Mapping of Kedaton Archaeological Sites Using Geomagnetic Methods (Preliminary Study)

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Abstract. Ancient civilizations in Jombang left many historical relics in the form of temples, artifacts, and other archeological sites. Kedaton site is one of the newly discovered archeological sites. This site is buried under a few meters thick of Mount Kelud’s pyroclastic flow. Therefore, the distribution patterns of the site is needed to improve the excavation plan in order to maintain the structure of the site. One of the technical approaches that can be applied to map the site’s distribution in detail is geophysical survey. Geomagnetic method is a method commonly used in the case of archeological site investigations because of its non-destructive nature. The mapping process on Kedaton site is conducted by applying geomagnetic survey that utilizes physical parameters in the form of magnetic susceptibility. The reduce to pole filter is applied to magnetic data processing to aid interpretation, coupled with horizontal gradient method and analytic signal method further clarify the boundaries of magnetic anomaly sources. Reduce to pole filter indicates that the site’s brick detected as moderate to high magnetic anomaly values (more than 450 nT). This research succeeded in mapping clearly the boundaries of the site with an area of up to 6000 meters2 with the shape of the site resembling a building with several chambers. The main chamber is in the north which is the widest chamber, and small chambers are found on the south side.

1. Introduction
Jombang-Kediri-Mojokerto Regencies were a place of ancient civilizations, from Medang Kamulan (10th-11th century) until Majapahit (12th-15th century) and therefore is very rich in cultural heritage, such as artefacts of ancient temples and springs. Kedaton site is a recently found temple located in Bulurejo Village, Diwek Sub-district, Jombang Regency, East Java Province. Geographically, Kedaton site located in 638122.63 E and 9156240.68 S, about 31 km to the north of Mount Kelud [1]. It is predicted to be associated with Majapahit’s legacy Tikus temple and Segaran Spring, which is 18 km east of the site. The structure of the site is composited by ancient red bricks. It was incidentally discovered by residents in the late 2019 under ±2 meters thick of Mount Kelud’s pyroclastic flow deposit. Since then, Jombang Regency authority alongside with Balai Pelestarian Cagar Budaya Jawa
Timur (Cultural Heritage Preservation Office of East Java) has been cooperating with national institutes to conduct a feasibility study to improve the excavation plan. Several technical approaches, including geological and geophysical studies were applied to locate the buried structure and to comprehend the geo-chronological events of the site. The vulnerable condition of the site requires the use of non-destructive method, as it can provide useful information about the site without intrusive intervention.

Geomagnetic is one of the geophysical methods that often applied for sub-surface archaeological investigation. It is one of geophysics passive method since it doesn’t need energy source during acquisition [2]. It is used in the investigation of Palgading Temple, Yogyakarta to map the distribution of the temple’s remains that buried 3-4 meters below the surface [3]. Geomagnetic provides the magnetic anomalies (susceptibility) of underground materials by measuring the variations in the intensity of the magnetic field. According to [4], the archaeological structures made of earth typically, such as burnt soil, has a higher susceptibility than the surrounding materials, which caused by the burning process. Previous archaeological research conducted by [5], Aïn Kerouach archaeological site, Morocco has shown that the contrast between obtained magnetic anomalies of the buried artefacts and the lithology of the site is effective in mapping the artefacts distribution.

In order to obtain a more accurate result, we use the Horizontal Gradient Method (HGM) [6] and Analytic Signal Method (ASM). These methods can estimate the minimum and maximum of the magnetic source depths but differ in the accuracy and sensitivity to noise and anomaly interference [7]. The first method uses the magnitude of horizontal gradient to locate magnetic contacts and obtain the maximum values of horizontal anomalies [8], hence reduce the interference effects and yield a more precise delineation of magnetic bodies compared to vertical gradient method [9]. While the second method uses the square of the analytic signal amplitude and produces precise horizontal locations of magnetic contacts. According to [7], analytic signal method is more sensitive to noise and aliasing in the data, compared to HGM. However, the reduction of aliasing effects may reduce the resolution. A research with a similar method was conducted in the study of structural situation of Sohag, Egypt and was succeeded in detecting the source of the anomaly [10]. In the referred research, HGM and ASM method was able to detail the basin structure of Sohag region by enhancing the susceptibility contrasts boundaries [9].
2. Methods
Data acquisition were carried out on November 12, 2019 in an area of 250 X 180 meters covering 73 stations (Figure 2). The instrument used was a Geometric PPM Magnetometer with a gradiometer sensor. This acquisition results the value of the magnetic field variation in units of nT. The first step in data processing is diurnal variations correction to reduce variation in the earth's magnetic field caused by solar activity at different times and locations on earth. The diurnal variation correction value is obtained from the difference between the reading of the instrument at the base station and the measurement stations. The second correction is the IGRF (International Geomagnetic Reference Field) Correction that aims to reduce the influence of the main magnetic field of the earth's core. The IGRF value used is accessed via https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm.
Figure 2. Data acquisition map in Diwek Archeological Site. Black point showing acquisition station in the area.

After the total magnetic field anomaly is obtained then a Reduction to the Pole (RTP) step is performed to eliminate the polar disturbance in the magnetic object (dipole) so that it becomes a monopole.

We used Reduce to Pole (RTP) filter for magnetic data processing. This filter was first introduced by [11] to solve the problem of asymmetric anomalous body. The principle of Reduce to Pole is converts the magnetic anomaly caused by arbitrary sources into the anomaly that would be produced by the same sources, if it's located at the pole and magnetized by induction only [12]. The output of this step is the RTP (Reduce to Pole) anomaly [13]. Since the anomaly is estimated to be at a shallow depth, this study focuses on how to emphasize the anomaly boundary. To determine the magnetic anomaly’s contact with the surrounding environment, two types of methods are used: Horizontal Gradient Method and Analytic Signal.

The horizontal gradient method requires first-order horizontal derivatives and reduction to pole. This method has been widely used in mapping the boundaries that show the constriction of magnetic susceptibility. This method uses the principle that the horizontal derivative of RTP magnetic field produced by anomalous tabular body tends to have maximum values at the edges of anomaly in case the edges are vertical and well-separated from each other [14]. This method is strong in detecting shallow magnetic sources, but is less sensitive to noise in data [7]. The horizontal gradient method uses the magnitude value of horizontal gradient, which for gridded data is defined as

$$|H(x,y)| = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2}$$  \hspace{1cm} (1)

where $M$ is reduced-to-pole anomaly and $\partial x$ & $\partial y$ are derivative with respect to $x$ and $y$ respectively.

Analytic Signal Method (ASM) is the square root of the sum of squares of the derivatives in $x$, $y$, and $z$ directions. It is applied to determine the magnetic source geometry [15]. This method requires first-order horizontal and vertical derivatives of the magnetic field [7]. The Analytic Signal Method uses the square of analytic signal amplitude of the potential field [16], which for gridded data is defined as [17]

$$|A(x,y)|^2 = \left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2$$  \hspace{1cm} (2)

The advantage of Analytic Signal Method is the amplitude function which is always positive and there is no need to make assumption of the direction of the anomalous body magnetization [18].
3. Result and Discussion

Site outcrops can be seen in Figure 3 and the map of the total magnetic anomaly shows magnetic contrast as shown in Figure 4. Medium anomaly contrast with values ranging from 600 nT through outcrops suspected to be walls of archeological buildings with northeastward distribution patterns from the outcrop point. On the west side of the outcrop has a magnetic anomaly value relatively lower than the outcrop point (symbolized by AO1 and AO2) with values up to 400 nT, while on the east side of the outcrop has a relatively higher value up to 750 nT. Because the target anomaly is in the form of bricks, it tends to have a magnetic susceptibility value higher than rocks and soil around the study site, but from the results of the total magnetic anomaly map, the outcrops are in the medium value zone. When reviewing this, it is certainly difficult to determine the distribution of these archaeological sites due to the apparent location of the target anomaly. This is because the map on the total magnetic anomaly is still influenced by two poles, so it is very possible that the target anomaly is located between the low and high magnetic intensity values. Whereas in locations that do not have anomalies also tend to have medium values. Therefore, the total magnetic anomaly map can only be used for initial estimates of site distribution. But not yet strong enough in the delineation of the boundaries of archaeological sites.

Figure 3 A. Site outcrop AO1 (source: personal documentation), B. Site outcrop AO1 and AO2 (source: Join Media, Jombang Informasi)
Reduce to Magnetic Pole is a method that can be applied to overcome the apparent anomaly due to the influence of two magnetic poles. This method uses the reduce to pole transformation to eliminate anomalous skewness. This transformation makes the anomaly exactly above the source of the anomaly so that it is easier to interpret the existence of the source of the anomaly. The reduce to magnetic pole map can be seen in Figure 5. The site’s brick detected as moderate to high magnetic anomaly value (>450 nT). However, it is still difficult to delineate the site pattern clearly due its moderate value in the AO1 outcrop. Judging from the obvious one of the anomalies that represent outcrops shows that this filter is better in determining the position of the anomaly. This led the writer to carry out further analysis based on the reduce to pole magnetic map.

The Horizontal Gradient Method (HGM) is applied to the results of the reduce to pole magnetic filter in order to get the limits and peaks from the anomaly source clearly. This method applies a
derivative of magnetic intensity to the x and y axes which are horizontal planes. The results of HGM can be seen in Figure 6. The results show clearly the boundaries of the anomalous source in the form of site outcrops at points AO1 and AO2. The anomaly source which is a brick structure is detected clearly as high anomaly value. Based on that result, we suspect that high anomaly values indicate the presence of structures.

To enhance the result, analytic signal also applied in data processing. Analytic signal method is more sensitive to noise and aliasing in the data than horizontal gradient method. Consequently, apparent contacts are less continuous, and strike direction estimated within small window are less accurate. But it should be highly accurate in finding the location of isolated contact. The result of analytic signal can be seen in Figure 7. The site’s outcrop detected as high anomaly. Can be seen that analytic signal result has a different character with HGM based on its sensitivity. But both result shows a same pattern.

Interpretation of the distribution of archeological sites is based on both HGM and analytic signal map. The author confirms that from the results of both method, site’s bricks are indicated with high-
value anomalies. This is the basis for the delineation of the site distribution patterns which can be seen in Figure 8.

From the AO1 outcrop, it is suspected that the site has a continuity to the northeast along approximately 60 meters (marked with number 1). The outcrop of the AO2 site, has a continuity to the south along approximately 25 meters (marked with number 2). The high anomaly pattern on the south side of the study area is assumed to be the southernmost wall. However, it is possible that the continuity of the site in the south of the study area will be discovered because it still shows a continuous high anomaly pattern to the south. East of wall 2, it is found that the site’s structure has a continuity pattern to the east with a total length of about 65 meters (marked with number 3), the largest structure found here. The north side of site’s structure 3 is thought to have a structure site with a north south orientation that has a length of around 40 meters (marked with number 4). The arrangement of this pattern shows that the site has two sites with the main large chamber and another small chamber, thought to be a throne (kedaton). This distribution pattern clearly shows that this archeological site has a building pattern with an orientation that extends from north to south. But the author has not been able to interpret zones with high anomaly values on the north and northeast sides also the detail model of the throne because of the small data points in both zones. Further research needed to ensure about the detail model. This distribution pattern clearly shows that this archeological site has a building pattern with an orientation that extends from north to south.

4. Conclusion
This research concludes that the magnetic method can clearly map the distribution of archeological sites, supported by precise data processing, making the results of the magnetic method more accurate. Fired bricks which is the main material of Kedaton site, detected as moderate to high magnetic intensity anomaly values (more than 450 nT). Archeological site is thought to be a building consisting of several chambers. The site has a continuous distribution pattern from north to south. The area of the building is estimated to reach approximately 6000 meters².
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