

## Rock Magnetism and Geochemistry Analysis to Identify Volcanic Pleistocene Outcrop Deposits in Sangiran, Central Java, Indonesia

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### Abstract

Received:  
4 September 2025  
Accepted:  
17 March 2026  
Published:  
31 May 2026

Mineral analysis of ancient sediment in the Pleistocene Outcrop in Sangiran, Central Java is important for understanding the geological evolution and paleoenvironmental condition. This study aims to characterize the sedimentary layer through a combination of rock magnetic methods and geochemical analysis, focusing on analyzing geological conditions, types of minerals, magnetic susceptibility values, and magnetic properties. A total of 52 magnetic susceptibility data points were measured on each layer of the outcrop, which then six samples were taken to represent the overall value of the outcrop for further analysis. The results of sediment magnetic susceptibility measurements showed a value ranged between  $3.39 \times 10^{-3}$  SI to  $120.97 \times 10^{-3}$  SI. X-Ray Fluorescence characterization shows the presence of metal oxides (iron and aluminium), which are magnetic elements. The presence of the silicon element indicates that the sedimentary minerals originate from volcanic eruptions. X-Ray Diffractometer analysis identifies the presence of magnetic minerals in sediments such as hematite, magnetite, and almandine, as well as non magnetic minerals like cristobalite and anorthite. The Vibrating Sample Magnetometer analysis confirmed that the sediment had magnetic saturation values from 0.29 emu/g to 8.74 emu/g, magnetic remanence values of 0.03 emu/g to 0.80 emu/g, and coercivity field values from 0.03 emu/g to 0.71 kOe. This shows that all samples are multi-domain. Based on the overlapping sediment samples with different mineral, suggesting that the layers did not occur in a single period, and the crystallization of almandine exhibits an amorphous form with a slow cooling rate.

**Keywords:** Rock Magnetic; Geochemical analysis; Ancient sediment; Pleistocene; Indonesia

### 1. Introduction

The analysis of an outcrop is very important tool and useful in geological studies because of its ability to describe the process of rock formation on the Earth's surface, analogy to understand the subsurface structure, provide the geological history of the region, represent the geological structure and its material content (Head and Simmons, 2021). The formation of outcrops can be caused by several processes, including natural processes such as erosion, transportation by water and wind, even tectonic activity, as well as human-induced processes like mining and construction (Zeng et al., 2018). The

outcrops can be found in various forms on Earth's surface, such as mountains, valleys, cliffs and beaches. Outcrops have a significant scientific value, as they can provide direct information about the geological history of an area (Ghosh et al., 2018; Yates et al., 2019). Through the outcrop analysis, geologists can study rock formation processes (Menegoni et al., 2019; Xu et al., 2020), identify the types of minerals present (Slatt et al., 2018; Soto et al., 2020) and gain insight into the tectonic history that shaped the area (Zeng et al., 2018; Celestino et al., 2020).

A very popular and interesting outcrop site to be revealed is Sangiran site, which is located in Indonesia and has produced a considerable amount of fossils, especially the oldest ancient human fossils in Indonesia (Sémah et al., 2022; Widiyanto and Noerwidi, 2023; Puspaningrum et al., 2024). Previous researchers have stated that the Sangiran area is responsible for 50% of the fossils found in the region. However, in this study, the focus is concentrated on the outcrops which revealed in this area. Preliminary data from (Hyodo et al., 2011) and (Matsu'ura et al., 2020) are cited as the basis for the sampling ages and identified outcrops.

Research on minerals at Sangiran, conducted by Brasseur et al. (2015), showed a correlation between chrome, iron oxides and manganese, in addition to clay minerals, especially smectite and quartz fractions consisting of hematite, quartz, and magnetite, were also identified. According to the findings of Tomita et al. (1993), smectite can be identified as a mineral that resulting from the weathering of volcanic glass. Hematite is present in volcanic flows, although in limited quantities. As suggested by Smyth et al. (2008), quartz is formed from plinian eruptions, where material is ejected over considerable distances during volcanic eruptions. As pointed out by Jiang et al. (2018), magnetite is a mineral formed from iron-rich fluids produced by volcanic magma systems (Pilchin, 2011; Velasco et al., 2016). The discovery of various minerals in Sangiran provides evidence of the existence of magnetic materials resulting from volcanic eruptions, which can be detected through the rock magnetism method. The rock magnetism method is an approach that is often used to see variations and changes in the characteristics of magnetic minerals in soil (Karimi et al., 2011), sediments (Maher et al., 2009; Maher, 2011; Famera et al., 2013) and rocks (Li and Fu, 2019; Tang et al., 2021). One of the parameters assessed is magnetic susceptibility. Measurements using magnetic susceptibility can be done in a safe, expedient, easy, and non-destructive way (Legowo et al., 2023a).

The identification of minerals contained in a layer or rock, both the type and the forming elements, can be done through the material characterisation process. One of the material characterisations used is X-ray diffraction (XRD), which is used to ascertain the crystal structure of the mineral, thus facilitating its identification (Bijaksana et al., 2013; Tiwow et al., 2018; Putra et al., 2023a). Research conducted by (Bakruddin and Sembiring, 2019) regarding mineral identification in granite rocks at the South Aceh location using XRD, show the presence of quartz, anorthoclase, microcrystals, and sanidine minerals. Another study on XRD characterisation for mineral identification was conducted by Hiraga et al. (2002), which determined the mineral content of quartz and albite in schist rock crystals. The identification of elements and iron oxides contained in minerals is carried out using X-Ray Fluorescence (XRF). Research conducted by Zawadzki et al. (2020), Laha et al. (2022) and Mulyaningsih et al. (2022) on the identification of soil constituents using XRF shows that the dominant elements are iron (Fe), titanium (Ti), silicon (Si), calcium (Ca), and manganese (Mn). Mineral characterisation using XRD and XRF was also conducted by Legowo et al. (2021), who used fine sediments of the Bengawan Solo River as the object of research. In this study, magnetite was identified as the dominant mineral.

As no previous studies have been conducted on magnetic minerals in Sangiran, it will initially refer to minerals in the surrounding area as a starting point. As shown by Legowo et al. (2023b), research on magnetic minerals in the Solo Basin shows positive susceptibility values and the presence of ferromagnetic minerals. Given that Sangiran where is located within the Solo Basin, it can be postulated that ferromagnetic minerals are also present in Sangiran. Therefore, magnetic susceptibility measurements and comprehensive mineralogical analysis of the Sangiran outcrop can be carried out to

determine how much magnetic mineral content is present, which will indicate the presence of volcanic deposits. These findings are expected to provide important baseline data to support future geological and paleoenvironmental reconstructions in this area.

## 2. Location and Geological Setting

The Sangiran Formation is situated in the Sangiran area, located in Sragen Regency, Central Java. The Sangiran site is divided into several clusters, including Krikilan, Bukuran, Ngebung, Manyarejo, and Dayu. This research focuses on the Manyarejo cluster, which is the only cluster with volcanic material deposits and easily accessible outcrops. The research site shown in Fig. 1 is edited from Matsu'ura et al. (2020), focusing on the geological formation of the sampling point that is located at the following coordinates: S 07°26'49.50" and 110°51'44.51" E.

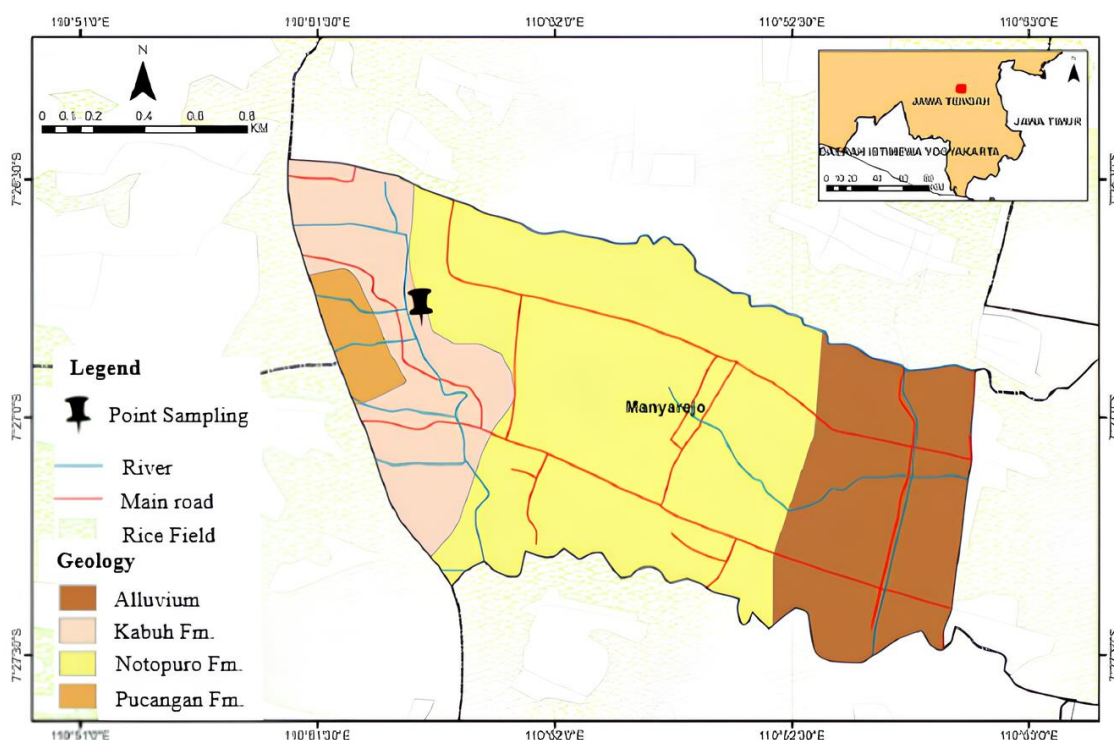


**Fig. 1.** Sampling location modified from (Matsu'ura et al., 2020)

The Sangiran Formation, located in the tectonically active western sector of the Java Plateau, lies near the boundary between the Indo-Australian and Eurasian plates. This area is influenced by high tectonic activity, so in this area various geological structures were produced, such as faults and folds. These faults and folds influenced the distribution of rock and sediment formations on the layer in an outcrop. The main faults, including the Baribis Fault and the Cimandiri Fault, may dominate the geological structure formation process in the Sangiran area (Septama et al., 2021; Winarto et al., 2022).

The presence of folds indicates that rock compression and deformation due to tectonic stresses are present there, which can produce an evolution of geological structures in Java. These provide valuable insights into the deformation history and geological activity that affecting the Sangiran Formation (Berghuis et al., 2021). The Sangiran Formation has experienced significant tectonic and volcanic activity, which has influenced the Formations in the research area as shown in Fig. 2. The tectonics and geological structure of the Sangiran Formation play a crucial role in understanding the geological and paleoecological evolution of the region. A comprehensive study of these structures not only provides

insights into the geological history of the area but also facilitates their application in resource exploration and scientific research.

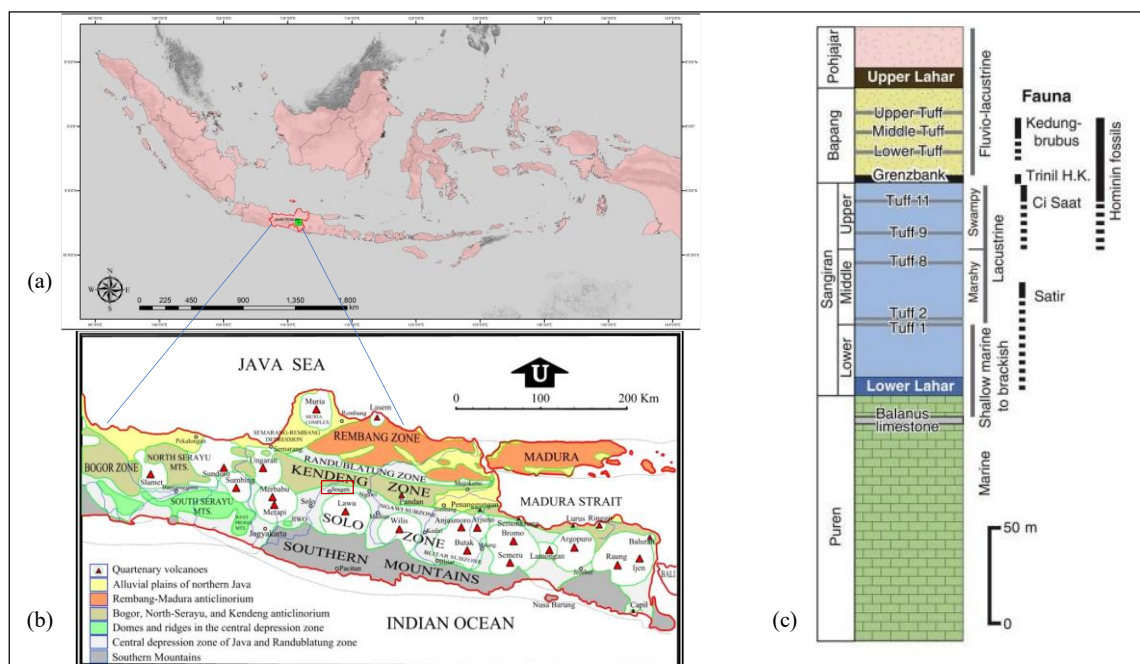


**Fig. 2.** Geological condition of Sangiran; a) is a physiographic map of Indonesia; b) is the Solo depression zone map, which is situated between two distinct zones, namely the Kendeng zone and the southern mountain zone that has been modified by Van Bemmelen, (1949); c) is the layer structure located in the Sangiran area (Matsu'ura et al., 2020)

The Sangiran Formation, located on Java Island, is a significant stratigraphic unit dating from approximately 1.5 million to 500 thousand years ago, spanning the early to Middle Pleistocene epoch. It is renowned for its rich fossil record, including early human fossils such as *Homo erectus*, as well as diverse Pleistocene fauna (e.g., ancient elephants, buffalo, and other mammals) and flora. These fossils provide insight into the Pleistocene ecosystem of the region, which was a mosaic of tropical forest, savanna, and grassland. In addition, the geological structure of our research site is shown in Fig. 3. This shows several geological categories by their physical properties.

One of the layers in the outcrop revealed fossils, in the S6 layer, which were preserved under plastic and protected by the "Sangiran Early Man Site" for archaeological research. This formation provides important evidence for understanding the paleoenvironment and early human history of the region. The rock formation of Sangiran is dominantly from volcanic and sedimentary deposits, such as layers of tuff and alluvium, which were deposited by volcanic activity and fluvial sedimentation processes. The depositional environment of the Sangiran Formation is characterized by a highly dynamic process with complex interactions between volcanic and fluvial processes. During these depositional periods, the area was located in an alluvial plain environment, influenced by the volcanic activity of the surrounding volcanoes.

### 3. Materials and Methods

#### 3.1. Collecting of Sample

In this research, all samples were collected from the outcrop on the Manyarejo cluster. Kappameter *KT6* is used to obtain the magnetic susceptibility values at each layer vertically. This measurement can estimate the presence of magnetic minerals contained within the sediments. A total of

19 layers were identified in the outcrop, which also contained material deposits consisting of pumice, gravel, clay, and volcanic ash. The total number of the collected samples was approximately 20, because there were two samples taken from the same layer in Code S4, which consists of different physical appearances of material in the same layer. A detailed description of the obtained samples can be found in Table 1.

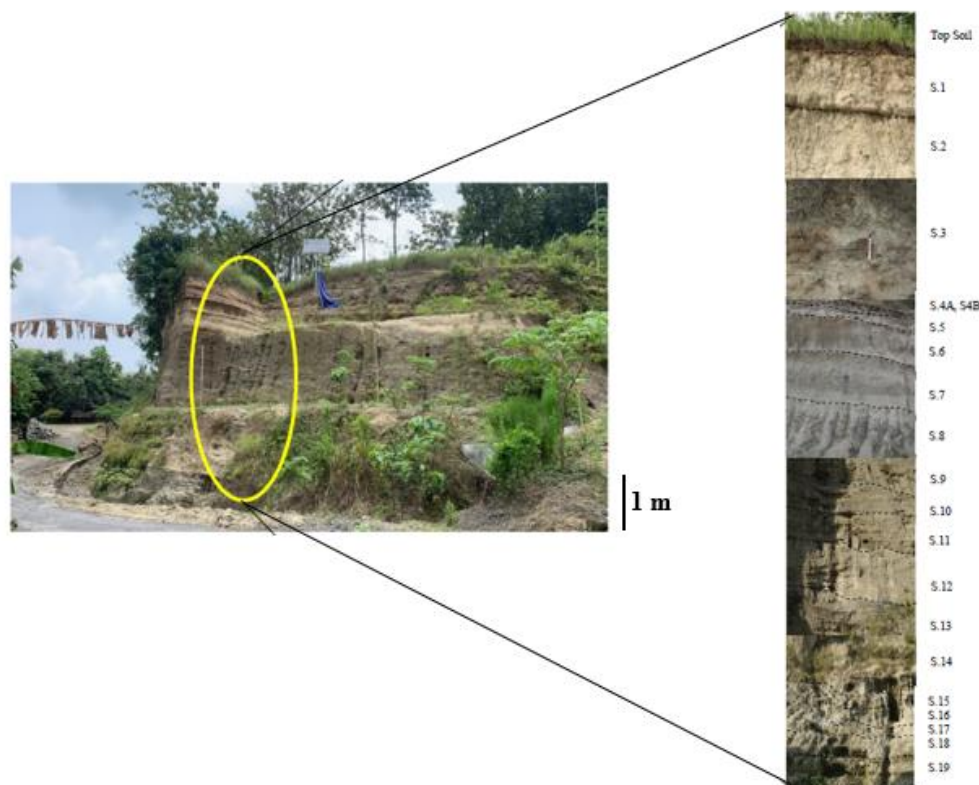


**Fig. 3.** The outcrops obtained in the Manyarejo cluster are presented herewith

**Table 1.** The description of the collected samples

| Code | Description                                                                                                                                                                                                                                                                                         |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| S6   | The layer is 2.40 m in thickness, shows a brownish colour, and is composed of ash. It contains very small pebbles (less than 5 mm), as well as a layer rich in silica (Si).                                                                                                                         |
| S7   | This layer is 2.90 m thick and brownish grey, showing almost the same consistency as layer S6. This is because layer S7 is in direct contact with the layer above it.                                                                                                                               |
| S9   | The layer in the area in question exhibits a hue that can be described as “slightly greyish brown.” It should be noted that this layer does not contain volcanic ash. However, chemical and physical weathering processes occur within this layer. The layer in question has a thickness of 0.63 m. |
| S10  | This layer has a thickness of 0.60 m and is characterised by a greyish brown colour, which distinguishes it from layer S9. The presence of pumice particles less than 2 mm in size within this layer suggests that this outcrop is the result of the accumulation of volcanic material.             |
| S18  | The layer in direct contact with the sedimentation process, with a thickness of 0.20 m, shows a distinct and clear sedimentation process. This layer contains material < 1 mm in size, indicating that the deposition process of this layer was caused by ancient river flow.                       |
| S19  | This 0.20 m-thick layer is composed of volcanic material, including pumice less than 3 millimetres in size, which shows a blackish-grey colour.                                                                                                                                                     |

The magnetic susceptibility data is used as the initial data point in the sampling process, which categorizes the samples into six main categories that represent the wide variety of samples obtained.

### 3.2. Analysis of Sample

Sample analyses were conducted using two analytical methods, rock magnetic analysis and geochemical analysis. Rock magnetism is a fundamental physical property that plays an important role in geological and geophysical research. It provides valuable insights into the Earth's geomagnetic history, rock formation processes, and paleoenvironmental conditions. Its ability to explain the magnetic properties of rocks, record geomagnetic history, and geological processes makes these methods important in this study. Geochemical analysis is used to determine the chemical composition and minerals of rocks. This analysis uses various analytical techniques to identify elements and minerals in geological samples, to understand rock formation, and evolution. In this study, chemical analysis are used to confirm the magnetic mineral content in the samples. Sand-sized samples (40 mesh) were prepared by washing with distilled water and dried for chemical analysis. XRF *PaNalytical X'Pert Pro* are used to test the magnetic content, then XRD *PaNalytical Minipal 4* to determine the type of minerals contained. VSM *Quantum Design PPMS VersaLab* was used to determine magnetic properties. XRD tests were conducted at the Mathematics and Natural Sciences Laboratory of Universitas Sebelas Maret, while XRF and VSM tests were conducted at the Integrated Laboratory of Universitas Negeri Malang.

## 4. Results

### 4.1. Magnetic Properties

#### 4.1.1. Magnetic susceptibility

In this study, the measured magnetic susceptibility values of the sediments are shown in Table 2. The results of the study show that each layer has a magnetic susceptibility value greater than  $10^{-3}$ , this indicating that each layer contains ferromagnetic material, based on the magnetic properties of the material. This classification is based on the findings of César de Mello et al. (2020), which state that materials with magnetic susceptibility values  $>10^{-7}$  SI are included in the ferromagnetic category. The presence of ferromagnetic materials indicates a high concentration of magnetic minerals in these layers. A higher magnetic susceptibility value indicates a greater abundance of magnetic elements, with a minimal presence of non-magnetic elements.

A review of the 20 samples revealed that six samples were representative of several samples taken. If the Sangiran sedimentary layer was formed from volcanic eruption deposits, as proposed by Hyodo et al. (2011) and Larick et al. (2001), a hypothesis emerges as the cause of the anomaly that occurs. The hypothesis, which posits differences in susceptibility values despite the proximity of the layers, suggests that the Sangiran sedimentary layers were formed during disparate volcanic periods. Alternatively, the deposits may consist of two distinct mineral types, exhibiting markedly contrasting magnetic characteristics despite a similar color. If the mineral type is the same, the discrepancy can be attributed to the ejecta mass, which originally contained a significant amount of magnetic minerals but has since undergone a reduction in mass.

As the mass of the sedimentary material increases, the magnetic susceptibility tends to rise. To ascertain the mineral composition of the six samples, a detailed characterization was conducted. The research conducted by Tütünsatar et al. (2023) at Golcuk Volcano (Isparta), Turkey, using magnetic susceptibility data, has confirmed that the igneous rock in question has a value of  $17 \times 10^{-3}$  SI to  $25 \times 10^{-3}$  SI. The result of the magnetic susceptibility value in this research ranges from  $3.39 \times 10^{-3}$  SI to  $120.97 \times 10^{-3}$  SI, which shows that the volcanic activity plays a role in the formation of these sediments.

Higher magnetic susceptibility values indicate that magnetic minerals are dominant in the formation of sediments in that layer.

**Table 2.** The data of magnetic susceptibility values

| Code | Magnetic susceptibility<br>( $\times 10^{-3}$ SI) | Description                                                                                                                                                               |
|------|---------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| S1   | 1.52                                              | The S1-S3 materials in question exhibit identical characteristics and colors.                                                                                             |
| S2   | 1.63                                              |                                                                                                                                                                           |
| S3   | 7.12                                              |                                                                                                                                                                           |
| S4A  | 5.54                                              | The cross-bedding layers in S4A and S4B were found to be contained within the same layer, thus resulting in the collection of two samples with disparate characteristics. |
| S4B  | 13.03                                             |                                                                                                                                                                           |
| S5   | 1.46                                              | S5-S8 layer with the same color but different materials                                                                                                                   |
| S6   | 3.39                                              |                                                                                                                                                                           |
| S7   | 35.63                                             |                                                                                                                                                                           |
| S8   | 38.90                                             |                                                                                                                                                                           |
| S9   | 8.19                                              | The stratigraphic sequence consists of S10-S13 layers of medium to small-sized gravel and pebbles.                                                                        |
| S10  | 46.80                                             |                                                                                                                                                                           |
| S11  | 18.12                                             |                                                                                                                                                                           |
| S12  | 1.17                                              |                                                                                                                                                                           |
| S13  | 5.19                                              |                                                                                                                                                                           |
| S14  | 25.72                                             | S14-S19 layer is composed of volcanic material. Its formation is the result of the deposition process occurring in slow-moving riverine environments.                     |
| S15  | 22.15                                             |                                                                                                                                                                           |
| S16  | 17.73                                             |                                                                                                                                                                           |
| S17  | 45.77                                             |                                                                                                                                                                           |
| S18  | 31.22                                             |                                                                                                                                                                           |
| S19  | 120.97                                            |                                                                                                                                                                           |

The highest value in sample S19 indicates the presence of volcanic activity rich in ferromagnetic minerals in this layer, so that its source can be traced. This layer is at the bottom, which shows that its formation is older than the layer above it, so it can trace volcanic activity at that time.

#### 4.1.2. Vibrating sample magnetometer (VSM)

The magnetic properties of the sediment samples have been determined through the use of a vibrating sample magnetometer. The results of the characterization of the sediment samples are presented in the form of a hysteresis curve, as shown in Fig. 4, illustrates the relationship between the magnetic field and magnetization, which is characterized by a narrow curve area. This indicates that the material requires minimal energy to magnetize, or it is easily magnetized. Consequently, this curve substantiates the presence of ferromagnetic minerals. Furthermore, this curve corroborates the susceptibility values obtained, exhibiting a high positive value, thereby confirming the presence of magnetic minerals at the research point.

Table 3 illustrates the magnetic properties of the samples, expressed in terms of remanent magnetization ( $M_r$ ), saturation magnetic ( $M_s$ ), and coercivity field ( $H_c$ ) values. The three values of magnetic properties exhibit considerable variation between samples.

The characterization of the six samples showed that samples S7, S10, and S19 exhibited very high  $M_s$  values, indicating strong magnetic properties. The range of  $M_s$  values for the entire sample is 0.29 to 8.74 emu/g. In addition, the  $M_r$  value is higher in samples S7, S10, and S19 than in the other three samples. The elevated  $M_r$  value also indicates that the magnetic properties of the three samples are

considerable. The  $H_c$  value of the entire sample set ranges from 0.03 to 0.71 KOe, exhibiting a notable contrast to the  $M_r$  value, which spans from 0.03 to 0.80 emu/g.

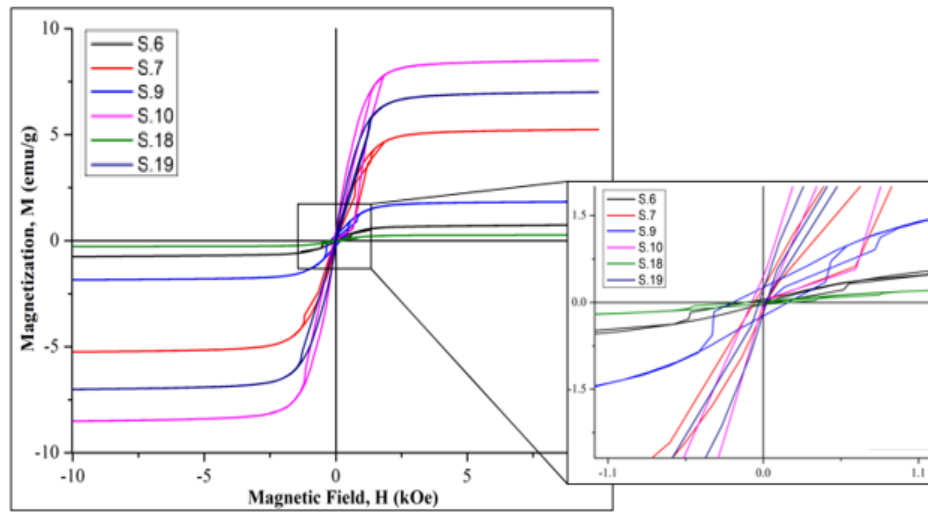


**Fig. 4.** The hysteresis curves illustrate the magnetic properties of the samples

**Table 3.** The values of saturation magnetism, remanent magnetism, the magnetic ratio, and the coercive field

| Code | $M_s$ (emu/g) | $M_r$ (emu/g) | $M_r/M_s$ | $H_c$ (KOe) |
|------|---------------|---------------|-----------|-------------|
| S6   | 0.95          | 0.05          | 0.05      | 0.10        |
| S7   | 5.41          | 0.81          | 0.15      | 0.05        |
| S9   | 1.98          | 0.54          | 0.27      | 0.20        |
| S10  | 8.74          | 0.23          | 0.03      | 0.71        |
| S18  | 0.29          | 0.03          | 0.10      | 0.16        |
| S19  | 7.23          | 0.20          | 0.03      | 0.03        |

The observed discrepancy in the  $H_c$  and  $M_r$  values can be attributed to the presence of minor elements that remain intermingled. The ease with which the material can be magnetized by the external field indicates that the entire sample contains a type of magnetic domain in the form of a multidomain structure. According to Kumar et al. (2020) and Yi et al. (2022), the type of magnetic domain present in the sample can be determined by calculating the  $M_r/M_s$  value. As shown in Table 3, the overall  $M_r/M_s$  value of the sample in this research is below 0.5, which categorizes it as a multidomain structure.

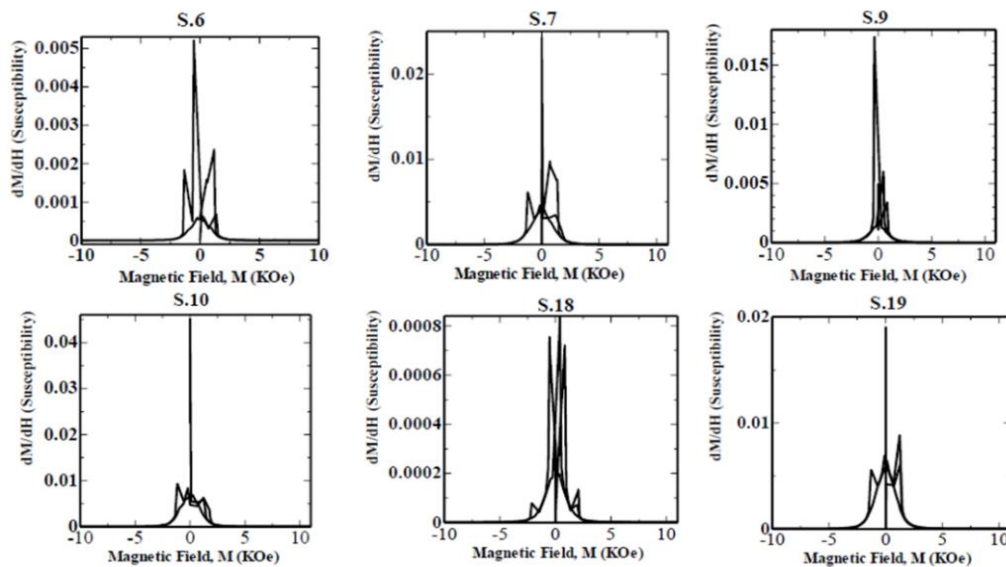


**Fig. 5.** A plot is presented between magnetic field and magnetic susceptibility values

Accordingly, Fig. 5 illustrates the correlation between magnetic field value and magnetic susceptibility value. The presence of multiple domains, as indicated by the graph, is evident through the emergence of a curve with two peaks, separated by a domain wall, which characterizes the type of multiple domains. The observation of a multi-domain magnetization mode suggests that the rock grains formed are of considerable size, a consequence of the abrupt cooling experienced during the rock formation process.

## 4.2. Geochemical Analysis

### 4.2.1. X-Ray fluorescence (XRF) analysis

The characterization technique employed to ascertain the dominant elements and oxides present in the Sangiran samples utilizes X-Ray Fluorescence (XRF). The elemental composition of the sediment samples is presented in Table 4.

**Table 4.** The elemental composition of each sample, as determined through X-ray fluorescence (XRF) analysis

| Element | The elemental composition is expressed in percentage form (%) |       |       |       |       |       | Average |
|---------|---------------------------------------------------------------|-------|-------|-------|-------|-------|---------|
|         | S6                                                            | S7    | S9    | S10   | S18   | S19   |         |
| Al      | 11.00                                                         | 10.00 | 12.00 | 9.40  | 9.70  | 9.50  | 10.27   |
| Si      | 39.20                                                         | 34.70 | 33.30 | 27.50 | 27.70 | 24.70 | 31.18   |
| K       | 1.40                                                          | 1.59  | 1.00  | 0.62  | 0.47  | 0.35  | 0.91    |
| Ca      | 12.00                                                         | 19.20 | 24.90 | 20.00 | 22.30 | 19.20 | 19.60   |
| Ti      | 1.81                                                          | 1.85  | 1.79  | 2.04  | 2.01  | 2.51  | 2.00    |
| Fe      | 31.70                                                         | 30.00 | 24.80 | 37.20 | 35.20 | 41.00 | 33.32   |
| Etc.    | 2.89                                                          | 2.66  | 2.21  | 3.24  | 2.62  | 2.74  | 2.73    |

As evidenced from Table 4, iron (Fe) and silica (Si) are the most prevalent elements. The iron (Fe) element content in the six samples exhibited a range of 24.80 to 41.00 %. The silicon (Si) element in the six samples exhibited a content range of 24.70 to 39.20%. The elevated levels of Fe and Si are a noteworthy finding. As stated by Legowo et al. (2023b), the Mount Lawu product exhibits a high percentage value of elemental content, specifically iron (Fe), at approximately 40%. Conversely, the elevated (Si) value observed in the six samples can be attributed to Mount Merapi. This conclusion is supported by the findings of Zulaikah (2019) which indicates that the pure (Si) value of Mount Merapi ranges between 40 and 50%.

As stated by Legowo et al. (2023b), the values of Fe and Si are inversely proportional. This was not found in our six samples, which showed almost balanced Fe and Si values. The differences in the eruption cycles of Mount Lawu and Mount Merapi cause the balance between these elements. The last eruption record of Mount Lawu is in 1885, and currently in a resting phase, which has the potential to cause an eruption in the future. This contrasts with Mount Merapi, that have an eruption cycle of 2-7 years. This phenomenon can be observed in the sedimentation process of the Kabuh Formation, where Mount Lawu releases volcanic material rich in Fe in with large quantities during one eruption. In addition, Mount Merapi releases volcanic material rich in Si at various intervals. Although the volume of this eruption is relatively limited, its periodic repetition during a cycle of 2-7 years has facilitated the accumulation of high Si elements, resulting in a balance between Fe and Si.

The Fe sedimentation process in the Kabuh Formation is the result of the geomorphological process of Mount Lawu, which is located in the central zone of Central Java. This zone is a depression area containing young volcanic deposits which is included in the Quaternary Volcanic Sequence, within the Kabuh Formation which is still present. In general, the Kabuh Formation resulted from the second

regional uplift episode of the Kendeng Mountain Range in the north and the Southern Mountain Range in the south, which were occurred approximately 400,000-900,000 years ago. During this period, eruptions from surrounding volcanoes facilitated the deposition of volcanic material in the Kabuh Formation. In addition to the Fe and Si elements, Ca is also present and has a high value because the Kabuh Formation was once a layer where living things lived. Therefore, over time, the contents that characterize the life of living things are found. Aluminium (Al) also has a high value and provides supporting evidence for the existence of magnetic minerals other than Fe. The significant correlation between Fe and Al content in the samples indicates the presence of distinctive characteristics of volcanic material. Mineralogically, this indicates the presence of Al substitution into the iron oxide structure, a characteristic of sediments resulting from rock weathering in the Central Java volcanic zone.

The largest elements in the sample are Fe and Si indicating that the possible minerals that could have formed are hematite ( $\text{Fe}_2\text{O}_3$ ), magnetite ( $\text{Fe}_3\text{O}_4$ ), and silica ( $\text{SiO}_2$ ). The discovery of these two elements through XRF analysis corroborates the mineral evidence from XRD characterization, indicating that the dominant Fe and Si are the result of volcanic eruptions. Silicon (Si) is a magma-forming element and the origin of all igneous rocks, and it is associated with Fe as the main volcanic ash element. The similarity of the XRD and XRF characterization results, which are dominated by iron (Fe) compounds, indicates that the type of magnetic material of the minerals found is ferromagnetic. While, the silica percentage of approximately 40-60% indicates that the origin rock minerals are basaltic-andesitic. Magma with a high silica content is known to trigger explosive eruptions because it makes the magma having a high viscosity, so that volcanic gases are trapped, causing the internal pressure to build up an extreme level until it finally explodes violently, shattering the magma into pyroclastic fragments. Explosive eruptions accompanied by ash, interspersed with lava flows, are a defining characteristic of stratovolcanoes (Heinrich et al., 2020; Gabellini et al., 2022). Both Lawu and Merapi have stratovolcanoes characteristic, so the Si element is dominant in each layer. But, in the S19 sample, the highest Fe content is present, which correlates with the magnetic susceptibility value, showing that Lawu's volcanic activity in the past, is dominant at this layer.

#### 4.2.2. X-Ray diffraction (XRD) analysis

The characterization technique employed in determining the mineralogical composition of the Sangiran collection relies on XRD. As a result of this characterization process, a diffraction pattern is generated, which contains several distinct peaks. The samples that have undergone characterization exhibit a range of peak patterns. Consequently, it is essential to correlate the peaks with the mineral database housed in (RUFF) to ascertain the mineralogical classification of the sample.

As illustrated in Fig. 6, five minerals were identified that exhibited similarities with the sample peak: cristobalite, anorthite, hematite, magnetite, and almandine. The main mineralogical composition is characterized by the presence of iron (Fe) and silicon (Si) which can be associated with volcanic eruption activity. The mineral cristobalite is found in cavities as felsic igneous rocks, while anorthite is a member of the plagioclase group. As the rock conditions become increasingly mafic, this group contributes to the formation of igneous rocks with a calcium-rich composition. Hematite is an accessory mineral in igneous rocks, especially lava, which forms under oxidizing conditions. Magnetite minerals often occur in mafic and ultramafic extrusive rocks as a result of differentiation during the magmatic stage. Almandine minerals are the result of volcanic activity, namely the crystallization of magma in andesite rocks (Cao et al., 2021).

The five mineral findings obtained through XRD analysis indicate that the characterized layers are predominantly composed of two distinct mineral types. The mineralogical composition of S6 is predominantly anorthite, while S7 is characterised by the presence of almandine and magnetite.

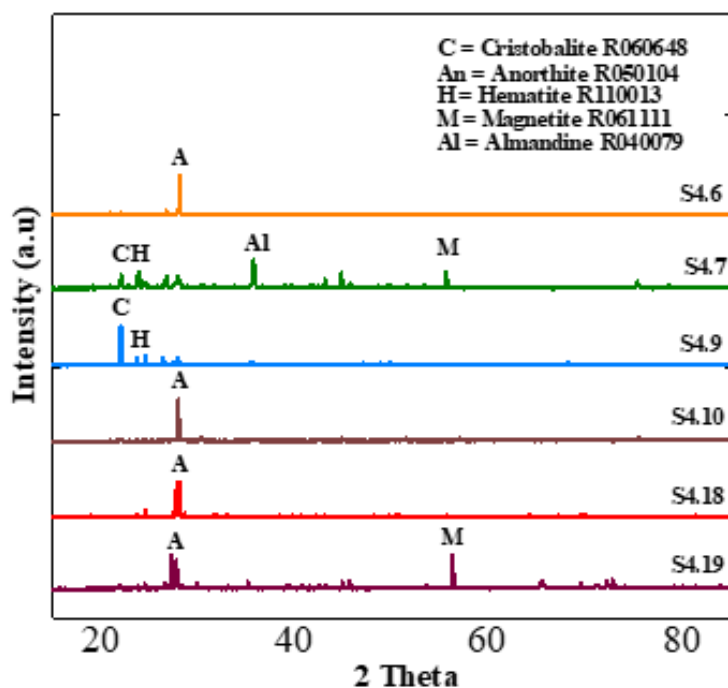


**Fig. 6.** A graphical representation of the material present in the sample is presented herewith

S9 is predominantly composed of cristobalite and hematite, whereas S10 is primarily constituted of anorthite. In contrast to S18 and S19, which both exhibit anorthite-dominant minerals. This is because both layers are derived from a single type of massive layer. The discrepancy in mineral types of the overlapping layers indicates that the morphological process of Sangiran was not a simultaneous occurrence but rather the result of multiple eruptions occurring over a specific timeline. The thickness of each layer is influenced by the ejected material that accumulates under the influence of gravity, thereby becoming the dominant layer-forming mineral. In sample S19, it is dominated by magnetite minerals, meaning that the formation of this layer is not influenced by high oxidation, in contrast to sample S9 which contain hematite, indicating the presence of an oxidation process in the formation of this layer. Both magnetite and hematite are present in sample S7, indicating the presence of various sedimentary processes in this layer. This is based on the fact that natural magnetic minerals are more stable in hematite, while magnetite is easily oxidized (Butler, 1992).

Table 5 illustrates the methodology employed to ascertain the crystal size, as delineated by the following equation:

$$D = \frac{K\lambda}{\beta \cos \theta}, \quad (1)$$

in this context, D represents the crystal size, K denotes to the crystal form factor 0.9–1,  $\lambda$  denotes to the X-ray wavelength,  $\beta$  signifies the full width at half maximum (FWHM) value rad, and  $\theta$  denotes the diffraction angle (degree).

**Table 5.** The crystal size of samples obtained from the field

| Code | Crystal size (nm) |
|------|-------------------|
| S6   | 73.66             |
| S7   | 84.50             |
| S9   | 66.72             |
| S10  | 98.66             |
| S18  | 172.85            |
| S19  | 97.55             |

The calculated crystal size distributions for the various samples exhibit minimal differences, except for sample S18. The observed increase in crystal size in sample S18 can be attributed to several factors, including the cooling rate, availability of space and nucleation, composition of magma and solution, pressure, and time. This crystal size is employed in the reinforcement of the VSM characterization outcomes about the magnetic domains of each sample. As stated by Nisticò et al. (2020), the crystal size of a material within the range of 20-80 nm is classified as single domain, while the multi-domain type encompasses a crystal size range of 80-100 nm. Therefore, it can be concluded that the crystal size of the entire sample falls within the aforementioned range and is therefore classified as multi-domain.

## 5. Discussion

The mineralogical findings within the sedimentary layer of the research site can be utilized to ascertain the morphological process that has occurred at the research site. The mineral findings, as determined through XRD, include anorthite, cristobalite, hematite, magnetite, and almandine. These findings exhibit similarities with those observed in minerals from Mount Merapi and Mount Lawu. A review of the similarities between these minerals is conducted through an examination of the relevant literature about the mineral structure of the two mountains. Anorthite minerals are identified as the parent material of volcanic material on Mount Merapi (Zulaikah, 2019). Additionally, cristobalite and magnetite have been identified in the volcanic material of Mount Lawu (Putra et al., 2023b). Additionally, the volcanic material of Mount Lawu is characterised by the presence of Fe oxides with high values, as evidenced by the analysis of sediment samples. Revealed the presence of cristobalite, a mineral, in Old Lawu Volcanic Complex. Magnetite, another mineral, was also identified in Old LVC (Nurcholis et al., 2019), although it constituted only 1-3% of the total minerals present in the mountain. Hematite was also found to be one of the minerals present on Mount Lawu (Das et al., 2020; Putra et al., 2023b).

Almandine is one of the minerals identified in the sample, with XRF results indicating (Ca) values of approximately 12-24%. In a study (Das et al., 2020) was investigated almandine in intrusive rocks in India. Ca-rich almandine underwent magma crystallization at temperatures between 950 and 1050°C was found. The amorphous form of almandine is a consequence of the slow cooling rate of the crystal, with the amorphous form in almandine being influenced by the absence of maximum intensity during the freezing process (Ctibor et al., 2020). A literature study was conducted to ascertain the correlation between magma crystallization in almandine and the volcanic activity of Mount Merapi and Mount Lawu. The magma crystallization observed at Mount Merapi occurred within a temperature range of 800°C, resulting from geochemical processes involving gases and minerals. The crystallization of magma in almandine, occurring within the temperature range observed in the crystallization of Mount Merapi and Mount Lawu, provides compelling evidence that the almandine found in the sample originated from the volcanic activity of the two mountains. Over time, this material has been transported by agents such as gravity, wind, and water to Sangiran, situated within the Solo depression zone.

## 6. Conclusions

The presented results indicate that the magnetic susceptibility value in the Manyarejo Cluster outcrop sediments exhibits a range of  $3.39 \times 10^{-3}$  SI to  $120.97 \times 10^{-3}$  SI. The sample is classified as ferromagnetic, exhibiting a slight paramagnetic bias. The minerals were identified in the samples following XRD and XRF characterization, included cristobalite, anorthite, hematite, magnetite, and almandine, which are dominated by Fe and Si elements. The five minerals were found to be originated from Mount Merapi and Mount Lawu. The magnetic properties of the sediment samples indicate that the five minerals are belong to the multi-domain type. The overlapping sediment samples exhibit

different mineral types, suggesting that the formation of layers did not occur in a single period. The crystallization of almandine exhibits an amorphous form with a slow cooling rate.

### Author contributions: CRediT

Muhammad Irfan Nawawi: data curation, formal analysis, writing-original draft; Shandiyano Putra: data curation, methodology; Nesya Adelia Putri Jauhari: data curation; Budi Legowo: methodology, funding acquisition, supervision; Agus Tri Hascaryo: methodology, validation; Wahyu Widiyanta: supervision; Budi Purnama: conceptualization, supervision, writing-review and editing.

### Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this study.

### Acknowledgments

This study was financially supported by Penelitian Fundamental (PF-UNS) Universitas Sebelas Maret Surakarta, contract number 194.2/UN27.22/PT.01.03/2024

### Funding sources

This work was supported by Universitas Sebelas Maret Surakarta, contract number 194.2/UN27.22/PT.01.03/2024 (Funding name: Budi Legowo).

### Data Availability

All data generated or analyzed during this study are included in this published article and/or its supplementary materials

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