

Preliminary Study of Geo-Magnetic Phenomena at The Arjuno–Welirang Volcano, Indonesia

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Abstract

Mount Arjuno–Welirang is an active volcano in East Java that exhibits volcanic activity in the form of shallow and deep earthquakes, as well as fumarolic emissions. This study aims to monitor the subsurface dynamics of the volcano through the integration of magnetic and seismic methods. Magnetic field measurements were carried out using a proton precession magnetometer to obtain local magnetic anomalies after applying diurnal corrections, IGRF correction, and regional–residual anomaly separation. The RTP and residual maps reveal high-anomaly zones that are interpreted as shallow magma intrusions, as well as low-anomaly zones associated with hydrothermal alteration and fracturing. These interpretations are integrated with the lithology of the Qvaw Formation, which consists of lava, volcanic breccia, and tuff. In addition, MAGDAS data were used to analyze diurnal geomagnetic variations (H, D, Z), which show significant fluctuations during certain periods, indicating local geomagnetic disturbances likely influenced by seismic activity or subsurface geological processes. The combination of magnetic and seismic methods provides a more comprehensive understanding of magma pathways, hydrothermal fluid dynamics, and potential increases in volcanic activity, thereby supporting disaster mitigation efforts in the Arjuno–Welirang region.

Keywords: Arjuno–Welirang, magnetic, MAGDAS, volcanic monitoring.

1. Introduction

Indonesia, located along the Pacific Ring of Fire, contains approximately 127 active volcanoes, of which 69 active systems are monitored by the Center for Volcanology and Geological Hazard Mitigation (PVMBG) (Maryanto, Nadhir and Santoso, 2018). Mount Arjuno–Welirang is one such active volcanic complex, exhibiting persistent fumarolic activity, indicating an active magmatic–hydrothermal system beneath the volcano. According to recent monitoring reports from PVMBG (2025), seismic activity beneath Mount Arjuno–Welirang has included persistent shallow and deep volcanic earthquakes, as well as frequent emission-type events. This seismicity suggests ongoing magma supply from deeper sources and its gradual migration toward the shallow volcanic system, indicating sustained subsurface magmatic activity beneath the complex (Shapiro et al., 2017). Although no definitive evidence of imminent eruptive activity has been identified, the observed increase in seismicity toward the end of the observation period highlights the dynamic nature of the magmatic–hydrothermal system and emphasizes the importance of continuous geophysical monitoring to improve understanding of subsurface processes and potential volcanic hazards. The seismic events observed beneath the Mount Arjuno–Welirang complex, therefore, indicate persistent volcanic activity and underscore the value of geomagnetic observations for investigating subsurface magmatic–hydrothermal processes associated with this volcanic system.

Volcanic activity is not only reflected in seismicity but can also be identified through variations in the Earth's magnetic field, commonly known as the volcano-magnetic effect (Kato,

1934; Stacey et al., 1965). These magnetic anomalies are generated by subsurface magmatic processes that alter the thermal, mechanical, and electrical properties of surrounding rocks (Stacey et al., 1965). As magma rises, heating beyond the Curie temperature may cause demagnetization, while stress changes and fluid migration can produce additional magnetic variations (Blanco-Montenegro et al., 2024; Gailler et al., 2023). Therefore, geomagnetic monitoring provides valuable complementary information to seismic observations for understanding subsurface volcanic processes and improving volcanic hazard assessment.

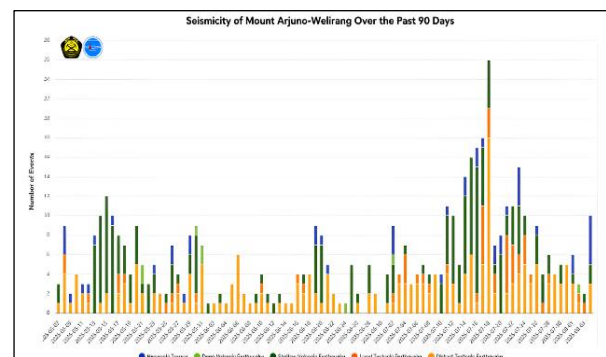


Fig 1. Seismic Data of Arjuno–Welirang for the Past 90 Days (PVMBG,2025).

Both short- and long-term changes in the geomagnetic field have been extensively linked to geodynamic processes, including earthquakes and volcanic activity (Tanaka, 1993;

Fujinawa et al., 2006; Kotzarenko et al., 2019). Volcanic processes have been shown to induce subtle magnetic field variations, typically ranging from 5 to 15 nT (Rossignol, 1982). These variations are generally attributed to subsurface magmatic and hydrothermal processes, such as temperature fluctuations, fluid migration, and stress redistribution within volcanic systems (Takahashi et al., 2017). Due to persistent seismic activity beneath the Arjuno–Welirang complex, a MAGDAS-based geomagnetic observation station was established in Cangar to investigate potential geomagnetic anomalies associated with volcanic activity. Continuous magnetic field measurements from the observation network, together with comparative analysis using a reference station, offer an effective method for identifying localized geomagnetic variations related to subsurface volcanic processes.

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Numerous studies have documented geomagnetic anomalies in seismically active regions associated with earthquake activity (Nagata, 1976; Johnston, 1997; Yen et al., 2004; Hattori, Han and Huang, 2013). These anomalies are typically interpreted as resulting from changes in rock magnetic properties or stress-induced magnetization variations within the seismogenic zone. Consequently, geomagnetic signals have been extensively investigated as potential indicators of subsurface geodynamic processes and possible seismic precursors (Nagao et al., 2002; Hattori, Han and Huang, 2013). In volcanic environments, magnetic methods have also been widely used to characterize subsurface structures and volcanic systems (Rizki et al., 2023). These applications are particularly significant because volcanic activity is closely linked to complex magmatic and hydrothermal processes that continuously alter subsurface conditions (Yudiantoro et al., 2022).

Geophysical methods are widely used to investigate the subsurface magmatic–hydrothermal characteristics (Ibrahim, Utami, and Raharjo, 2024). Despite their utility, these methods often exhibit limited sensitivity to subsurface heterogeneity, which can compromise the accuracy and reliability of geophysical interpretations (Ma and Soleimani, 2017; Wang et al., 2018; Feldkamp and Quirk, 2019). As a result, integrating multiple geophysical approaches has become essential to enhance interpretation reliability and achieve a more comprehensive understanding of subsurface magmatic–hydrothermal processes (Darmawan, Kurniadi, and Suprijanto, 2023).

In addition to magnetic methods, this study also refers to seismological theory to support the interpretation of volcanic activity at Mount Arjuno–Welirang. Seismological studies are used as a fundamental framework for understanding volcanic system dynamics, including magma migration, the occurrence of volcanic tremors, and subsurface activity changes associated

with potential eruptions. Numerous studies have demonstrated that seismic activity is closely related to inflation and deformation processes within volcanic edifices caused by magma movement beneath the surface (Huang, Zhao and Wang, 2016; De Plaen et al., 2019; De Plaen et al., 2016; Donaldson et al., 2017; Olivier et al., 2019). Therefore, the integration of magnetic data with a seismological theoretical approach is expected to provide a more comprehensive understanding of volcanic activity and support the development of more effective monitoring and disaster mitigation systems at Mount Arjuno–Welirang. However, local-scale disaster risk reduction efforts, particularly in Batu City, remain limited due to the absence of independent community-based forums in each village and the lack of collaboration with private stakeholders.

Although geomagnetic observations are widely applied in volcanic monitoring, studies that integrate geomagnetic and seismic observations within a unified framework remain limited, especially in Indonesian volcanic environments such as Mount Arjuno–Welirang. Furthermore, the use of MAGDAS observations for local-scale volcanic monitoring is not yet well established, as MAGDAS is primarily employed for regional and global geomagnetic studies. Evaluating the potential of MAGDAS observations to detect volcanic-related geomagnetic anomalies is therefore a critical step toward broadening its application in volcano geophysics.

This study presents a novel application of MAGDAS observations for volcanic monitoring by extending their conventional use from large-scale geomagnetic and space weather studies to the local-scale investigation of volcanic activity at Mount Arjuno–Welirang. The novelty of this research lies in the combined use of MAGDAS data and land-based geomagnetic survey observations to identify geomagnetic anomalies associated with subsurface volcanic processes. This approach remains rarely explored, particularly in Indonesian volcanic environments, and offers new potential for improving the understanding of volcanic activity through integrated geomagnetic analysis.

2. Methodology

2.1 Magnetic Principles

Magnetic methods are based on the interaction between the Earth's magnetic field and the magnetic properties of subsurface materials. The force between magnetic poles follows an inverse-square relationship, where the magnitude of the force decreases with increasing distance, expressed as:

$$\vec{F}_m = \frac{\mu_0 \rho_1 \rho_2}{4\pi r^2} \hat{r} \quad (1)$$

Where \vec{F}_m is the magnetic force, r is the distance between poles, ρ_1 and ρ_2 are pole strengths, and μ_0 is the permeability of free space.

Magnetic susceptibility (χ) describes how strongly a material responds to an external magnetic field and is a key parameter in magnetic surveys. The induced magnetization is proportional to the applied field:

$$\vec{M} = \chi \vec{H} \quad (2)$$

(Weis, Heagy and Oldenburg, 2023)

where \vec{M} is magnetization and \vec{H} is the magnetic field strength. Rocks with higher concentrations of magnetic minerals generally exhibit higher susceptibility values.

The magnetic susceptibility values of volcanic rocks generally range from low to high, depending on the lithology type and geological conditions. A description of each commonly used rock type is presented in Table 1.

Table 1. Magnetic Susceptibility Values for Volcanic Rocks (General Range) (24).

Rock Type	Magnetic Susceptibility (SI)
Basaltic-andestic lava	0.01-0.1 SI
Volcanic breccia	0.0005-0.05 SI
Tuffaceous breccia	0.0001-0.02 SI
Tuff	0.00001-0.005 SI

The total magnetic field measured at the surface is influenced by both the Earth's magnetic field and the induced response of subsurface materials, which can be expressed as:

$$\vec{B} = \mu\vec{H} \quad (3)$$

Where \vec{B} is magnetic induction and μ is magnetic permeability. Variations in these properties produce magnetic anomalies that can be used to identify subsurface structures and geological variations, particularly in volcanic environments.

2.2 Magnetic Methods

The magnetic method is a geophysical technique used to measure variations in the Earth's magnetic field intensity at the surface, which arise from differences in the distribution and magnetic susceptibility of subsurface materials (Kaufman et al., 2008; Clement, 2021). The recorded anomalies represent small variations superimposed on the Earth's main magnetic field and are widely utilized in preliminary surveys for volcanic monitoring. Magnetic data interpretation, which reflects local variations in magnetization, is useful for identifying geological contacts and subsurface structures that are not directly observable at the surface. Magnetic anomalies may result from variations in lithology, the presence of highly magnetized rock bodies, or geological structures such as faults, folds, and surface morphology. In volcanic regions, these anomalies are also influenced by temperature changes, hydrothermal alteration, and the movement of fluids and magma, which can modify the magnetic properties of rocks. Therefore, magnetic anomaly analysis is effective for identifying geological structures, fracture zones, and subsurface dynamics associated with volcanic activity, as well as supporting the interpretation of residual magnetic anomaly maps (Rizki et al., 2023)

2.3 Integration of Magnetic and Seismological Data

Magnetic and seismic methods are closely related, as both can detect subsurface physical changes associated with volcanic activity. Magnetic data are sensitive to mineralogical and temperature variations, such as demagnetization caused by rock heating, hydrothermal alteration, or fluid and magma intrusion (Johnston, 1997; Takahashi et al., 2018). In contrast, seismic data record changes in pressure, magma migration, and fracturing through variations in seismicity and wave velocity. For instance, heating or fluid movement may reduce magnetic susceptibility, while increased fracturing leads to lower seismic wave velocities. This combination of decreasing magnetic values and increasing seismic activity is often indicative of subsurface heating, alteration processes, or magma migration toward the surface. Therefore, integrating magnetic and seismic approaches is effective for identifying magma pathways, weak zones, and hydrothermal system development, as well as for assessing potential increases in volcanic activity (Johnston, 1997; Hattori et al., 2013).

In this study, geomagnetic data obtained from the MAGDAS station were processed using diurnal variation and IGRF corrections to produce magnetic field anomalies. Seismic activity information was derived from official reports and used to identify periods of increased volcanic activity. The interpretation was then conducted by comparing the temporal patterns of magnetic anomalies with the reported seismic

activity to provide a more comprehensive understanding of subsurface dynamics (Johnston, 1997; Takla et al., 2014)..

2.4 Data Acquisition and Processing

Data collection was carried out in the area surrounding Agro Techno Park Cangar, Sumber Brantas Village, Bumiaji District, Batu City, East Java (Fig. 2). The geophysical method employed in this study is the magnetic method. This method utilizes the Earth's magnetic properties, which arise from variations in the distribution of magnetized materials beneath the surface, based on differences in the magnetization levels of rocks induced by the Earth's magnetic field. These variations occur as a result of differences in the magnetic properties of subsurface materials.

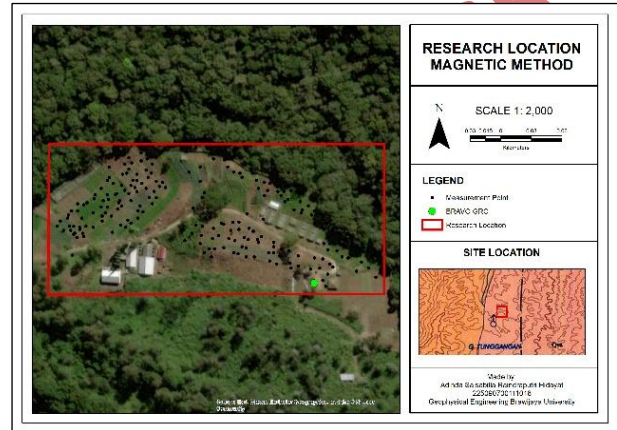


Fig 2. Research Location

The primary instrument used in this survey is a Proton Precession Magnetometer, type G-856 AX. This instrument functions to measure the total intensity of the Earth's magnetic field in nano-Tesla (nT) based on the principle of proton precession. This principle operates by utilizing proton resonance within a hydrocarbon fluid contained in the sensor, where the proton precession frequency is directly proportional to the strength of the Earth's magnetic field at the measurement location. Magnetic data were acquired at 206 magnetic measurement points, with station spacing ranging from 7 to 15 meters, distributed across the study area to ensure adequate spatial resolution of the magnetic field variations.

Supporting tools such as a geological compass, measuring tape, and field data sheets were used for orientation, distance measurement, and data recording. Prior to data acquisition, all equipment must be inspected, including batteries, cables, and reading tests in an area free from magnetic disturbances. During measurement, the operator must keep the instrument away from metallic objects such as mobile phones, watches, and belts to avoid artificial magnetic interference.

After field data collection, the acquired data were processed using Geosoft Oasis Montaj 8.4, Global Mapper, Google Earth, and Microsoft Excel. The initial processing steps included diurnal variation correction and IGRF correction to obtain a clean total magnetic anomaly. Geological information and model parameters were then incorporated to support the analysis. The corrected data were separated into regional and residual anomalies to more easily identify the anomaly sources targeted in the study (Seftyand & Yulianto, 2015).

The flowchart (Fig. 3) illustrates the main stages of magnetic data processing designed to enhance anomaly clarity and facilitate the identification of anomaly sources. Through transformation and filtering processes, the data are separated into regional and residual components, allowing for more accurate subsurface interpretation supported by geological information.

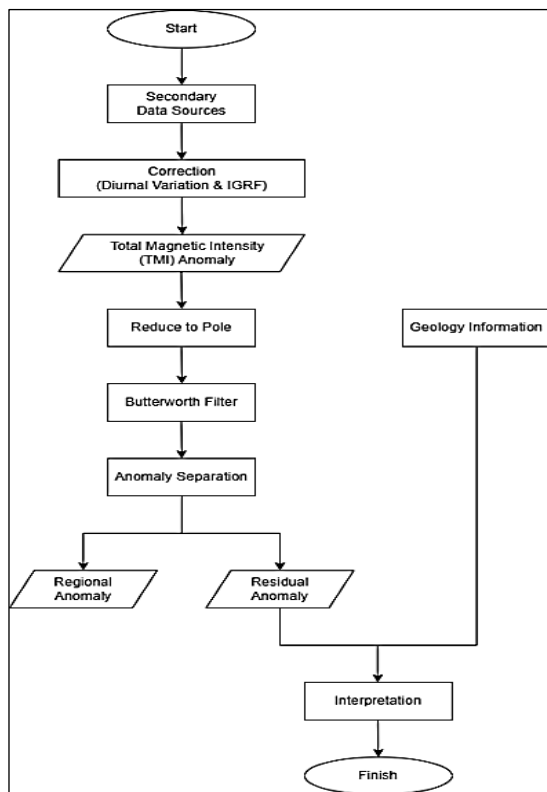


Fig 3. Research Flowchart

3. Results & Discussions

3.1 Magnetic Data Processing Results

In the magnetic data processing stage, several maps were produced from each processing step. The total magnetic field data obtained from field measurements still contained contributions from the Earth's main magnetic field and external magnetic fields. To extract the total magnetic anomaly data relevant to the research objectives, corrections were applied, including diurnal correction (removal of external magnetic field effects) and IGRF correction (removal of the Earth's main magnetic field) (Sehah, Raharjo and Risyad, 2020). The total magnetic anomaly data, once levelled onto a flat surface, were subsequently corrected for regional magnetic effects, as the research focuses on local subsurface features. After separating regional and local anomalies, the resulting local anomalies were interpreted through subsurface modeling using the Oasis Montaj software.

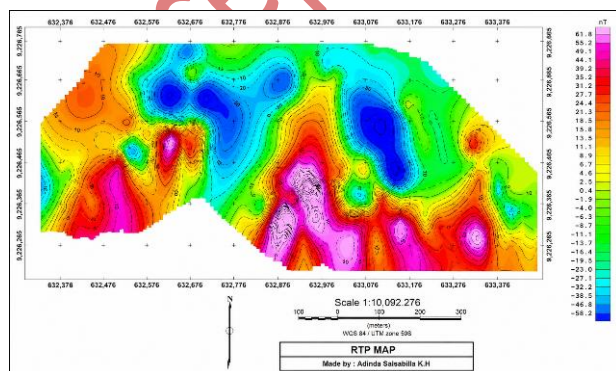


Fig 4. Results of the Reduce to Pole (RTP) Map

Reduction to the Pole (RTP) is a process used to transform magnetic anomalies that initially appear as dipoles (with both positive and negative poles) into monopole-like anomalies (with only a positive peak). This is achieved by adjusting the

magnetic field direction at the measurement location as if it were situated at the Magnetic North Pole. During this process, the original magnetic field inclination and declination values are converted to standard values at the North Pole—0° declination and 90° inclination. As a result, the magnetic anomalies become easier to interpret. The purpose of RTP is to position the magnetic anomaly directly above the subsurface source or causative body (e.g., magnetic rock units or buried objects). Figure 4 illustrates the reduce-to-pole (RTP) magnetic anomaly map obtained following the data processing

Based on the RTP map, a clear contrast can be observed between zones of high and low magnetic anomalies, with values ranging from approximately -1263 nT to $+854$ nT. After applying reduction to the pole, the high-anomaly zones appear prominently in the central to southern regions, represented by red to purple colors with values generally exceeding $+300$ nT up to $+854$ nT. These high magnetic responses indicate rocks with high magnetic susceptibility, producing strong magnetic intensities (Hrouda, 2002). The causative sources are interpreted as shallow intrusive bodies or dikes, which are typically rich in magnetic minerals. Conversely, the low-anomaly zones, distributed in the central-upper to eastern regions, are characterized by green to blue colors with values ranging from approximately -500 nT to -1263 nT. These anomalies reflect rocks with low magnetic susceptibility, which may result from weathering processes, hydrothermal alteration, or structural controls such as faulting that reduce the magnetic properties of the rocks (Finn & Morgan, 2002).

The presence of sharp gradients, indicated by closely spaced contour lines, suggests a distinct lithological boundary or active geological structure, such as faults or fracture zones. These transitions mark significant changes in subsurface properties and may control the distribution of magnetic sources. Furthermore, based on spectral analysis, the estimated depth of the magnetic sources ranges from approximately 0.005 to 0.025 km (5–25 meters), indicating that the anomalies are generated by shallow subsurface structures. Overall, the RTP map indicates that the central-southern region is dominated by high-susceptibility rocks, while the central-upper and eastern parts are characterized by low-susceptibility materials, particularly in areas affected by fracturing or alteration processes (Kearey et al., 2002). Figure 5 illustrates the residual anomaly map.

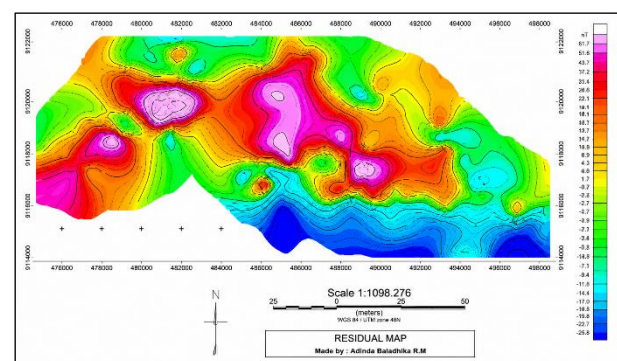


Fig 5. Results of the Residual Map

This residual magnetic map illustrates the distribution of high-frequency magnetic anomalies within the study area, representing variations in the magnetic properties of subsurface rocks. Quantitatively, the magnetic anomaly values range from approximately -753.6 nT to $+794.2$ nT. Red to magenta colors, corresponding to values of about $+300$ nT up to $+794.2$ nT, indicate high magnetic anomalies, which suggest the presence of strongly magnetized volcanic rocks such as solid lava or shallow intrusions. These zones may represent pathways or sources of past magma movement. Meanwhile, blue to cyan colors, with values ranging from approximately -200 nT to $-$

753.6 nT, correspond to low magnetic anomalies. These are typically associated with hydrothermal alteration zones, highly fractured regions, or rocks that have undergone demagnetization due to thermal processes.

The presence of moderate anomalies (green to yellow colors), ranging between approximately -200 nT to $+300$ nT, indicates transitional zones with mixed or intermediate magnetic susceptibility, possibly reflecting gradual lithological changes. Additionally, the sharp gradients indicated by closely spaced contour lines reflect significant lateral contrasts in magnetic properties, suggesting the presence of geological boundaries such as faults or lithological contacts. These high-frequency anomalies further imply that the causative sources are relatively shallow, consistent with near-surface geological features. Residual map highlights localized magnetic variations, where high-anomaly zones dominate the central region, while low-anomaly zones are more prominent toward the southern part, indicating areas affected by alteration, fracturing, or thermal demagnetization processes.

When correlated with the geological setting of the study area, which is dominated by the Qvaw volcanic formation consisting of lava, volcanic breccia, and tuff, the magnetic anomaly distribution reflects variations in rock magnetic susceptibility and structural control. High magnetic anomalies are interpreted to correspond to compact volcanic lava or shallow intrusive bodies with relatively high magnetic susceptibility, whereas low magnetic anomalies may indicate altered or fractured volcanic rocks affected by hydrothermal processes, which tend to reduce rock magnetization. The elongation of several high-anomaly zones from southwest to northeast, together with their alignment with mapped lineaments, suggests that regional geological structures within the Arjuno–Welirang volcanic complex may control the distribution of magnetic sources and act as preferential pathways for magma migration and hydrothermal fluid circulation.

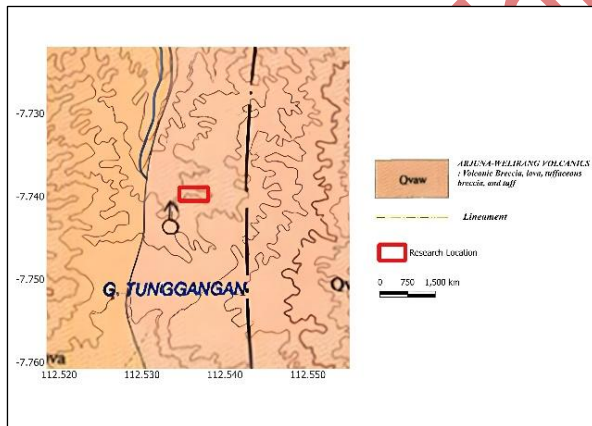


Fig 6. Geological map of the Cangar area (modified from Santosa & Suwarti, 1992)

3.2 Magnetic Data Acquisition System (MAGDAS)

The MAGDAS magnetometer is a highly sensitive fluxgate-type instrument capable of measuring even the smallest fluctuations in the geomagnetic field. It is equipped with three sensors mounted along three mutually perpendicular axes to measure the H, D, and Z components, where (H) represents the North–South horizontal geomagnetic component, (D) refers to the East–West horizontal component, and (Z) is the vertical geomagnetic component. The range or amplitude of diurnal geomagnetic variation is calculated by determining the difference between the maximum and minimum hourly mean values for each geomagnetic component (H, D, and Z) within a single day (Yumoto, 2006).

Because geomagnetic signals associated with seismic activity are extremely difficult to identify when observing raw data alone, several MATLAB scripts were utilized to assist in the analysis and processing of the dataset. One of the steps carried out involved examining how the geomagnetic field changes over the course of a day (diurnal variation). To achieve this, the magnitude of daily fluctuations in each magnetic field component (H, D, and Z) was calculated. This was done by finding the difference between the highest and lowest average values for each component within a 24-hour period. In other words, the diurnal geomagnetic variation range is obtained by subtracting the minimum value from the maximum value of each component throughout the day (E.M, A and T, 2018).

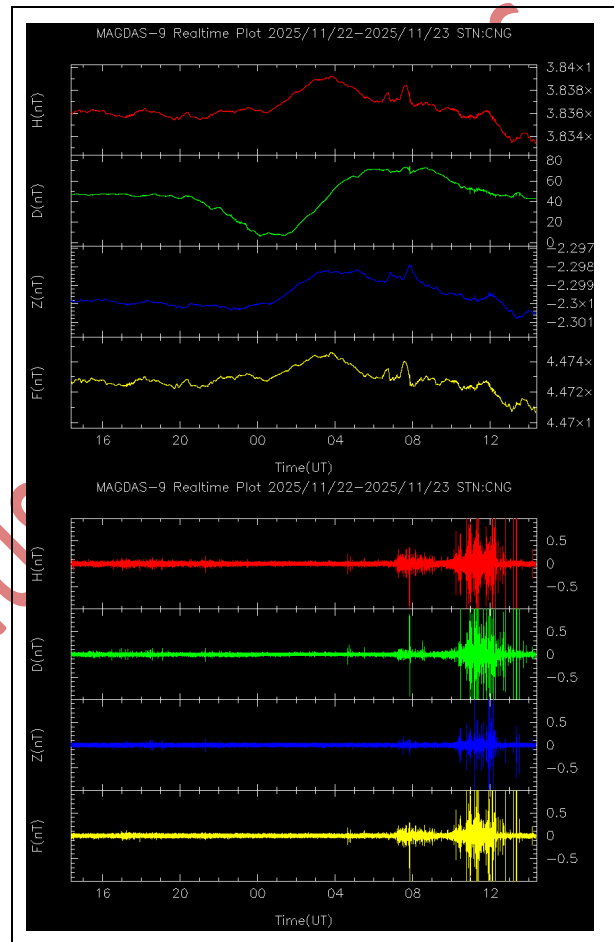


Fig 7. Display Magnetic Data Acquisition System (MAGDAS)

The MAGDAS plots illustrate the temporal variations of the geomagnetic field components (H, D, Z, and F) recorded during the period of 22–23 November 2025 in Universal Time (UT). In the first plot, the observed variations appear relatively smooth and gradual, representing normal diurnal geomagnetic fluctuations driven by ionospheric dynamics and the Earth’s daily activity. In contrast, the second plot exhibits abrupt and pronounced fluctuations across all components, particularly between 08:00–12:00 UT. Such sharp anomalies do not correspond to typical diurnal patterns and may indicate the presence of localized geomagnetic disturbances. These disturbances can arise from various sources, including physical activity near the station, electrical interference, instrumental vibrations, or geophysical phenomena. Given that the study area is situated near a volcanic or geothermal system, the intense perturbations recorded in the H, D, and Z components may reflect the instrument’s sensitivity to enhanced seismic activity, local vibrations, or subsurface fluid movement. Magnetometers are highly sensitive to minor ground motions,

causing such disturbances to be captured as magnetic anomalies. Therefore, the extreme fluctuations observed in the second plot suggest the occurrence of anomalous activity near the observation site. To confirm the underlying cause, these magnetic variations should be correlated with seismic data or field observations from the surrounding area.

4. Conclusions

Based on the conducted research, the geomagnetic observations are consistent with the increasing seismicity trend at the Arjuno–Welirang volcanic complex, indicating ongoing subsurface volcanic activity. The RTP and residual magnetic maps delineate high-anomaly zones ranging from 854 to 794.2 nT and low-anomaly zones from -753.6 to -1263 nT, which are associated with possible intrusive bodies, magma migration pathways, and hydrothermal alteration zones. These findings are consistent with the characteristics of the Qvaw Formation, which comprises highly magnetic lava and breccia units alongside low-magnetization altered tuff.

The analysis of MAGDAS data reveals significant geomagnetic fluctuations in the H, D, and Z components that show temporal correspondence with increased seismic activity, suggesting possible associations with subsurface magmatic processes, hydrothermal fluid movement, and local stress changes. To strengthen this interpretation, the geomagnetic observations were integrated with passive seismic data, which record naturally occurring ground vibrations generated by tectonic, volcanic, and hydrothermal processes without artificial energy sources. In volcanic and geothermal environments such as the Arjuno–Welirang volcanic complex, elevated seismic activity may coincide with localized geomagnetic disturbances caused by fracture reactivation, shallow volcanic tremors, or subsurface fluid migration. The temporal agreement between anomalous variations in the geomagnetic components and increased seismic signals therefore suggests that the recorded magnetic perturbations are more likely related to active subsurface geophysical processes near the observation area rather than solely external noise or instrumental disturbances. This study also demonstrates the potential application of MAGDAS data for local-scale volcanic and geothermal monitoring, extending its conventional use beyond global geomagnetic observations (Takla et al, 2018).

Overall, the results provide an enhanced understanding of subsurface conditions beneath the Arjuno–Welirang system. This integrated approach has strong potential to be utilized as an early indication tool for detecting volcanic unrest and to support the development of more effective local-scale monitoring and early warning systems in Batu City and surrounding areas.

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