

CHAPTER 2

Magnetic Surveys

This chapter provides the basis for a theory concerning potential field data, including magnetic gradient data and derivative and analytical signals of total magnetic intensity data. The processing of magnetic data by derivative and analytical signals were used to enhance data signals and to show magnetic maps for interpretation.

2.1 Magnetic Anomalies in Archeology

Magnetic methods can be applied to archaeological investigations, wherein the magnetic field depends upon contrasts between the magnetic properties of the feature of interest and its surrounding environment. Magnetic fields are produced by a contrast in magnetization, whether it is induced as a result of a magnetic susceptibility contrast or remanent. Magnetic anomalies are displayed in features such as buried walls, structures, pottery, bricks, tombs, etc. (Gubbins and Herrero-Bervera, 2007).

The remanent magnetization of archaeological site relative intensity maintains magnetism in any substance associated with it, in such objects as bricks, tiles, pottery, kilns, hearths and similar features. Remanent magnetization, called ‘thermoremanent magnetization’, is created when a magnetite-bearing-clay is heated to a relatively high temperature and cooled in the presence of the earth’s magnetic field. Magnetic domains which are randomly oriented then move during heating. While cooling, many domains align themselves with the ambient or earth’s field, thus becoming parallel to each other and creating a fixed magnetization with respect to the object, and parallel to the earth’s total field at the time of cooling (Ernenwein and Hargrave, 2009).

Any magnetic susceptibility depends upon iron oxides related to geology and the extent of conversion of anthropogenic influences. The value of magnetic susceptibility can vary between different sites, and enhancement can identify a contrast between areas

of higher susceptibility compared to background measurements. This contrast is used to obtain qualitative measurements of field magnetic susceptibility for archaeological prospection (Gubbins and Herrero-Bervera, 2007).

2.2 Magnetic Gradient

Gradient measurement data was collected using a sensor to measure the differences in the magnetic field within the orientation of the sensor. The magnetic intensity value was divided by sensor distance, and then measured at the midpoint of the sensor spacing. Gradient measurements were divided in 2 types of horizontal gradient (Figure 2.1(a)), which collected data using two sensors in parallel, which surveyed the scene lying parallel to the ground and in a vertical gradient (Figure 2.1(b)), thus collecting data using both sensors in parallel but surveyed perpendicular to the ground.



Figure 2.1 Magnetic data collection using dual sensors (a) Vertical gradient
(b) Horizontal gradient.

The vertical gradient and horizontal gradient were used to resolve interest in anomalies of the survey. The magnetic gradient defined shallower anomalies.

Any magnetic diurnal time variations errors were removed because of measuring at the same time. The gradients were used to quantitatively observe properties affecting anomalies in shape and location.

2.2.1 Magnetic Gradient Measurement

A gradiometer is a differential magnetometer, wherein any difference (ΔT) is measured between the two readings of the two sensors. A differential magnetometer, where one sensor was fixed and the other transverse, were connected to remove time variations.

The differential measurements, for all practical purposes, were the same as the usual single sensor total field measurement. More specifically, the gradient could be expressed as equation 2.1 (Breiner, 1999)

$$\frac{\Delta T}{\Delta r} \approx \lim_{\Delta r \rightarrow 0} \frac{T_r - T_{r+\Delta r}}{\Delta r} = \frac{dT}{dr} \quad (2.1)$$

where, $\Delta T = T_r - T_{r+\Delta r}$ is the total field differential between the two sensor positions spaced Δr apart, and $\frac{dT}{dr}$ is the derivative or gradient of T in the direction of r .

2.2.2 Magnetic Gradient Readings in the Field

The gradiometer measurements in applications are the vertical gradient $\frac{dT}{dz}$ and the two horizontal gradients $\frac{dT}{dx}$ and $\frac{dT}{dy}$, z being the vertical coordinate 'x' along the profile, and 'y' normal to the profile (Breiner, 1999) (see Figure 2.2).

Vertical gradient data is obtained by measuring the magnetic field at two points vertically above each other, and subtracting the data and dividing the results by the vertical separation of the measurement points. The results of anomaly peaks are thus located over the bodies (Breiner, 1999).

Horizontal gradient responses respond to phase transformation in the 'x' and 'y' directions. It can be observed that this is a good indicator of enhancements at high frequencies. Such phase transformation display results of anomaly peaks located over the edges of wide bodies as any enhancement at high frequencies sharpens the peaks as measurement is increased to the body edges (Breiner, 1999).

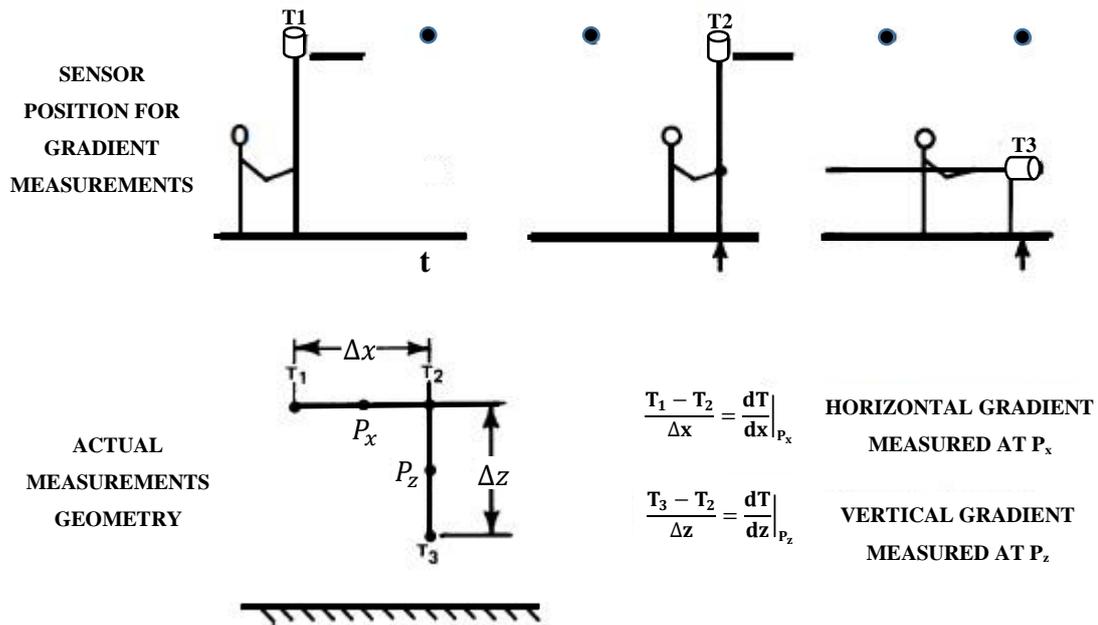


Figure 2.2 Gradiometer Measurement Procedures (Modified from Breiner, 1999).

2.3 Magnetic Data Processing

Concerning this review of basis used in potential field data processing, all operations of processing the frequency domain were used together, in this study. The derivatives and the analytic signals were used to enhance signals and to provide maps to help interpretation.

‘Fourier transform’ is mathematical model used to convert time domain and frequency domain. It is the basis of using the frequency domain in magnetic data processing. The data is transformed into the frequency domain, and the transformed data is processed and then transformed back into the time domain. Data processing is shown in Figure 2.3 as a wave-number domain, where the frequency domain is convoluted into a grid data in the time domain. Therefore, the convoluted inverse data in the spectrum is a result of such processing.

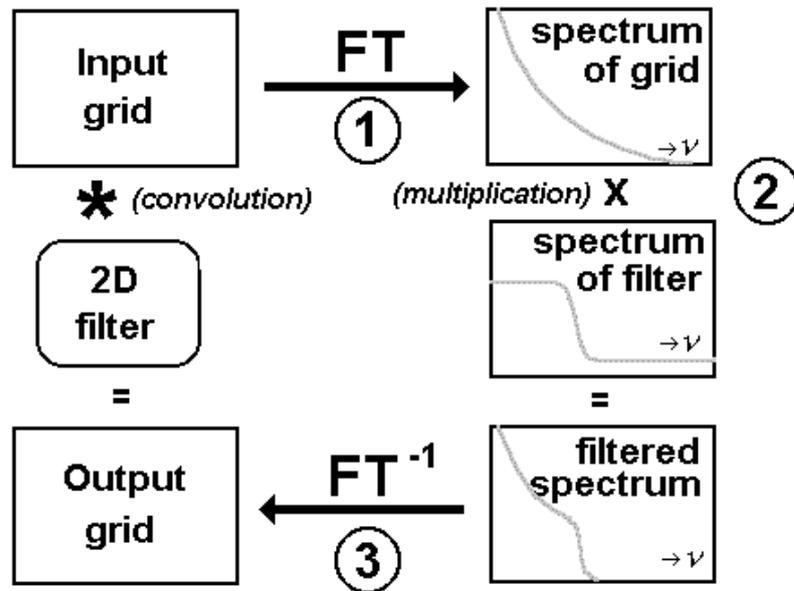


Figure 2.3 Flow chart of data processing in the frequency and time domain (From Reeves, 2005).

Data enhancement was used in the potential field survey as derivative and analytic signals. These are important because they help to interpret the information of geological structures. Noise should be removed, while anomalies are emphasized in data processing. The output is maps to interpretation.

2.3.1 Derivatives

- Horizontal derivatives in the 'x' or 'y' directions

Filter responses are used to calculate the nth horizontal derivatives in the 'x' or 'y' directions. It can be seen that this process involves a phase transformation as well as an enhancement of high frequencies. The phase transformation displays results of anomaly peaks located over the edges of wide bodies, and the enhancement of high frequencies sharpens peaks which increase the definition of the body edges. The process becomes extremely ambiguous for narrower bodies however, and it is thus difficult to see what advantage horizontal derivatives have over vertical derivatives, the latter displaying peaks over the tops of sources and indicate source outlines by steep gradients and inflections (Milligan and Gun, 1997).

The derivatives of the 'x' and 'y' directions can be used to create shaded images

which are required for some modeling algorithms, as per following equation,

$$L(\mu) = (ki)^n \quad (2.2)$$

Param n is the order of differentiation.
 k is the representative X or Y component of the wave-number.
 i is $i = \sqrt{-1}$

- The Total Horizontal Derivative

The total horizontal derivative is an effective tool used to detect the edges of magnetized structures. A commonly used edge detection filter is the total horizontal derivative (THDR) and is given using the following equation (Cordell and Grauch, 1985),

$$THDR = \sqrt{\left(\frac{dT}{dx}\right)^2 + \left(\frac{dT}{dy}\right)^2} \quad (2.3)$$

where, T is the magnetic field, and $\frac{dT}{dx}$ and $\frac{dT}{dy}$ are the two orthogonal horizontal derivatives of the magnetic field.

- Vertical Derivatives

The vertical derivative is commonly applied to total magnetic field data to enhance the shallow geologic sources in the data. As with other filters that enhance the high-wave-number components of the spectrum, one must often also apply low-pass filters to remove high-wave-number noise

$$L(r) = r^n \quad (2.4)$$

Param n is the order of differentiation.
 r is the wave-number (radians/unit) Note $r = 2\pi k$,
 k is the number of cycles/unit.

Derivative data have become almost a basic necessity in magnetic interpretation projects, but its application requires high quality data because its greater

enhancement of high frequencies results in greater enhancement of noise. Higher orders of derivatives are virtually never used to produce interpretation products and so, in principle, a derivative product could be produced where 'n' is not an integer in the above equation (Milligan and Gun, 1997).

2.3.2 Analytical Signals

The amplitude of the analytical signal anomaly tends to peak over the edges of wider bodies and the centers of narrower bodies, regardless of any remanence in the source. Therefore, the interpretation of analytical signal maps should provide simple and easily understood indications of magnetic source geometries (Milligan and Gun, 1997).

The analytic signal (Roest et al., 1992) is a function related to magnetic fields by the derivatives of the following equation,

$$|A(x, y)| = \sqrt{\left(\frac{dT}{dx}\right)^2 + \left(\frac{dT}{dy}\right)^2 + \left(\frac{dT}{dz}\right)^2} \quad (2.5)$$

where, $A(x, y)$ is the amplitude of the analytic signal at (x, y)
 T is the observed magnetic field at (x, y)

The analytic signal can be calculated through a combination of the horizontal derivatives and vertical derivatives.

2.4 Magnetic Data Acquisition

Magnetic surveys are conducted using a WCZ-2 Proton Magnetometer (Figure 2.5). During field surveys, it involves keeping the axis of the sensor horizontal and in an east-west direction at equatorial regions, which corresponds to arrows in an upwards configuration (Figure 2.4). At other regions, it is necessary to rotate the sensor to obtain the maximum signal strength. The GPS module is responsible for receiving the positioning of geography matching to the collection data point. Exploration within the body must not include any metal devices, in order to eliminate noise whilst measuring the magnetic field.

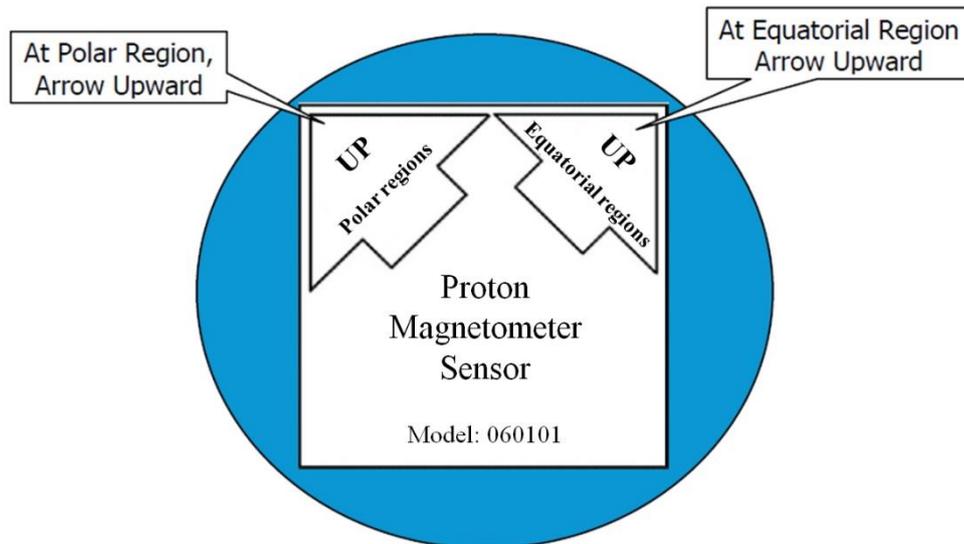


Figure 2.4 Signs at the sensor bottom (Modified from the WCZ-2 user manual).

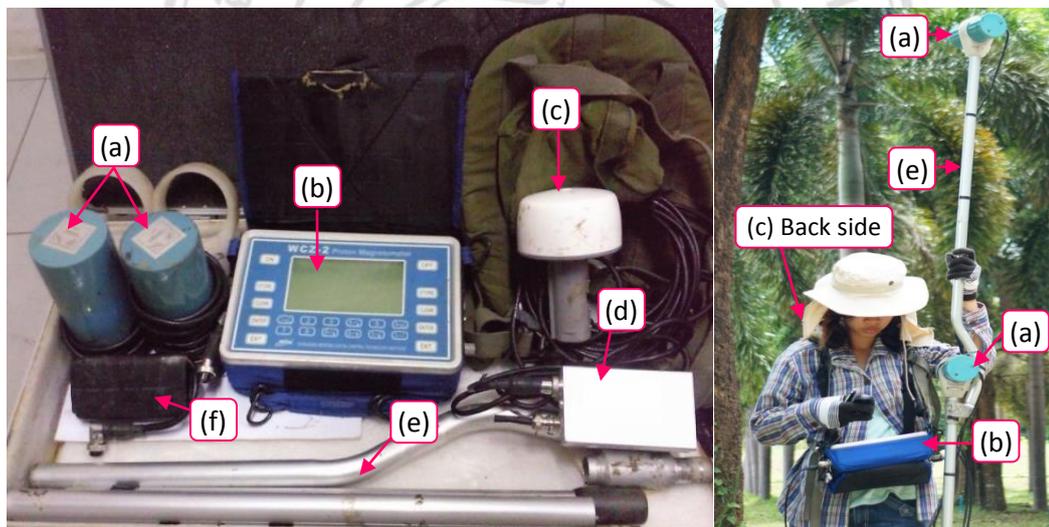


Figure 2.5 WCZ-2 Proton Magnetometer (a) 2 sensors, (b) LCD display, (c) GPS positioning module, (d) GPS adapter, (e) Collapsible aluminum staff, and (f) External battery.

The study area divided into 2 areas, measured $5 \times 20 \text{ m}^2$ (Figures 1.7 and 1.8), and the survey used 2 sensors to obtain vertical and horizontal gradients to resolve smaller archaeological features. The survey was conducted with a sensor separation of 0.5 m and then 1.0 m, respectively.

Line surveys have 6 line surveys per area, 20 m long, with a line spacing of 1.0 m and measurement interval of 1.0 m per line (Figure 2.6). The direction of survey from southwest to northeast was S55°E or 305°, in azimuth, and the reference point for taking data from high ground was circa 0.5 m.

The horizontal gradient for both areas used the same system, by adjusting the direction of the sensor in a horizontal gradient not related to the magnetic field or direction of the pole, thus, made to measure the same system in both areas.

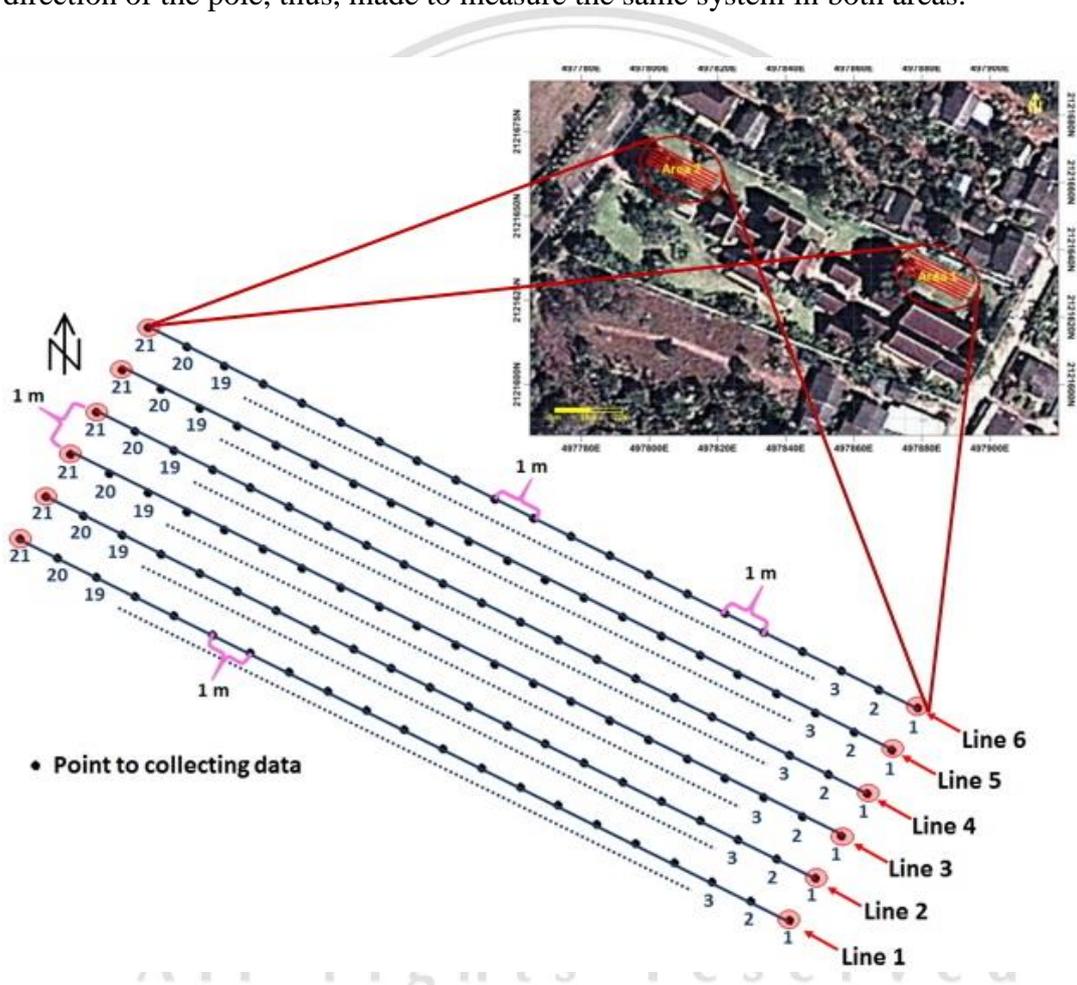


Figure 2.6 Magnetic plan survey.

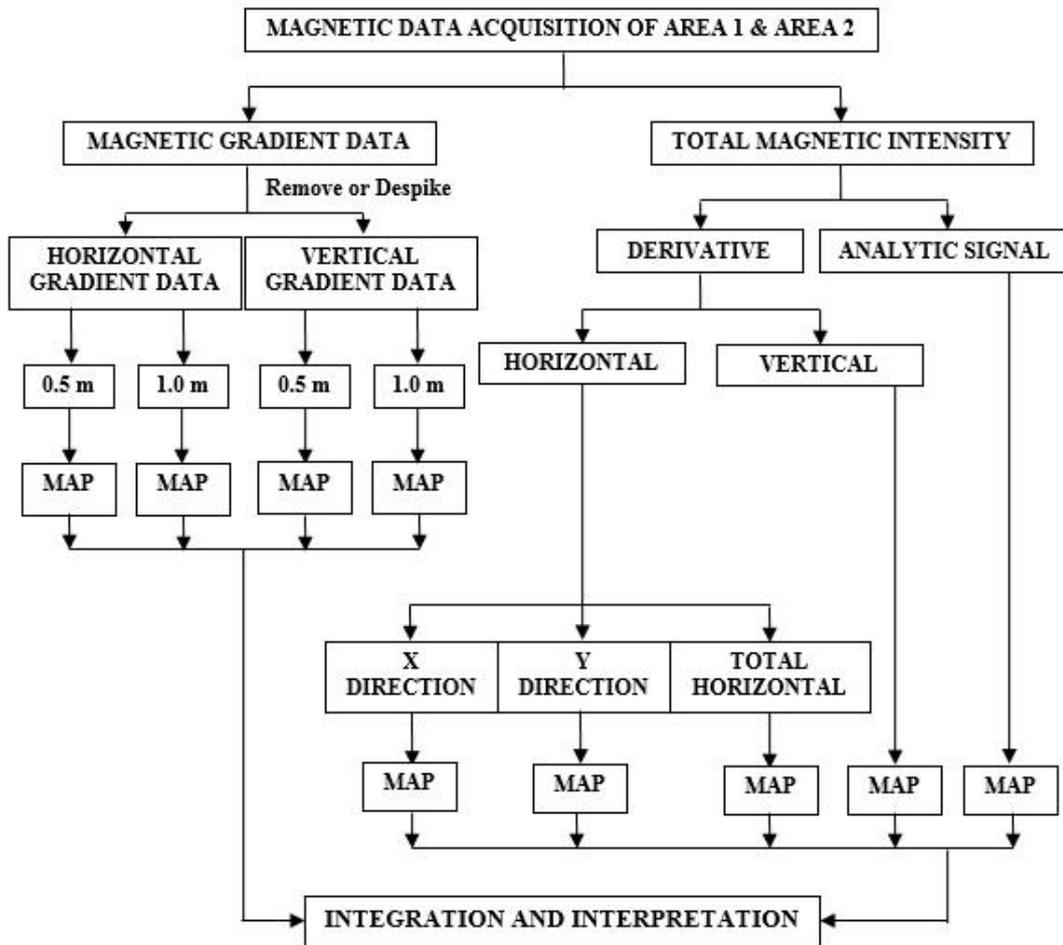


Figure 2.7 Flowchart of magnetic data processing.

2.4.1 Data Correction

Measured magnetic data were downloaded into WCZ-2 software for data editing and calculation. The magnetic gradient data was calculated and checked for each dataset, and this defined datasets contained vaulting values (spikes) which were over and above the standard dataset mean value (Figure 2.9). The vaulting values may have arisen through instrument error, user error, or iron debris.

Therefore, data quality control had to be completed by deleting any abnormal values (peaks or spikes), as shown in Figure 2.8. Location information (X and Y) and magnetic gradient data were calculated and then converted into an XYZ file format before exporting. Figure 2.9 shows an example of one line magnetic data, where the 'Stn_no' is the station number for taking data, 'mag_field' is the average total magnetic intensity from 2 sensor reading, 'gradient' is the magnetic field gradient or the

differences between 2 sensor readings divided by sensor spacing, ‘longitude’ is defined in terms of meridians which are half-circles running from pole to pole within the survey area, ‘latitude’ is an equatorial reference plane in the survey area, and ‘X_WGS’ and ‘Y_WGS’ are the coordinates of X and Y in reference to the WGS84 datum.

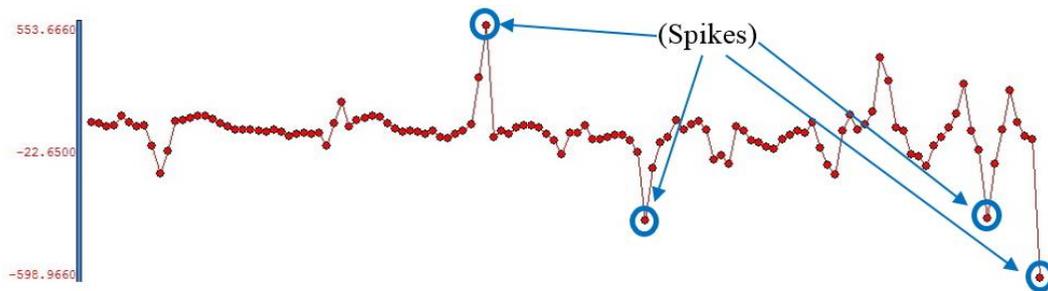


Figure 2.8 Examined spike magnetic gradient values shown in blue circles.

stn no	mag fld	gradient	longitude	latitude	X WGS	Y WGS
1.0000	44731.4000	117.9000	98.9799	19.1880	497874.0000	2121634.0000
2.0000	44734.4000	115.8000	98.9799	19.1880	497874.9000	2121633.5500
3.0000	44737.8000	90.3000	98.9799	19.1880	497875.8000	2121633.1000
4.0000	44739.6000	94.6000	98.9799	19.1880	497876.7000	2121632.6500
5.0000	44752.3000	179.0000	98.9799	19.1880	497877.6000	2121632.2000
6.0000	44764.1000	78.9000	98.9799	19.1880	497878.5000	2121631.7500
7.0000	44749.4000	100.4000	98.9799	19.1880	497879.4000	2121631.3000
8.0000	44756.7000	109.4000	98.9799	19.1880	497880.3000	2121630.8500
9.0000	44718.2000	75.9000	98.9799	19.1880	497881.2000	2121630.4000
10.0000	44685.9000	80.0000	98.9799	19.1880	497882.1000	2121629.9500
11.0000	44837.6000	83.0000	98.9799	19.1880	497883.0000	2121629.5000
12.0000	44860.3000	93.7000	98.9798	19.1880	497883.9000	2121629.0500
13.0000	44853.5000	152.4000	98.9798	19.1880	497884.8000	2121628.6000
14.0000	44888.0000	122.3000	98.9798	19.1880	497885.7000	2121628.1500
15.0000	44887.3000	141.3000	98.9798	19.1880	497886.6000	2121627.7000
16.0000	44853.8000	147.0000	98.9798	19.1880	497887.5000	2121627.2500
17.0000	44794.1000	123.1000	98.9798	19.1880	497888.4000	2121626.8000
18.0000	44708.4000	117.1000	98.9798	19.1880	497889.3000	2121626.3500
19.0000	44628.2000	90.2000	98.9798	19.1880	497890.2000	2121625.9000
20.0000	44531.8000	85.5000	98.9798	19.1881	497891.1000	2121625.4500
21.0000	44363.1000	104.5000	98.9797	19.1881	497892.0000	2121625.0000

Figure 2.9 XYZ format of magnetic data.

- Gridding

Next, the XYZ files were imported into an Oasis Montaj program for gridding. The data gridded the gradient magnetic data to a 0.5 grid cell size (Figures 2.10 – 2.17), because its half a point collection data is spaced at 1 m. Thus, the largest possible value adequately captures the resolution of the process being modeled. It can be seen that the

sampling rate along the lines is much denser than across the lines, and therefore it is usually desirable to interpolate data onto a grid.

2.5 Magnetic Results

The results of the magnetic gradient represent the archaeological Intakhin kiln site information. The magnetic data results of magnetic gradient and derivatives of total magnetic intensity, plus the analytic signals of total magnetic intensity are also represented.

2.5.1 Magnetic Gradient Data

The considered anomalies with a high valued of anomaly and size of the anomaly were chosen to be circa 2 x 3 m, that similar to the kiln to be discovered.

The results of horizontal gradient at Area 1 used a 0.5 m sensor distance (Figure 2.10), and the low magnetic intensity range was -33 to 70 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 80 nT/m.

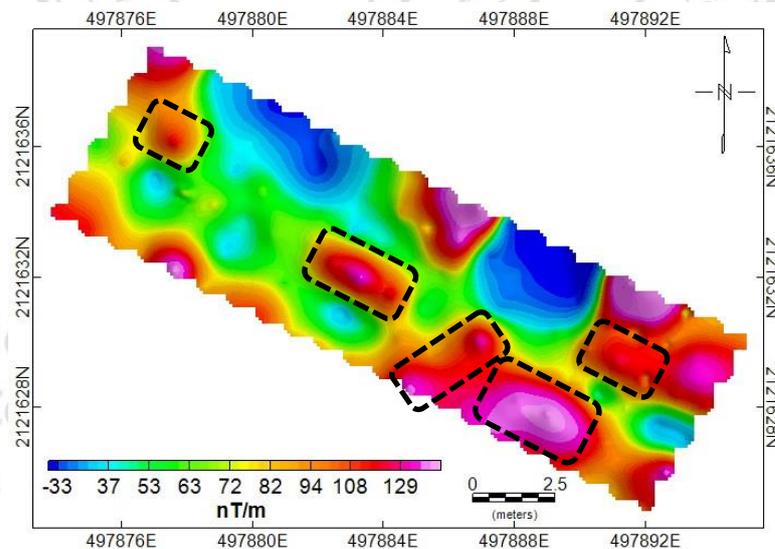


Figure 2.10 Magnetic horizontal gradient data of Area 1, distance of sensor was 0.5 m.

The results of horizontal gradient in Area 1 used a 1.0 m sensor distance (Figure 2.11), and a low magnetic intensity range from -64 to 60 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 70 nT/m.

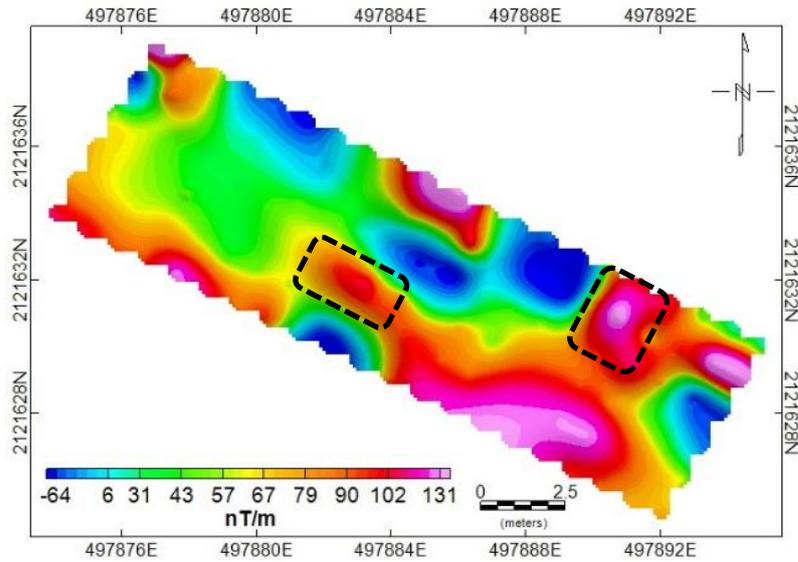


Figure 2.11 Magnetic horizontal gradient data of Area 1, distance of sensor was 1.0 m.

The results of vertical gradient in Area 1 used a 0.5 m sensor distance (Figure 2.12), and a low magnetic intensity range between -79 to -7 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 10 nT/m.

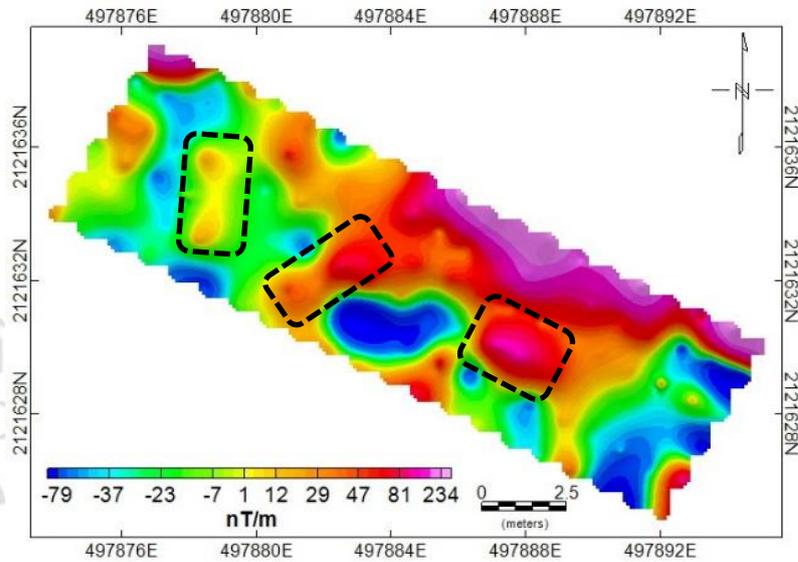


Figure 2.12 Magnetic vertical gradient data in Area 1, distance of sensor was 0.5 m.

The results of vertical gradient in Area 1 used a 1.0 m sensor distance (Figure 2.13), and a low magnetic intensity range between -61 to -6 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 20 nT/m.

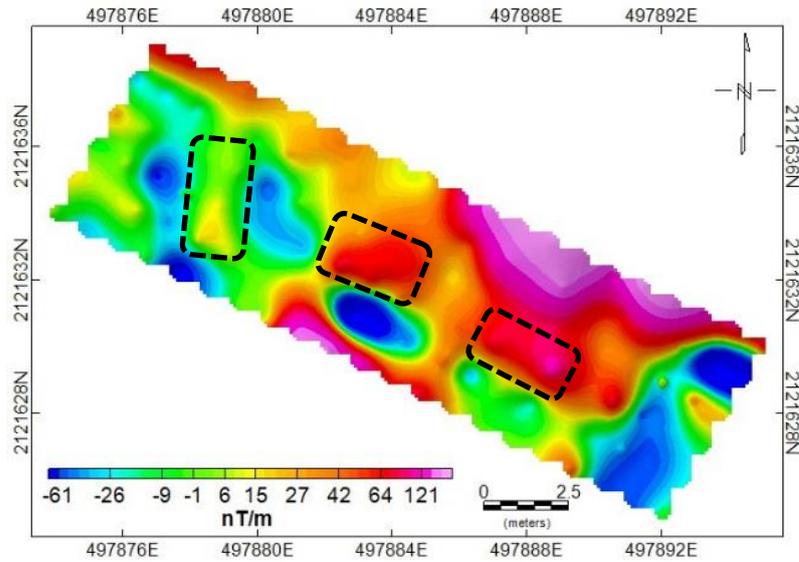


Figure 2.13 Magnetic vertical gradient data in Area 1, distance of sensor was 1.0 m.

The results of horizontal gradient in Area 2 used a 0.5 m sensor distance (Figure 2.14), and a low magnetic intensity range between -77 to -4 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 10 nT/m.

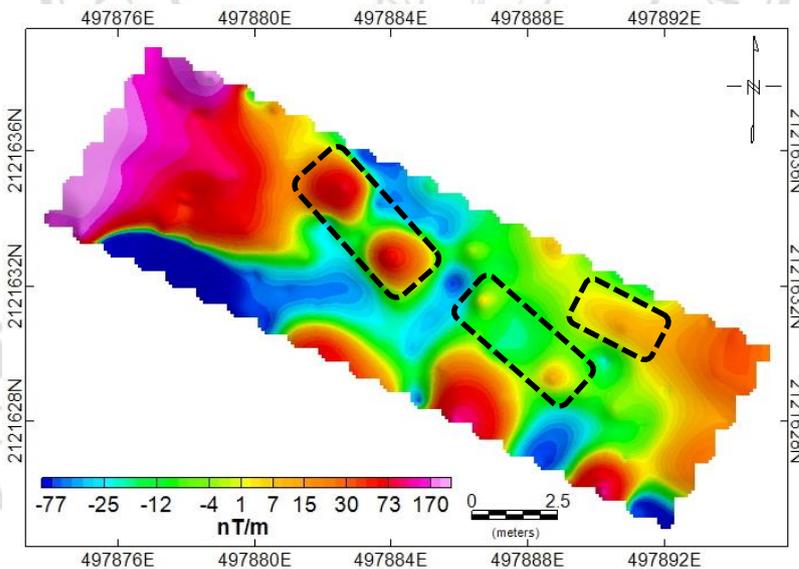


Figure 2.14 Magnetic horizontal gradient data in Area 2, distance of sensor was 0.5 m.

The results of horizontal gradient in Area 2 used a 1.0 m sensor distance (Figure 2.15), and a low magnetic intensity range between -150 to -19 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over -4 nT/m.

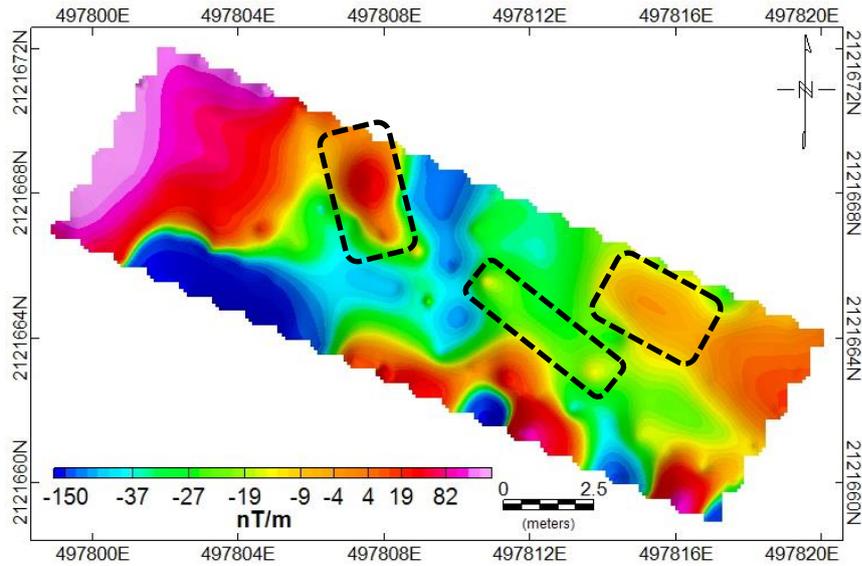


Figure 2.15 Magnetic horizontal gradient data in Area 2, distance of sensor was 1.0 m.

The results of vertical gradient in Area 2 used a 0.5 m sensor distance (Figure 2.16), and a low magnetic intensity range between -79 to -7 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 10 nT/m.

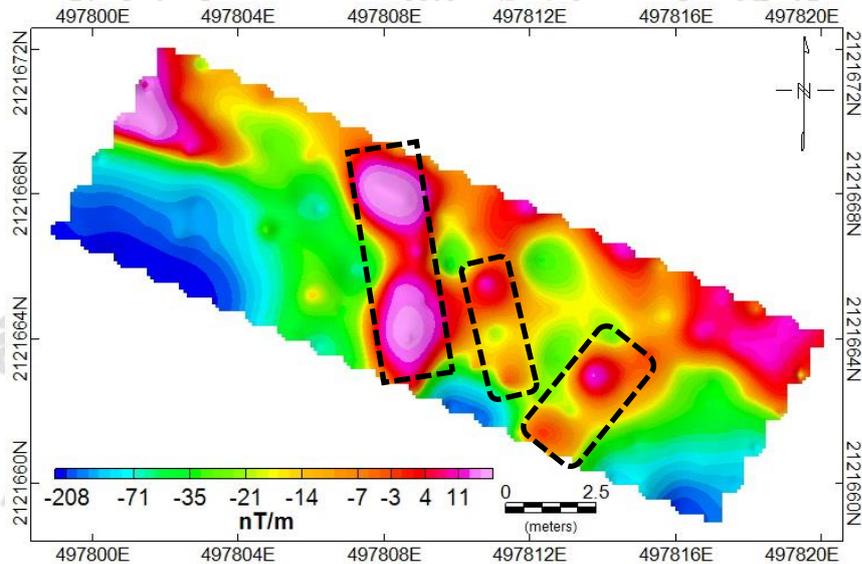


Figure 2.16 Magnetic vertical gradient data in Area 2, distance of sensor was 0.5 m.

The results of vertical gradient in Area 2 used a 1.0 m sensor distance (Figure 2.17), and a low magnetic intensity range between -201 to -11 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 0 nT/m.

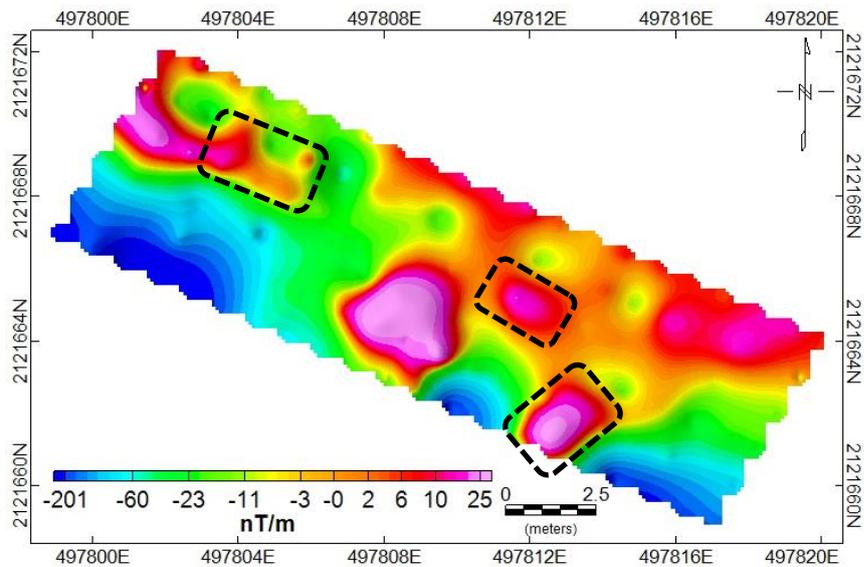


Figure 2.17 Magnetic vertical gradient data in Area 2, distance of sensor was 1.0 m.

The total magnetic intensity data is the value of the magnetic field accompanied by the magnetic gradient survey. The magnetic anomaly characteristic depends upon its magnetic latitude and the dip angle of the magnetization in the magnetized body.

This data can help interpret any anomaly. The value of total magnetic intensity data were filtered using x-y direction derivatives, total horizontal derivatives, vertical derivatives and analytical signals.

The database of total magnetic intensity data were used primarily with a vertical gradient sensor at 0.5 m. This value of sensor at 0.5 m was a measure in line with the line survey, using a bottom sensor height of more than 1.0 m, in order to reduce the value of noise near to the ground.

2.5.2 Total Magnetic Intensity Data Filtered by Derivative

The derivative enhances shallower anomalies and improves the resolution of closely spaced sources, by sharpening and separating magnetic anomalies. The magnitude of the derivative is usually highest over a center of magnetic body in the vertical derivative, whereas it is highest at the border of a magnetic body in the horizontal derivative.

The results of x-direction derivatives from total magnetic intensity in Area 1 (Figure 2.18), with a low magnetic intensity range of between -56 to -7 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 4 nT/m.

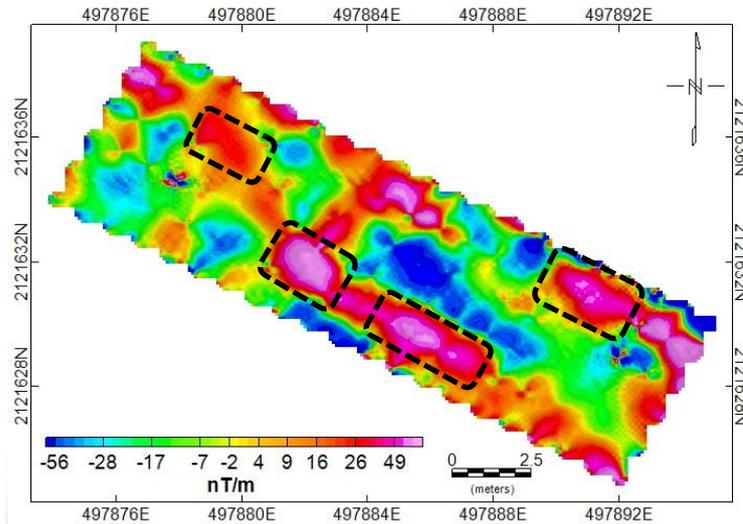


Figure 2.18 Derivatives of x-direction of total magnetic intensity in Area 1.

The results of y-direction derivatives from the total magnetic intensity of Area 1 (Figure 2.19), with a low magnetic intensity range between -64 to -2 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 11 nT/m.

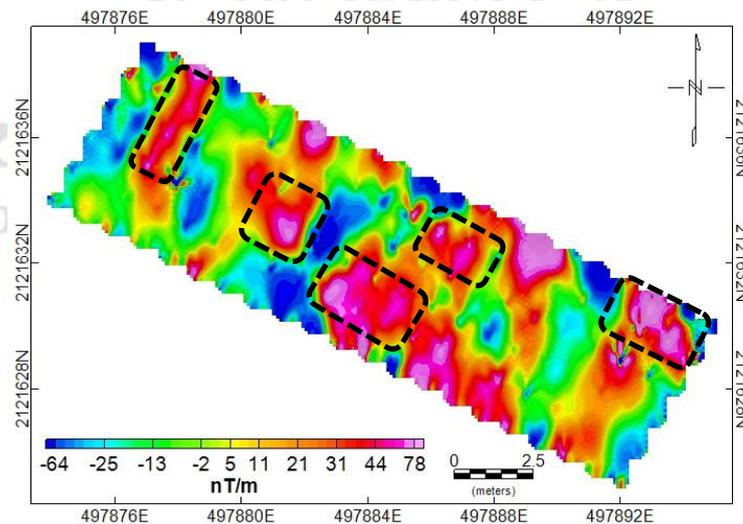


Figure 2.19 Derivatives of y-direction of total magnetic intensity in Area 1.

The results of total horizontal derivatives from total magnetic intensity in Area 1 (Figure 2.20), with a low magnetic intensity range of between 22 to 63 nT/m.

Anomalies interested in (black rectangles) had a high magnetic intensity range over 75 nT/m.

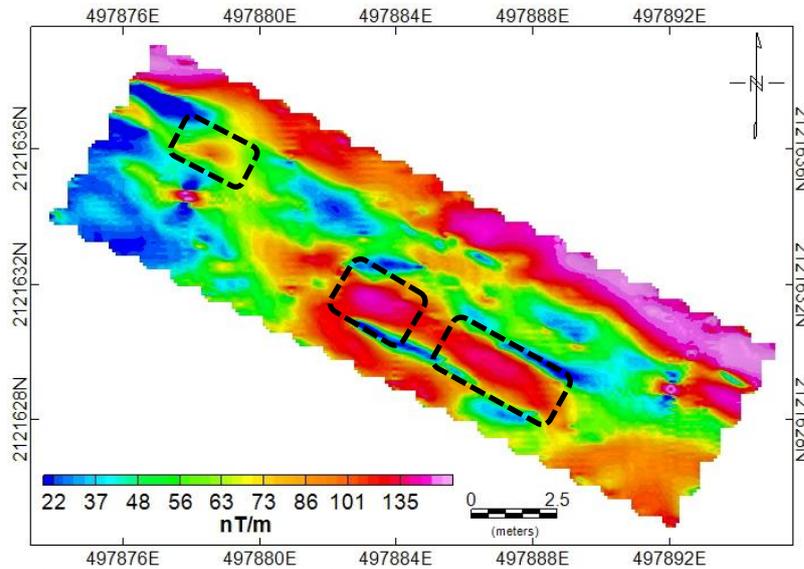


Figure 2.20 Derivatives of total horizontal magnetic intensity in Area 1.

The results of vertical derivatives from total magnetic intensity in Area 1 (Figure 2.21), with a low magnetic intensity range between -146 to -20 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 10 nT/m.

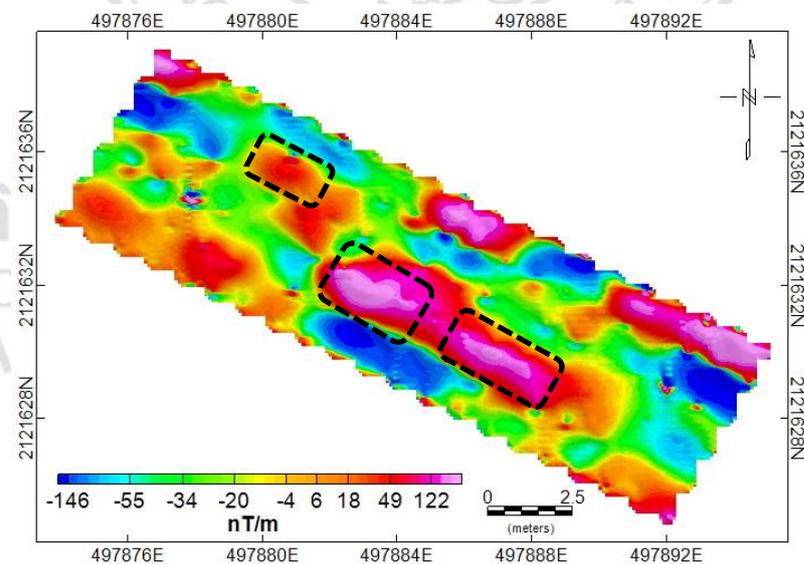


Figure 2.21 Derivatives of vertical total magnetic intensity in Area 1.

The results of total horizontal derivatives from total magnetic intensity in Area 2 (Figure 2.22), with a low magnetic intensity range between -296 to -50 nT/m.

Anomalies interested in (black rectangles) had a high magnetic intensity range over -20 nT/m.

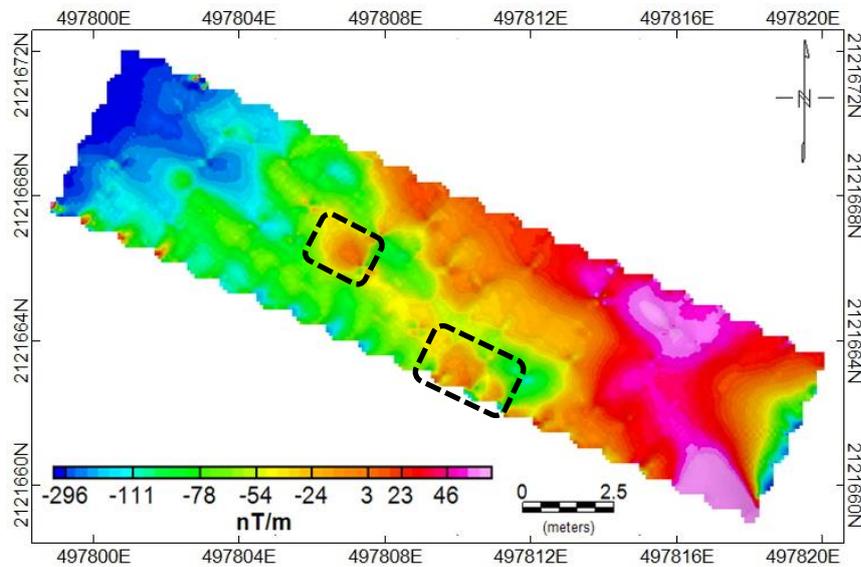


Figure 2.22 Derivatives of x-direction of total magnetic intensity in Area 2.

The results of y-direction derivatives from total magnetic intensity in Area 2 (Figure 2.23), with a low magnetic intensity range between -154 to -18 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 10 nT/m.

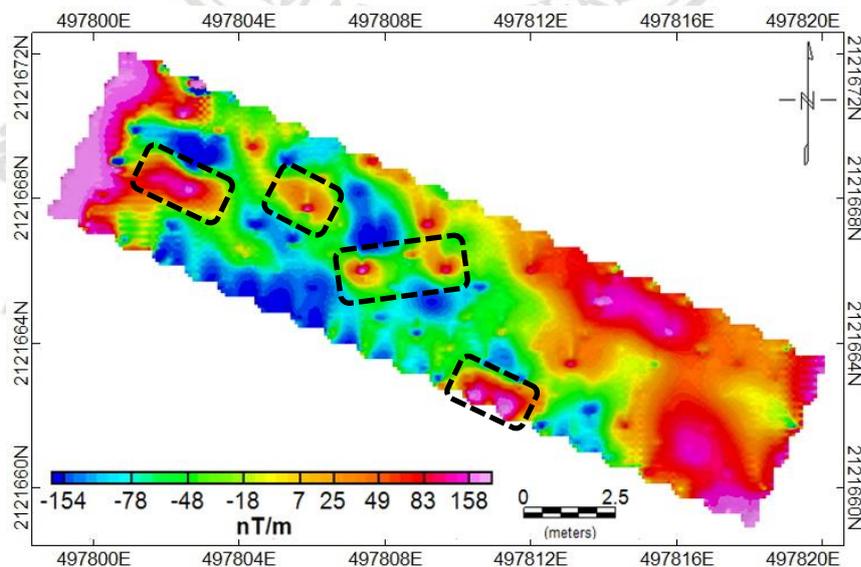


Figure 2.23 Derivatives of y-direction of total magnetic intensity in Area 2.

The results of total horizontal derivatives from total magnetic intensity in Area 2 (Figure 2.24), with a low magnetic intensity range between 86 to 160 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 180 nT/m.

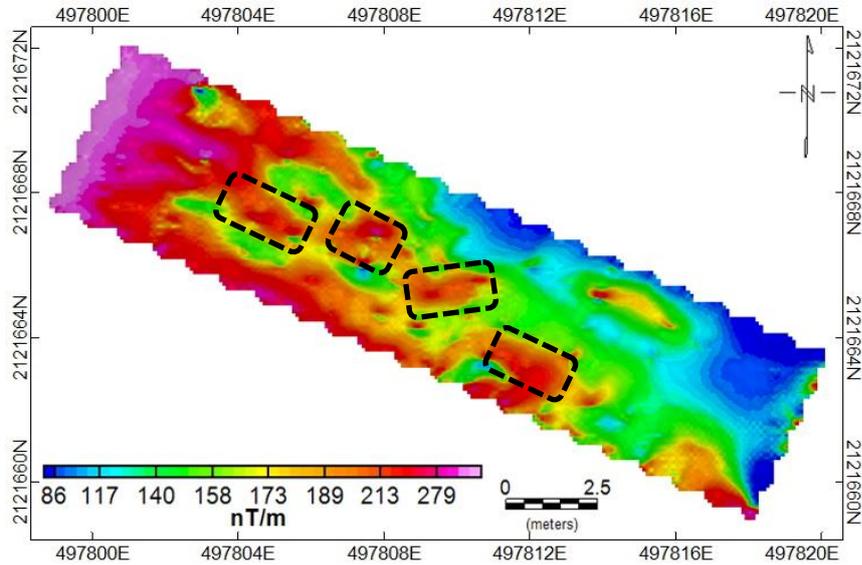


Figure 2.24 Derivatives of total horizontal magnetic intensity in Area 2.

The results of vertical derivatives from total magnetic intensity in Area 2 (Figure 2.25), with a low magnetic intensity range between -112 to -20 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 10 nT/m.

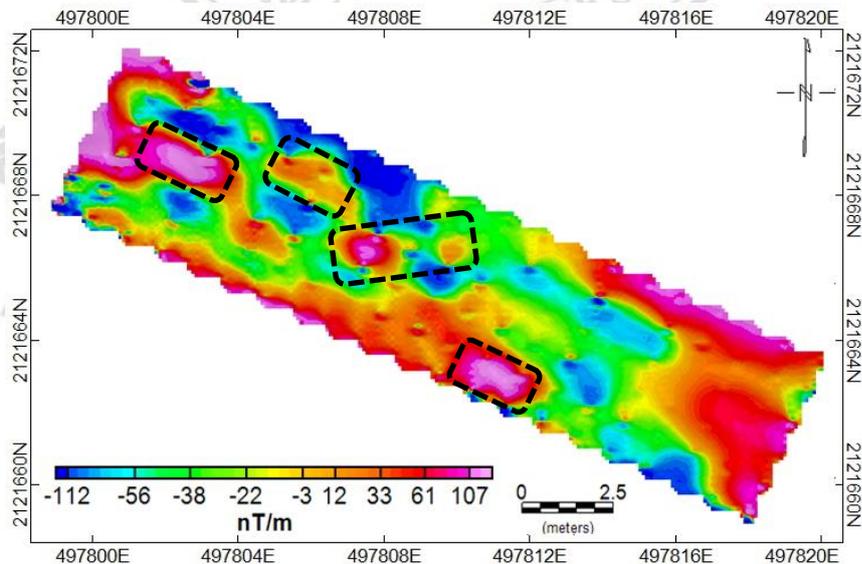


Figure 2.25 Derivatives of vertical total magnetic intensity in Area 2.

2.5.3 Magnetic Data of Analytical Signals

The advantages of the analytical signal method are defined as an absolute value, and help make reasoning concerning the direction of magnetic bodies, such as kilns.

The amplitude of an analytic signal anomaly tends to peak over the edges of wide bodies and the centers of narrow bodies, regardless of any remanence in the source. Therefore, any interpretation of analytical signal maps should provide simplistic and easily understood indications of the magnetic body (Milligan and Gun, 1997).

Concerning analytical signal enhancement mapping from total magnetic intensity in Area 1 (Figure 2.26), with a low magnetic intensity range 50 to 100 nT/m, anomalies interested in (black rectangles) had a high magnetic intensity range over 120 nT/m.

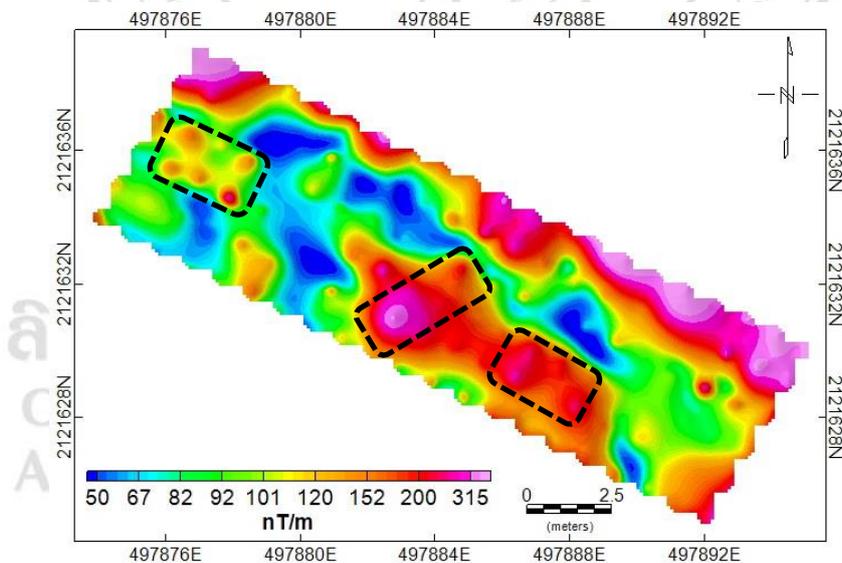


Figure 2.26 Analytical signal map of total magnetic intensity in Area 1.

Analytical signal enhancement map from total magnetic intensity in Area 1 (Figure 2.27), with a low magnetic intensity range between 50 to 100 nT/m. Anomalies interested in (black rectangles) had a high magnetic intensity range over 120 nT/m.

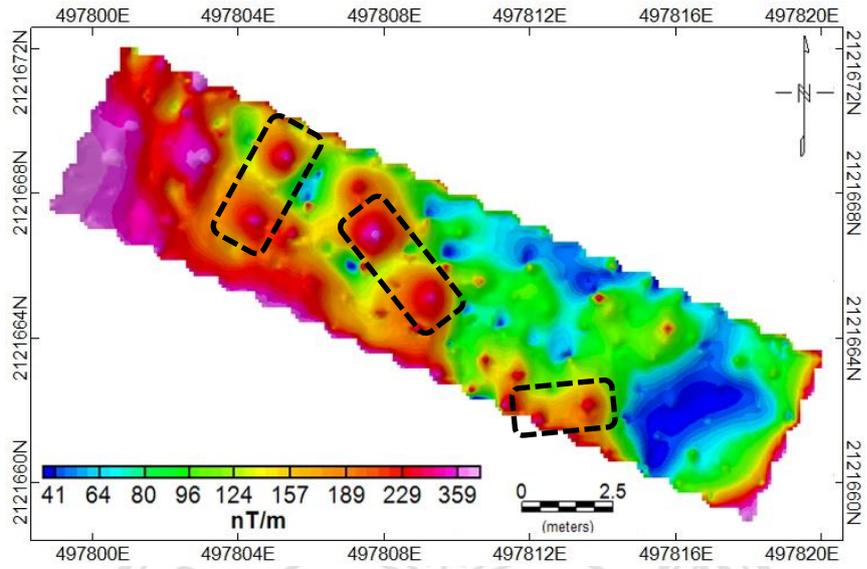


Figure 2.27 Analytical signal map of total magnetic intensity in Area 2.

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