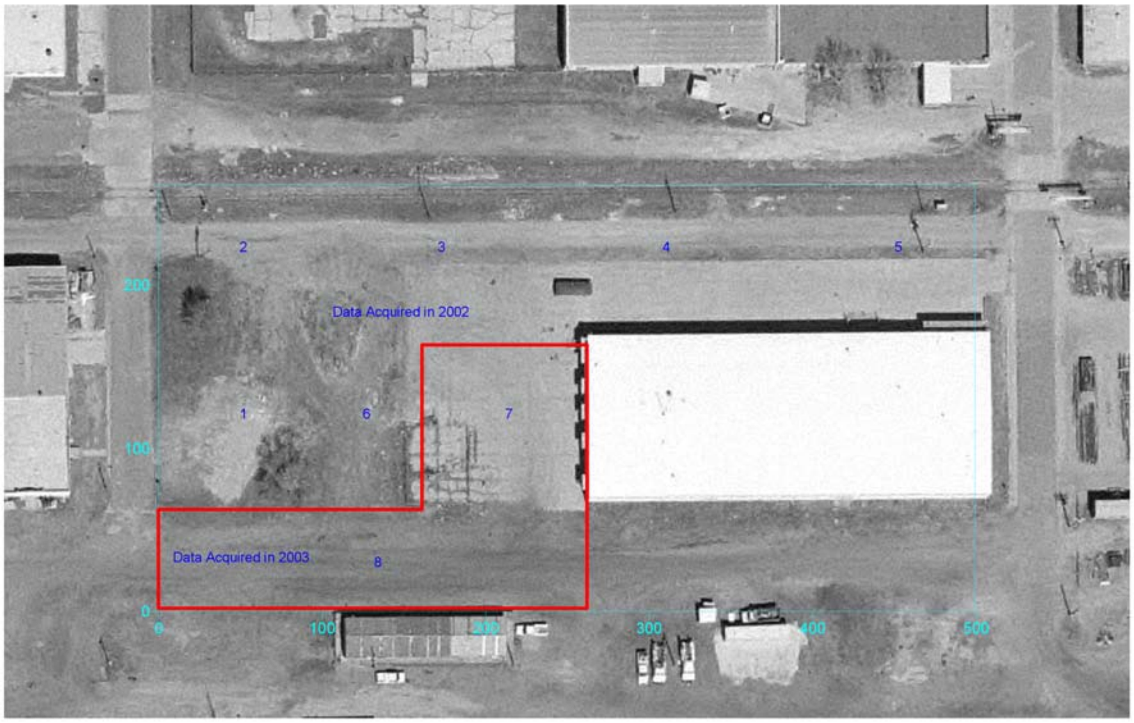


Figure 28. An 8-inch well was found at Stuckey Lumber & Coachlamp Village at a depth of 14 inches.

Grid Numbers of Magnetic Survey at Union Salt Co.



Total Field Component of Magnetic Anomaly at Union Salt Co.

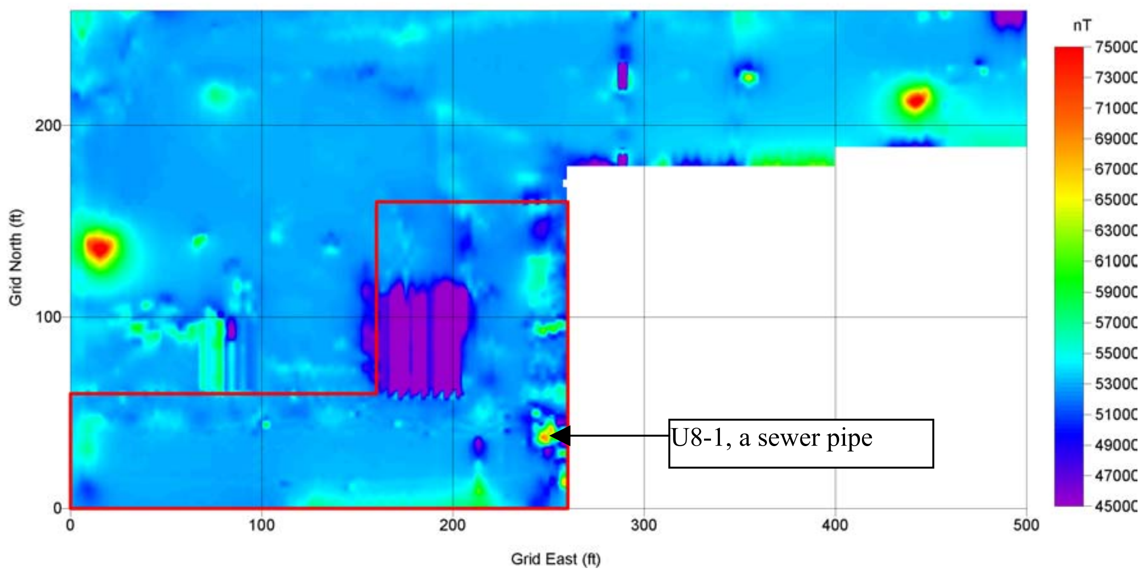


Figure 29. (top) Aerial photo showing Union Salt, Inc. with survey grids (numbers in blue). (bottom) Total field component of magnetic anomaly of the survey area. Survey within the red line boundary was completed in 2003. See Xia (2002c) for the survey in 2002.

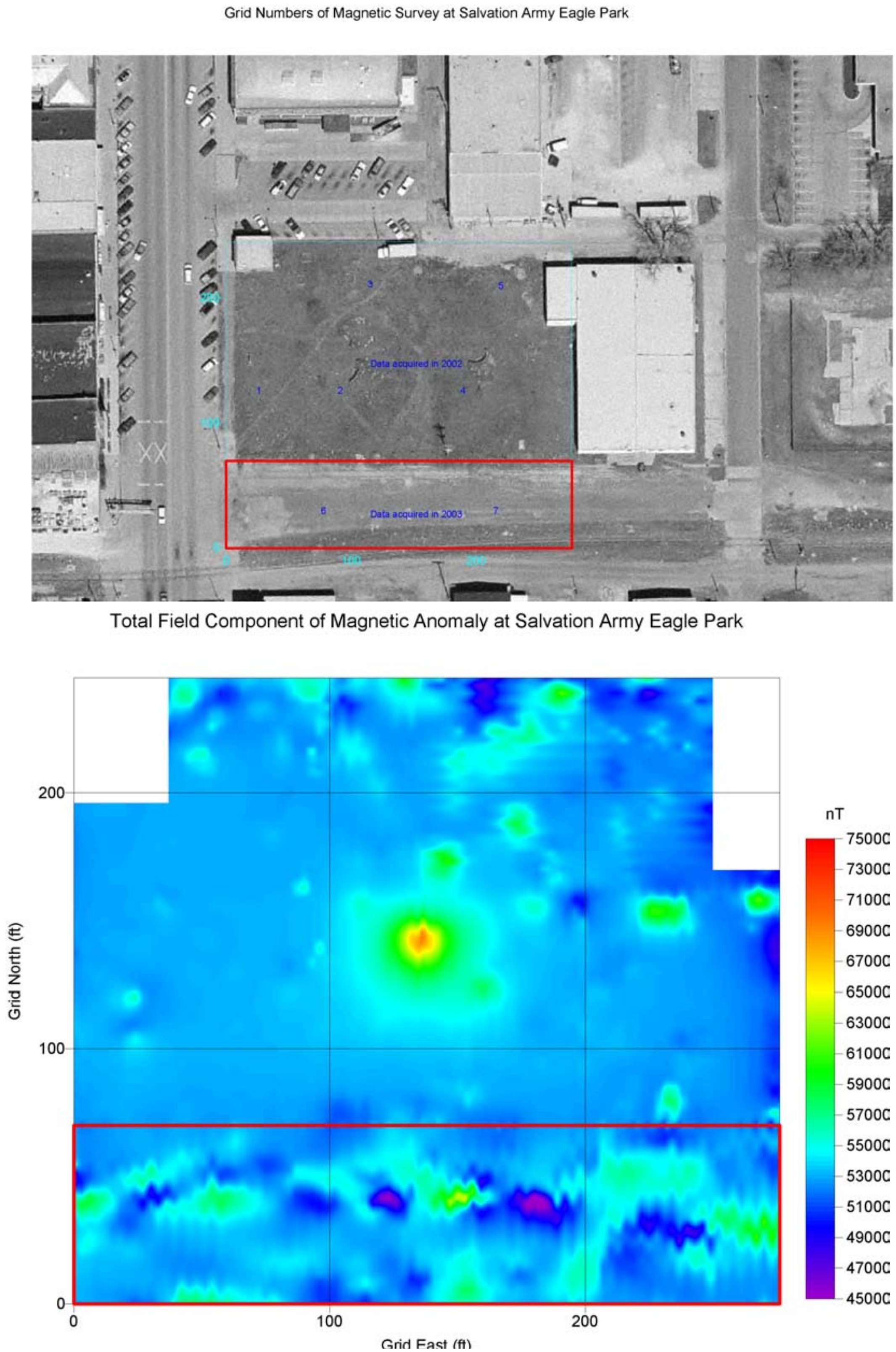
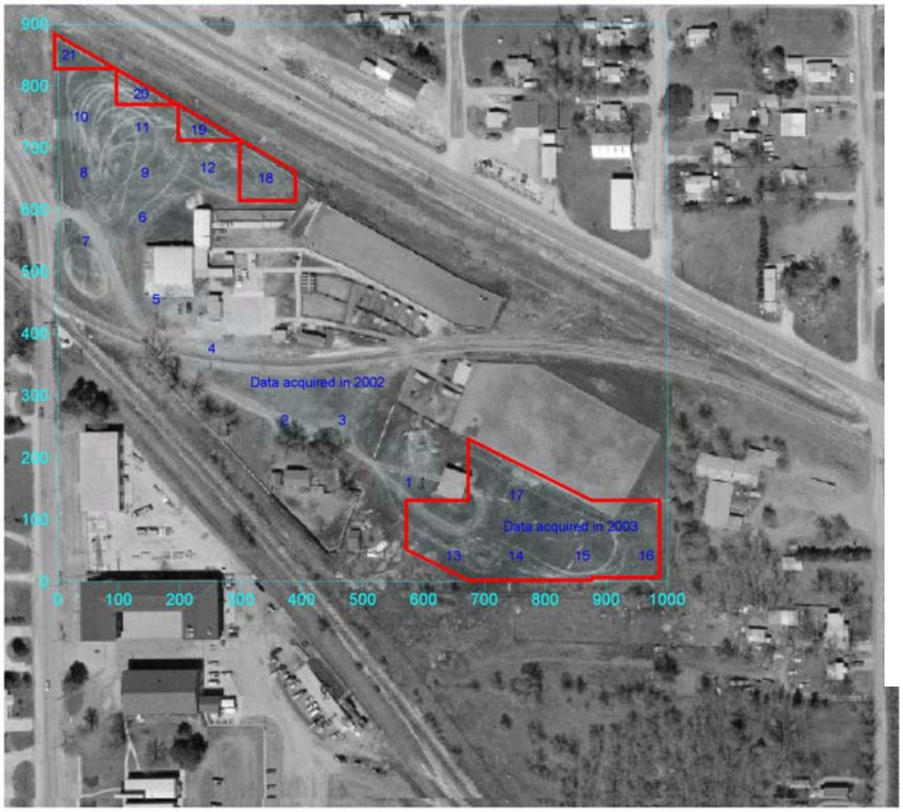


Figure 30. (top) Aerial photo showing Salvation Army Park with survey grids (numbers in blue). (bottom) Total field component of magnetic anomaly. Survey within the red line boundary was completed in 2003. See Xia (2002c) for the 2002 survey results.

dfas

Grid Numbers of Magnetic Survery at Ironhorse Equestrian Center



Total Field Component of Magnetic Survery at Ironhorse Equestrian Center

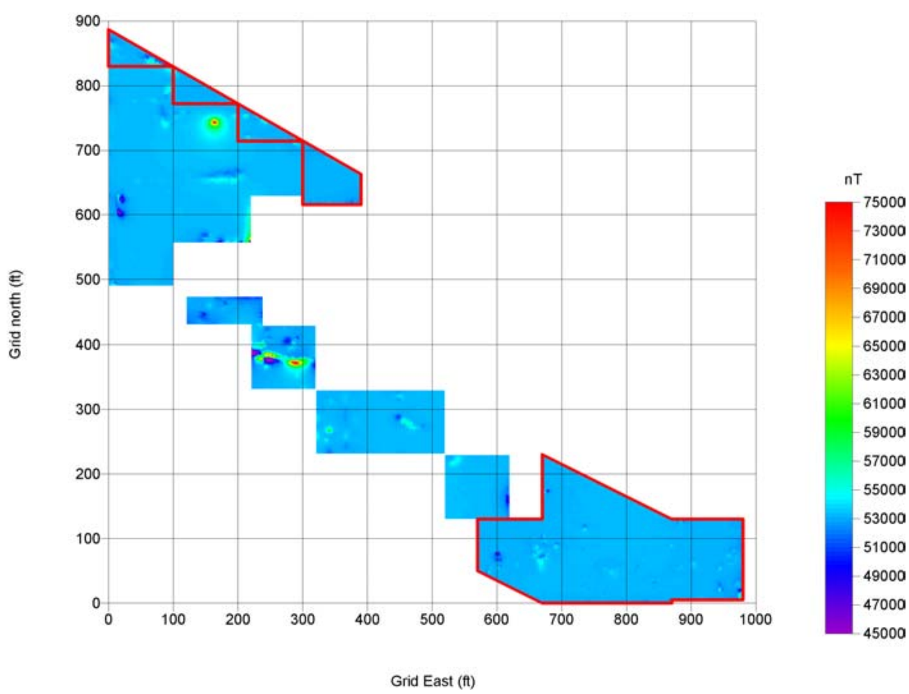
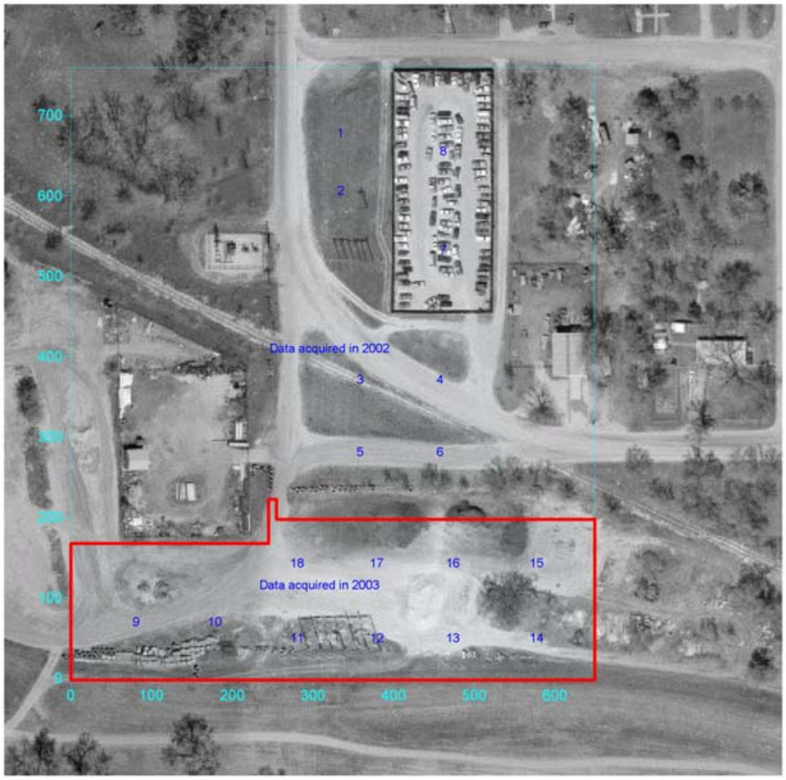


Figure 31. (top) An aerial photo of Ironhorse Equestrian Center with survey grids (numbers in blue).
(bottom) Total field component of magnetic anomaly. Survey within the red line boundary was completed in 2003. See Xia (2002c) for the survey in 2002.

Grid Numbers of Magnetic Survey at Monroe & Avenue E and F



Total Field Component of Magnetic Anomaly at Monroe & Avenue E and F

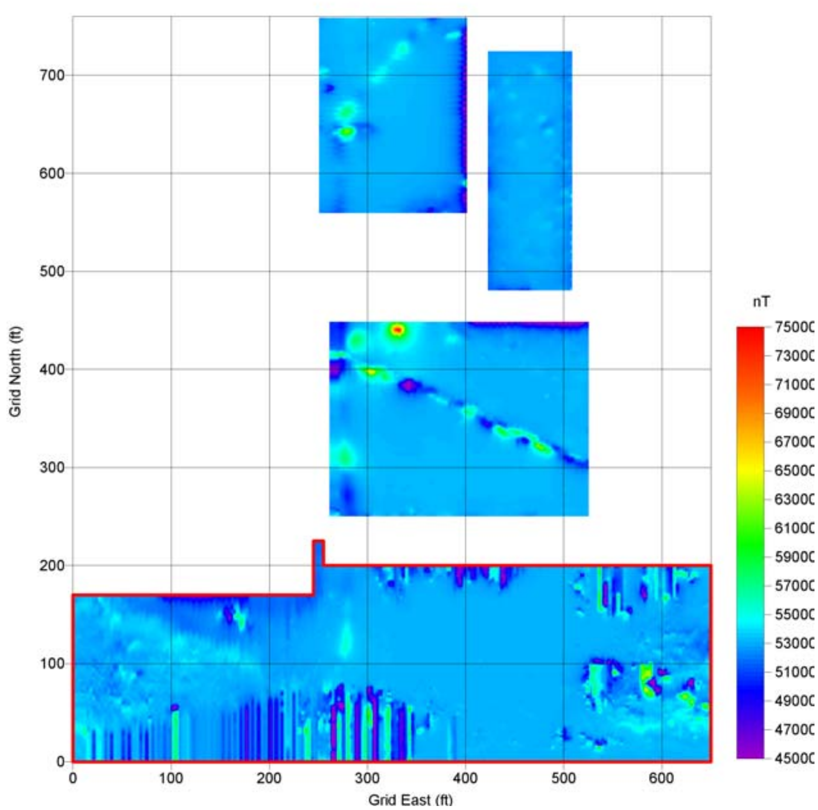
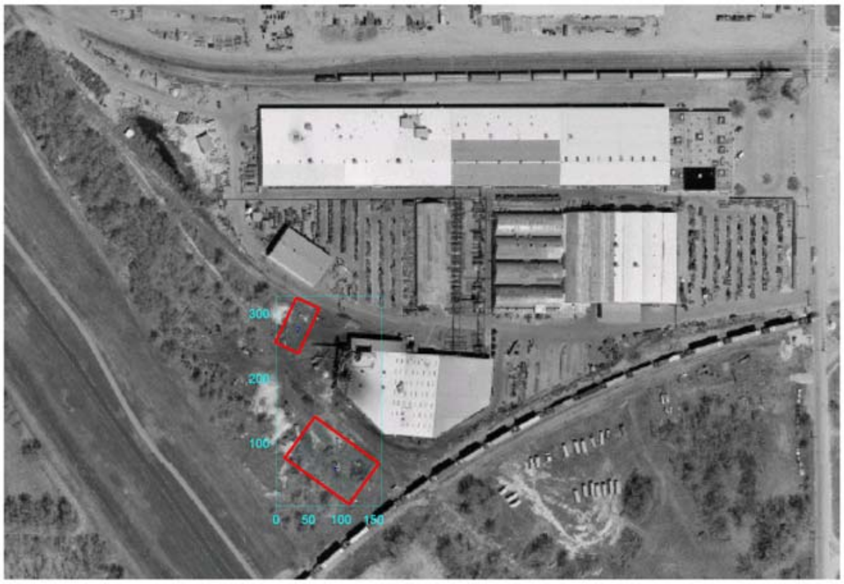


Figure 32. An aerial photo of Monroe St. & Avenue F with survey grids (numbers in blue) is shown in the top map. Total field component of magnetic anomaly is shown in the bottom map. See Xia (2002c) for the 2002 survey results.

Grid Numbers of Magnetic Survery at Krause Corp.



Total Field Component of Magnetic Survery at Krause Corp.

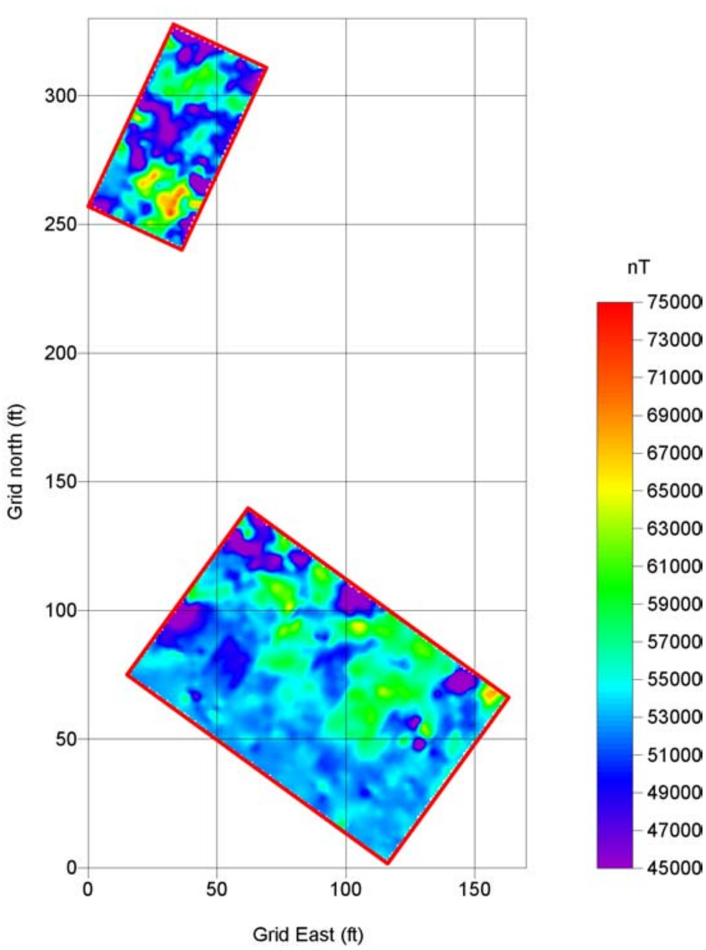


Figure 33. (top) An aerial photo of Krause Corp. with survey grids (numbers in blue).
(bottom) Total field component of magnetic anomaly is shown in the bottom map.

Table 1. Survey area

Site	X (ft)	Y (ft)	Area (ft^2)
K1	125	80	10205
K2	78	40	3120
V1	100	158	15800
V2	20	300	6000
V3	20	58	1160
L4	37	100	3700
L5	44	142	6248
L6	38	300	11400
L7	38	300	11400
L8	48	170	8160
S6	150	70	10500
S7	126	70	8820
U7	100	100	10000
U8	260	60	15600
M9	150	130	19500
M10	100	130	13000
M11	100	70	7000
M12	100	100	10000
M13	100	90	9000
M14	100	100	10000
M15	100	80	8000
M16	100	80	8000
M17	100	80	8000
M18	100	107	10700
E1	150	65	9750
E2	150	100	15000
E3	150	100	15000
E4	150	100	15000
E5	150	100	15000
E6	150	100	15000
E7	150	100	15000
E8	150	100	15000
E9	150	100	15000
E10	140	100	14000
E11	140	100	14000
E12	140	100	14000
E13	140	75	10500
E14	184	120	22080
E14A	100	100	10000
E15	184	100	18400
E16	184	100	18400
E17	184	75	13800
E18	140	100	14000
E19	164	88	14432

Table 1. (continued)

Site	X (ft)	Y (ft)	Area (ft^2)
E20	140	100	14000
E21	130	90	11700
E22	110	110	12100
E23	125	100	12500
E24	125	100	12500
E25	200	100	20000
E26	50	200	10000
E27	140	100	14000
E28	140	100	14000
E29	140	100	14000
E30	140	90	12600
E31	140	100	14000
E32	150	100	15000
E33	150	100	15000
E34	130	100	13000
E35	60	62	3720
E36	20	200	4000
E37	102	50	5100
E38	50	100	5000
E38A	50	34	1700
E39	80	36	2880
E40	100	132	13200
E41	40	100	4000
E42	75	35	2625
E43	30	24	720
P1	53	200	10600
P2	53	200	10600
P3	130	60	7800
P4	130	100	13000
P5	130	100	13000
P6	100	100	10000
P7	100	100	10000
P8	90	70	6300
P9	80	100	8000
P10	81	100	8100
P11	125	120	15000
P12	105	80	8400
P13	169	100	16900
P14	132	100	13200
P15	157	30	4710
P16	142	63	8946
P17	72	100	7200
P18	72	100	7200
P19	46	100	4600
I13	100	105	10500

Table 1. (continued)

Site	X (ft)	Y (ft)	Area (ft^2)
I14	100	130	13000
I15	100	130	13000
I16	110	125	13750
I17	200	50	10000
I18	90	73	6570
I19	100	28	2800
I20	100	28	2800
I21	100	28	2800
Total			1024796

Table 2. List of Anomalies.

The origin of the coordinate system is at the southwest corner of each grid. The name of anomaly starts with a letter that indicates the site and is followed by a number that indicates the grid number (see site maps). The number after "-" is a serial number of anomalies in each grid. The anomalies listed in bold are caused by brine wells.

Anomaly #	X	Y	Amplitude (nT)	Half-width (ft)	Interpretation	Source of anomaly
P3-1	**75**	**13**	**80515**	**12**	**Brine well (8 in)**	**An 8-in brine well at depth of 12 in**
P4-1	15	40	60730	4		A 2-in well at depth of 20 in
P5-3	33	32	57175	6		A 2-in well at depth of 45 in
P7-1	**93**	**48**	**81232**	**10**	**Brine well (8 in)**	**A 9-in brine well at depth of 20 in**
P8-1	72	6	60112	3		A 3-in well at depth of 16 in
P8-2	78	5	58562	4.5	Dipole	A 3-in well at depth of 26 in
P9-1	**15**	**75**	**79303**	**10**	**Brine well (8 in)**	**An 8-in brine well at depth of 42 in**
P9-2	48	24	64697			A 4-in well on surface*
P9-3	45	28	64324			A 4-in well on surface*
P10-2	51	96	61240	3.5		A 3-in well at depth of 12 in
P10-3	65	71	58600	3		A 1.5-in well at depth of 24 in
E1-1	69	15	60392	6		A 16-in well at depth of 35 in
P10-1	30	60	56174	3.5		Three 4" horiz. pipes with one broken end (27 in deep)
P12-1	105	7	61373	3.5		A 3.5' tank 24 in deep
P13-1	118	50	57237	3		End of 7" drainage pipe 24 in deep
P14-1	90	51	57392	3.5		Ends of four pipes (two 1", two 1.5") 12 in deep
E27-1	6	16	60319	3		Rebars 24 in deep
P5-1	92	63	83998	9	Brine well or R/R	R/R on surface*
P5-2	91	35	72402	7	Brine well or R/R	R/R on surface*
E11&12-1	**109**	**146**	**73878**	**11**	**Brine well (8 in)**	**An 8-in brine well at depth of 26 in**
E11&12-2	**33**	**72**	**69887**	**8**	**Brine/water well**	**An 8-in brine well at depth of 42 in**

Table 2. (continued)

Anomaly #	X	Y	Amplitude (nT)	Half-width (ft)	Interpretation	Source of anomaly
E11&12-3	**54**	**73**	**70679**	**8**	**Brine/water well**	**An 8-in brine well at depth of 39 in**
E11&12-4	**75**	**72**	**65772**	**6**	**Water well (2.5 in)**	**An 8-in brine well at depth of 51 in**
E11&12-5	**96**	**72**	**64333**	**6**	**Water well (2.5 in)**	**An 8-in brine well at depth of 57 in**
E11&12-6	**117**	**71**	**64673**	**6**	**Water well (2.5 in)**	**An 8-in brine well at depth of 53 in**
E11&12-7	**140**	**68**	**60855**	**6**	**Water well (2.5 in)**	**An 8-in brine well at depth of 101 in**
E16&17-1	**72**	**103**	**77726**	**12**	**Brine well (8 in)**	**An 8-in brine well at depth of 48 in**
E16&17-2	**66**	**73**	**69458**	**7**	**Water well (2.5 in)**	**An 8-in brine well at depth of 48 in**
E16&17-3	**79**	**72**	**65461**	**5**	**Water well (2.5 in)**	**An 8-in brine well at depth of 48 in**
E16&17-4	**93**	**71**	**67447**	**5**	**Water well (2.5 in)**	**An 8-in brine well at depth of 45 in**
E16&17-5	**107**	**71**	**64477**	**5**	**Water well (2.5 in)**	**An 8-in brine well at depth of 45 in**
E16&17-6	**175**	**141**	**72190**	**6**		**An 8-in brine well at depth of 16 in**
E23-1	**82**	**69**	**71620**	**13**	**Brine well (8 in)**	**A 6-in brine well at depth of 30 in**
E14-1	78	86	69948	10	Four anomalies	The same source of e14-4*
E14-2	87	95	68960	10	link together	The same source of e14-4*
E14-3	116	126	66443	10	Brine/water well?	The same source of e14-4*
E14-4	126	133	65832	10		A 9" horiz. pipe (45 degrees due north) 48 in deep
E14-5	117	95	59783	6		A 13" horiz. Pipe 43 in deep
E14-6	41	43	56575	4.5		A 2.5" horiz. Pipe in N-S 30 in deep
E15-2	21	85	63386	3	Dipole	End of a 14" horiz. Pipe in N-S 22 in deep
E15-1	6	89	62395	3	Dipole	Junk metal sheets and pipes (12 to 48 in)
E11&12-8	30	105	61207	4		A 0.75" pipe on surface*
E19-1	**90**	**65**	**80756**	**13**	**Brine well (8 in)**	**A 6-in brine well at depth of 29 in**
E21-1	**66**	**34**	**81974**	**14**	**Brine well (8 in)**	**An 8-in brine well at depth of 60 in**
E25-1	**138**	**76**	**79723**	**14**	**Brine well (8 in)**	**An 8-in brine well at depth of 13 in**
E43-1	15	13	66841	8	Brine/water well	A 3-in well at depth of 32 in
L7-1	**12**	**282**	**77736**	**12**	**Brine well (8 in)**	**An 8-in brine well at depth of 14 in**
V1-1	**90**	**110**	**71351**	**9**	**Brine well (8 in)**	**A known brine well***

Table 2. (continued)

Anomaly #	X	Y	Amplitude (nT)	Half-width (ft)	Interpretation	Source of anomaly
E26-1	36	26	71947	6	Brine well or sewer pipe	Buried R/R, the same as e42-1*
E26-2	45	86	80017	6	Brine well or sewer pipe	Buried R/R, the same as e42-1*
E37-1	88	46	67734	3	Brine well?	On the edge of building*
E38-1	30	100	68951	6	Dipole	A 3-D body*
E38-2	27	89	68479	3.5		Surface metal junk*
E40-1	69	109	75513	3.5		A 6" horizontal pipe in E-W (36 in deep)
E41-1	33	94	61327	3		A 1.5" vertical metal bar (4 in deep)
E41-2	27	75	59360	4		A 1.5" vertical metal bar (12 in deep)
E41-3	33	74	58640	3		A 1.5" vertical metal bar (18 in deep)
E42-1	9	24	64443	4.5		R/R at 13 in deep
E42-2	66	18	58834	3		A 6" horizontal pipe in N-S (16 in deep)
E32-1	33	7	58746	3.5		End of a 2.5" horizontal pipe in N-S (6 in deep)
U8-1	247	38	69345	3	Water well (2.5 in)	A sewer pipe
I19-1	12	37	58275	3		A 0.5" metal bar at surface*
I19-2	41	31	58310	4	Pole cable?	Electric pole cable*
L7-2	36	38	74883		Brine well (8 in)?	On corner of a shed*

*no digging on this anomaly

Appendix A. Normal Geomagnetic Field in Hutchinson, Kansas

(http://www.ngdc.noaa.gov/cgi-bin/seg/gmag/fldsnth1.pl)

Model: IGRF2000
Latitude: 38 deg, 3 min, 54 sec
Longitude: -97 deg, 54 min, 50 sec
Elevation: 0.50 km
Date of Interest: 5/23/2003

D (+East) (deg)	I (+Down) (deg)	H (nt)	X (+N) (nt)	Y (+E) (nt)	Z(+Down) (nt)	F (nt)
5d 44m	66d 34m	21291	21185	2127	49111	53527

dD (min/yr)	dI (min/yr)	dH (nT/yr)	dX (nT/yr)	dY (nT/yr)	dZ (nT/yr)	dF (nT/yr)
-6	-1	-16	-12	-39	-92	-91

Definitions

D: Magnetic Declination

Magnetic declination is sometimes referred to as the magnetic variation or the magnetic compass correction. It is the angle formed between true north and the projection of the magnetic field vector on the horizontal plane. By convention, declination is measured positive east and negative west (i.e. D -6 means 6 degrees west of north). For surveying practices, magnetic declination is the angle through which a magnetic compass bearing must be rotated in order to point to the true bearing as opposed to the magnetic bearing. Here the true bearing is taken as the angle measured from true North.

Declination is reported in units of degrees. One degree is made up of 60 minutes. To convert from decimal degrees to degrees and minutes, multiply the decimal part by 60. For example, 6.5 degrees is equal to 6 degrees and 30 minutes (0.5 x 60 = 30).

If west declinations are assumed to be negative while east declination are considered positive then

True bearing = Magnetic bearing + Magnetic declination

An example: The magnetic bearing of a property line has an azimuth of 72 degrees East. What is the true bearing of the property line if the magnetic declination at the place in question is 12 degrees West?

A magnetic declination of 12 degrees West means that magnetic North lies 12 degrees West of true north.

True bearing = 72 degrees + (-12 degrees declination)
= 72 degrees - 12 degrees declination = 60 degrees East

It should be noted that the magnetic declination becomes undefined at the North and South magnetic poles. These poles are by definition the two places where the magnetic field is vertical. Magnetic compasses become quite unreliable when the magnetic field vector becomes steeply inclined.

D is defined as *D = arc tangent(Y / X).*

dD: The change in declination with respect to time.

I: Magnetic Inclination

Also called magnetic dip, this is the angle measured from the horizontal plane, positively down to the magnetic field vector. If the vector components of F are X, Y, and Z then

*I = arc tangent(Z/square root(X*X + Y*Y))*

or

I = arc tangent(Z/H)

The north magnetic pole is defined as that position where I=90 degrees i.e. straight down. Similarly, the south magnetic pole is defined as that position where I= -90 degrees i.e. straight up.

dI: The change in inclination with respect to time.

H: Horizontal Component of the Magnetic Field

This is the magnitude of vector constructed by projecting the total field vector onto the local horizontal plane. In terms of the vector components of the field

*H = square root(X*X + Y*Y)*

dH: The change in the horizontal component with respect to time

X: North Component of the Magnetic Field

This is the magnitude of vector constructed by projecting the total field vector onto an axis lying in the direction of the Earth's rotational pole or true North.

dX: The change in X with respect to time.

Y: East Component of the Magnetic Field

This is the magnitude of vector constructed by projecting the total field vector onto an axis in the Eastward direction i.e. perpendicular to the X-axis.

dY: The change in Y with respect to time.

Z: Vertical Component of the Magnetic Field

This is the magnitude of vector constructed by projecting the total field vector onto an axis in the local vertical direction i.e. perpendicular to the horizontal plane.

dZ: The change in Z with respect to time.

F: Magnetic Field Vector

The Earths magnetic field, referred to as the geomagnetic field is a vector field i.e., at each point in space this field has a strength and a direction. This vector, F is referenced to a local coordinate system as follows: the vector is decomposed into three mutually perpendicular (orthogonal) vector components, which are referred as the X, Y, and Z components of the field, where the X and the Y components lie in the horizontal plane with X lying in the northward direction, Y lying in the eastward direction, while the Z component is taken in the local vertical direction. The strength of the magnetic field is usually given in units of nanoteslas (nT) and is taken in the usual mathematical fashion i.e.

$$\text{magnitude}(F) = \text{square root}(X*X + Y*Y + Z*Z)$$

The X, Y, and Z components completely describe the magnetic field vector, F however in the study of the Earth's magnetic field it is often convenient to describe this vector's direction through the use of two so-called "angular components" called the declination and the inclination. In addition the strength of the projection of the vector F onto the horizontal plane or the H component is often studied.

dF: The change in F with respect to time.

Magnetic Field Components

There are seven magnetic field elements: the total field vector (F), the X component or northward component, the Y component or eastward component, the Z component or vertical component, and the H or horizontal component. These five elements are often referred to as the force elements while the last two components, the declination and the inclination are referred to as the angular elements.

Appendix B. Total Field Component of Magnetic Anomalies and Vertical Gradient Anomalies at Eight Sites in Hutchinson, Kansas

1. Grids E1 – E43 at Concrete Enterprises, Inc.
2. Grids P1 – P19 at Pankratz Implement Co.
3. Grids L4 – L8 at Stuckey Lumber & Coachlamp Village
4. Grids U7 – U8 at Union Salt
5. Grids S6 – S7 at Salvation Army Eagle Park
6. Grids I13 – I21 at Ironhorse Equestrian Center
7. Grids M9 – M18 at Monroe Street & Avenues F
8. Grids K1 – K2 at Krause Corp.