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The Magnetic Properties of Indonesian Lake Sediment: A Case Study of a Tectonic Lake in South Sulawesi and Maar Lakes in East Java

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Abstract. Magnetic properties of sediments from two different environmental settings in Indonesia have been studied using rock magnetic methods and scanning electron microscopy (SEM). In the first setting, magnetic measurements were conducted on core sediments from two maar lakes in East Java (Lakes Lading and Bedali) that represent very confined environments where sediments are derived mainly from rocks and soils within the craters. In the second setting, similar measurements were obtained on core sediment from Lake Matano, a cryptodepression lake in tectonically active South Sulawesi where the area around the lake is dominated by highly magnetic lateritic soils. The results show that the predominant magnetic mineralogy in sediments from Lakes Lading, Bedali, as well as Matano is pseudo-single domain (PSD) magnetite (Fe_3O_4). Compared to that of Lake Matano, the maar lake sediments of Lakes Lading and Bedali have higher magnetic susceptibility as well as high intensity of ARM and SIRM. Variations in magnetic susceptibility in all core sediments are controlled mainly by the concentration of magnetic minerals. The homogeneity of magnetic minerals in these three lakes sediment provides an excellent setting for interpreting paleoclimatic signals as they will be recorded as anomalies of magnetic susceptibility.

Keywords: *lake sediment; maar lakes; tectonic lakes; magnetic minerals; paleoclimate.*

1 Introduction

Lake sediments are valuable natural archives of paleoenvironmental information, as each layer of the sediment can provide information about the environmental conditions at the time of deposition. This information can be stored as variations in the composition of pollen, organic matter, as well as magnetic minerals in each layer of sediment. Paleolimnological reconstructions of environmental change have expanded rapidly in recent years [1]; for instance, the history of human activity in Erhai valley, China has been studied through

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changes in pollen in lake sediment [2]. Correlation between the abundance of heavy metals, such as Pb, in sediments of Lake Ziegelsee, Germany, with the use of fossil fuels in the region has been demonstrated earlier [3]. Several studies also relate compositional changes in lake sediments to paleoclimatic variations [4], paleomagnetic field changes [5], as well as paleoecological [6], and environmental problems [7].

Indonesia has a high potential for paleolimnologic research as it has about 521 lakes with various origins, ranging from tectonic lakes, volcanic/ caldera lakes, maar lakes, to artificial lakes [8]. This variability in lakes in Indonesia is unique compared to that of other countries at high latitudes, whose many lakes were predominantly formed from glacial erosion or depositional processes [1]. A number of studies have been carried out in Indonesian lakes, ranging from investigations of general chemical and hydrobiological properties of lakes [8], to paleoclimatic studies. For examples, the morphometry, limnology, hydrology, sedimentology, and lithology of some maar lakes in East Java, Indonesia have been studied earlier [9,10]. Lakes in East Java were often selected for the study of paleoclimate because this region was the western boundary of area affected by the El Niño-Southern Oscillation (ENSO).

Despite having many lakes, lake-related research in Indonesia is still in its infancy. This is particularly true for research related to the magnetic properties of lake sediments and their applications. In many environments, the existence of magnetic minerals and their abundance in rock and sediment can reflect the environmental condition. The use of magnetic measurements (rock magnetic methods) in lake sediment studies is promising because they are simple, rapid, relatively inexpensive, and nondestructive [11,12] and have been proven to provide important paleoenvironmental information [13].

In this study, magnetic measurements were carried out on the sediments of maar lakes (Lakes Lading and Bedali, East Java) and a tectonic lake (Lake Matano) to obtain fundamental rock magnetic parameters, such as magnetic mineralogy, concentration, composition, distribution of grain size, and magnetic domain. Those measurements were supplemented by microscopic analyses to confirm the morphology and composition of extracted magnetic grains. These data allow us to determine the main sources of magnetic minerals to these lakes and also the predominant processes that might affect these properties. Moreover, we will discuss how the magnetic properties of maar lakes and tectonic might serve as proxy recorder of paleoclimatic changes.

2 Site Descriptions

Sediment samples in this research were taken at three lakes. The two lakes, Lakes Lading and Bedali, are situated southeast of Probolinggo in East Java, while Lake Matano is located near Malili in South Sulawesi (Figure 1). Lake Lading is located 4.5 km from the Lamongan crater while Lake Bedali is 8.4 km. The mean diameter of Lake Lading was 210 m while the lakes' maximum depth was 8.6 m depth. The crater's diameter was about 410 m with a depth to surface of the water about 75 m. The age of the lake is estimated to be at least some thousand years old [9]. Meanwhile, Lake Bedali has a mean diameter of 399 m and a maximum depth of 11 m. It has a crater diameter of about 1,060 m and a total depth of 162 m. Water level fluctuations are more than 2 m in both of these lakes [9]. In general, the Lamongan volcanic rocks are consist mainly of lava, ash to lappili tuff, lahars, and volcanic breccias [14,15].

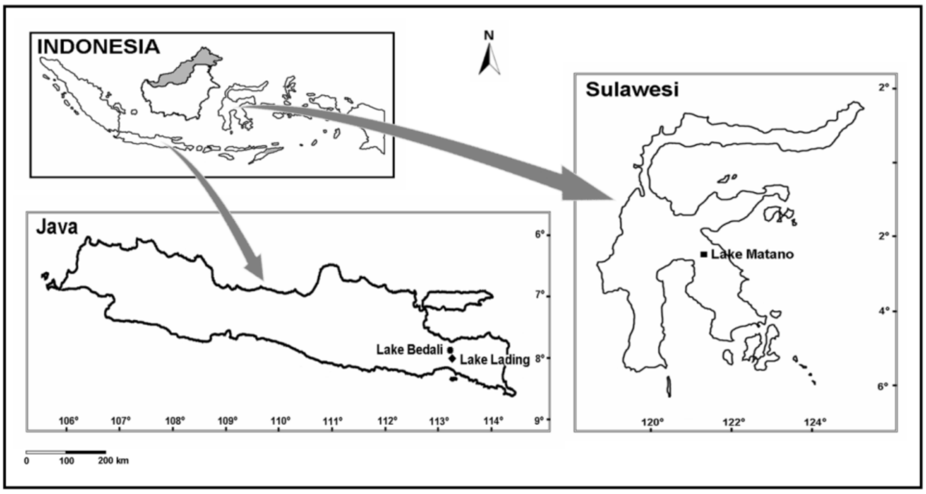


Figure 1 Map of sampling site in Indonesia showing the location of Lakes Lading, Bedali, and Matano.

Lake Matano is a part of the Malili Lakes System in South Sulawesi, Indonesia. This system consist of five lakes, with three larger lakes (Matano-Mahalona-Towuti) directly connected by rivers and two smaller satellite lakes, Lake Lontoa and Lake Masapi, isolated from the main chain of lakes. Matano has a surface area of 164 km^2 with maximum depth of 590 m. It is the deepest lake in Southeast Asia and the 8^{th} deepest lake in the world [16] with about 208 m existing in a cryptodepression (the deepest part is below sea level) [8].

Geologically, the nearby Matano Fault Zone is still active with tectonic movement of approximate 2 cm per year. Lake Matano is considered to be 1–4 million years old (*i.e.*, formed in the late Pliocene). All Malili lakes are surrounded by moderately steep to steep hills rising 200–700 m above the level of the lakes. Bathymetrically, Lake Matano resembles a near-to-perfect example of a graben lake, with very steep sides along the mid-northern and mid-southern sides reaching from an average 15° to 30° resulting in extensive almost vertical drop-off zones. Precipitation during the year is intense with almost 3 m of rainfall [17].

3 Sampling

The sediment core from Lake Matano was taken in 2007, while the sediment cores from Lakes Lading and Bedali were collected in 2008. See Table 1 for core information. The samples for this study were prepared by vertically extruding the cores in the field in 2 cm intervals for Lake Lading's core (LLS) and Lake Bedali's core (LBS) and in 1 cm intervals on Lake Matano's core (LMS). Extruded samples were sealed into polyethylene bags for transport to Institut Teknologi Bandung. In the laboratory, a sub-sample of each slice was packed into a standard oriented 10 ml cylindrical plastic holder. The sliced samples and the samples in plastic holders were stored in the refrigerator at a temperature of 4°C.

4 Methods

In this study, all samples were initially measured for the mass-specific magnetic susceptibility (χ) of the whole collection at two different frequencies, 0.47 kHz for low frequency magnetic susceptibility (χ_{LF}) and 4.7 kHz for high frequency magnetic susceptibility (χ_{HF}). Analyses were conducted with a Bartington MS2 susceptibility meter with MS2B dual frequency sensor. Each sample was measured five times to get the average value, with an air reading before and after each series for correction of drift. Percentage ratio of χ_{LF} - χ_{HF} to χ_{LF} gives the frequency-dependent susceptibility (χ_{FD}). This parameter can be used to detect superparamagnetic grains.

Anhysteretic remanent magnetization (ARM) on selected samples was acquired by exposing the samples to a peak alternating magnetic field of 80 mT with a constant field of 0.05 mT. ARM measurement started with sample demagnetization using an AF (alternating field) demagnetizer, then the ARM intensity was measured using a spinner magnetometer. The susceptibility of ARM (χ_{ARM}) was determined by dividing the ARM intensity by the size of the steady biasing field.

The acquisition of Isothermal Remanent Magnetization (IRM) was done by placing the selected samples in increasing magnetic fields of 100 mT, 300 mT, and 2.5 T using a pulse magnetizer 2G model 660. The IRM acquired at 2.5 T is referred to as the saturation isothermal remanent magnetization (SIRM). The IRM intensity was then measured using a spinner magnetometer.

To better constrain magnetic mineralogy and grain characteristics, selected samples were examined using a Scanning Electron Microscope (SEM) equipped with Backscattering Electron (BSE) mode to visually analyze iron-oxide grains as well as Energy Dispersive X-Ray (EDX) analysis to obtain their chemical composition. SEM measurements were carried out using Jeol JSM-6360LA at the Laboratory of Quaternary Geology of the Center for Geological Survey in Bandung. The SEM samples were magnetic grains extracted from representative samples from the upper section and the lower section of the cores from Lakes Bedali and Matano. The grains were extracted by mixing 5 grams of lake sediment with 200 ml of ethanol, then extracting the grains using a hand magnet. This process was repeated numerous times to ensure that the extracted grains are magnetic.

5 Results and Discussion

5.1 Variations of Magnetic Mineral Properties along the Cores

Figure 2 shows the profile of magnetic susceptibility in low frequency (χ_{LF}), ARM, and SIRM along the sediment core of Lakes Lading (LLS), Bedali (LBS), and Matano (LMS). The χ_{LF}, ARM, and SIRM share a similar pattern. The values of χ_{LF} on LLS increase from 112.8 to 309.0 × 10^{-8} m^3kg^{-1} with increasing depth in the sediment, with peaks at 12 cm and 30 cm depth. The ARM and SIRM (IRM on 2.5 Tesla) range from 79.38 to 121.81 × 10^{-6} Am^2kg^{-1} and 13.67 to 20.75 × 10^{-3} Am^2kg^{-1}, respectively, and show more subtle increases with depth with peaks in both ARM and SIRM at 12 cm depth.

The χ_{LF} profile from LBS can be divided into two magnetically distinct zones. The upper sections of the sediment core, from the surface to 18 cm depth, are characterized by increasing χ_{LF}, while the lower section from 18 to 30 cm has a relative steady value. χ_{LF} values in LBS range from 80 to 223.7 × 10^{-8} m^3kg^{-1}. ARM intensity range between 46.54 and 132.04 × $10^{-6}Am^2kg^{-1}$ and also shows generally increasing values with depth, while SIRM ranges from 6.57 to 20.06 × 10^{-3} Am^2kg^{-1} and increases strongly with depth.

Similar to LBS, the LMS profile of χ_{LF} also show two magnetically distinct zones with low χ_{LF} values of 78.8 × 10^{-8} m^3kg^{-1} at the surface rising to 247.1 ×

10^{-8} m^3kg^{-1} toward the base of the core. Small declines in susceptibility were recorded at 22 cm, 27 cm, and 52 cm depth. The ARM as well as SIRM also has a similar profile to χ_{LF}, although the down-core increases are smaller. The ARM intensity varies from 50.75 to 87.81 × 10^{-6} Am^2kg^{-1} while SIRM varies from 4.65 to 9.52 × 10^{-3} Am^2kg^{-1}.

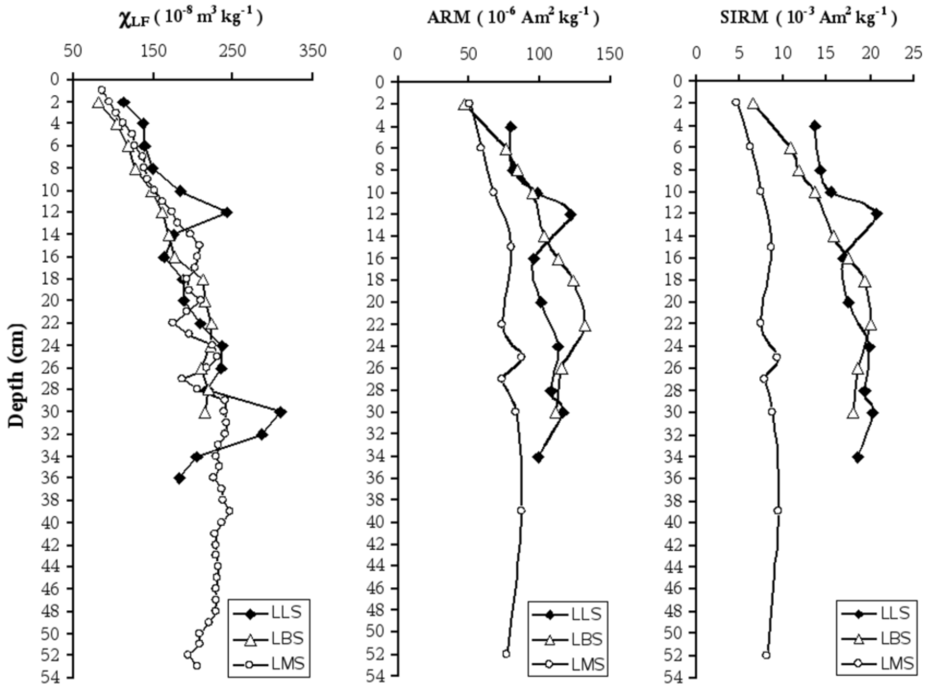


Figure 2 Variation of χ_{LF}, ARM, and SIRM versus depth for cores from Lakes Lading, Bedali, and Matano.

Isothermal remanent magnetization (IRM) measured on selected samples at 100 mT, 300 mT, and 2500 mT also shows interesting variations. The ratio of IRM_{300mT} to IRM_{2500mT} (SIRM), termed the S-ratio [18], can be used to infer the dominant magnetic mineral present and, in particular, to distinguish between magnetite and hematite. This differentiation is possible because the ferrimagnetic mineral (*i.e.* magnetite) will saturate at a lower field (around 300 mT) than the canted antiferromagnetic mineral (*i.e.* hematite). In our samples, the S-ratio of LLS, LBS, as well as LMS was more than 95%, indicating a dominant mineralogy of magnetite throughout the sediments (Figure 3).

The level of magnetic stability associated with magnetic domains can be approximated by an ARM acquisition curve or ARM intensity decay curve. Figure 4 shows the ARM intensity decay curves for sediments from all cores (LLS, LBS, and LMS). The normalized ARM decay curves for the three cores are very similar, suggesting similar domain state. The prediction of the domain state could also be inferred from the values of the median destructive field (MDF) in the normalized ARM decay curves, where MDF is the value of demagnetizing field needed to reduce the initial ARM by half. In this study, we estimated the MDF value by determining a sixth order polynomial equation for the ARM decay curve and solving for the MDF. The MDF for the representative LLS sample is 21.76 mT, while that for LBS and LMS are respectively 20.21 mT and 22.64 mT, indicating broadly similar magnetic stabilities.

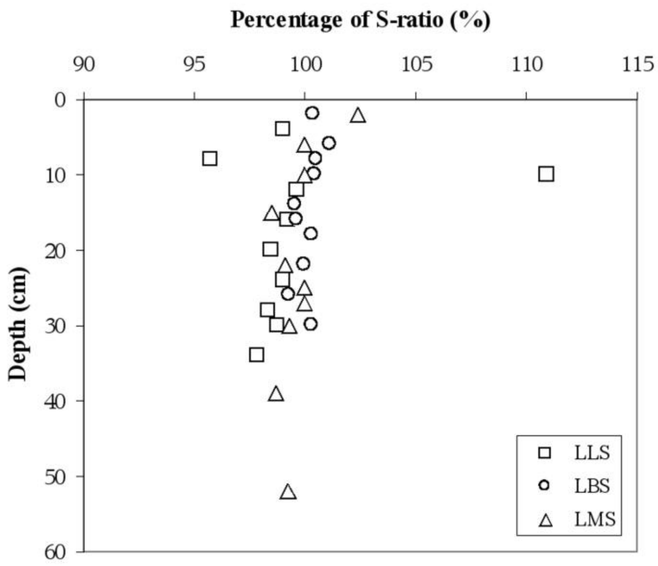


Figure 3 Scattergram of S-ratio showing that magnetite is the predominant magnetic mineral in LLS, LBS and LMS.

Plots of χ_{FD} values for each lake are given in Figure 5. Variations in χ_{FD} in LLS are within the range of 3.1 to 4.7%, while the range for LBS and LMS are 4.3 to 7.5% and 6.8 to 9.2%, respectively. In general, the LMS has a relatively higher value of χ_{FD}, followed by LBS, while that of LLS is the smaller of the cores. The mean value of χ_{FD} at LBS is 5.47%, significantly higher than that of a soil sample (STB-1) taken near the lake, with χ_{FD} of only 1.38%. Meanwhile, the mean value of χ_{FD} at LMS (8.09%) is very similar to that of the nearby soil

(7.12% for soil sample STM-2 and 9.63 for soil sample STM-1). The mean values of SIRM, ARM, and χ_{FD} in this study are given in Table 1.

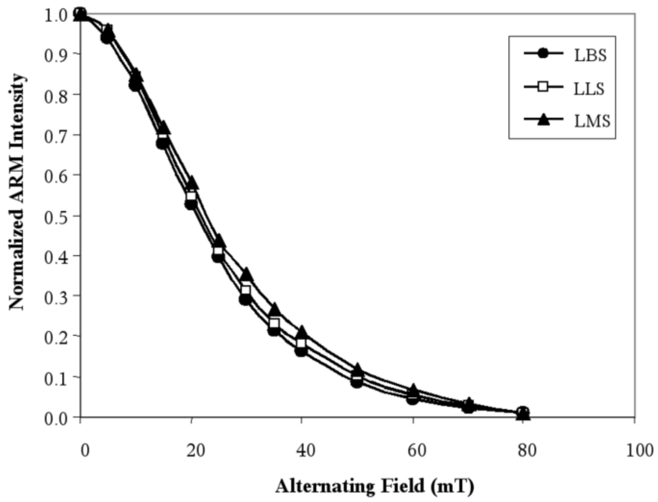


Figure 4 ARM decay curves for cores of LLS, LBS, and LMS.

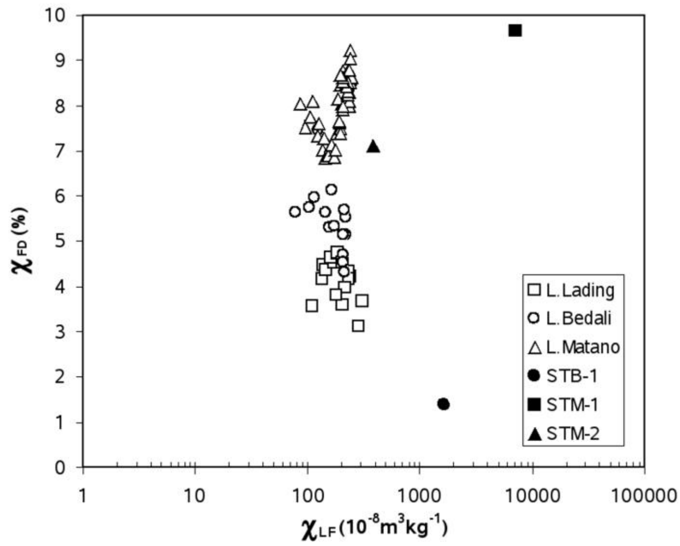


Figure 5 The scattergram of χ_{FD} -vs- χ_{LF} showing that different clusters for sediment and soil samples.

Table 1 Core Information and Selected Magnetic Parameters.

Sites	Position	Water Depth (m)	Length of Core (cm)	Mean ARM ($10^{-3}Am^2kg^{-1}$)	Mean SIRM ($10^{-3}Am^2kg^{-1}$)	Mean χ_{FD} (%)
Lading	S 8 deg 2.514' E 113 deg 18.751'	8.6	36	101.38	17.67	4.17
Bedali	S 7 deg 57.047' E 113 deg 16.242'	10.3	30	100.16	15.21	5.47
Matano	S 2 deg 31.478' E 121 deg 24.853'	500.0	53	74.17	7.84	8.09

5.2 Survey by Scanning Electron Microscopy

Additional information about magnetic mineralogy and grain size were obtained from scanning electron microscopy (SEM) analyses of selected samples. There are four investigated samples: two from Lakes Bedali and another two from Lake Matano. The two samples from Bedali represent the upper section (8-10 cm) and the lower section (24-26 cm) of the core sediments. Similarly, the samples from Lake Matano also represent the upper section (10-12 cm) and the lower section (46-48 cm) of the core sediments. SEM images of these selected samples are shown in Figures 6.

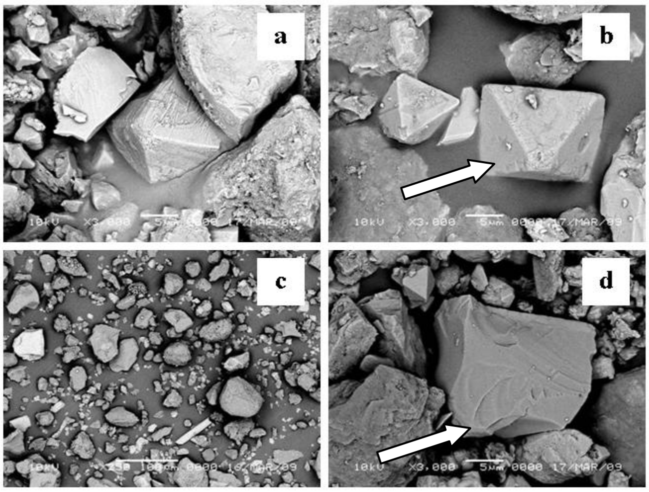
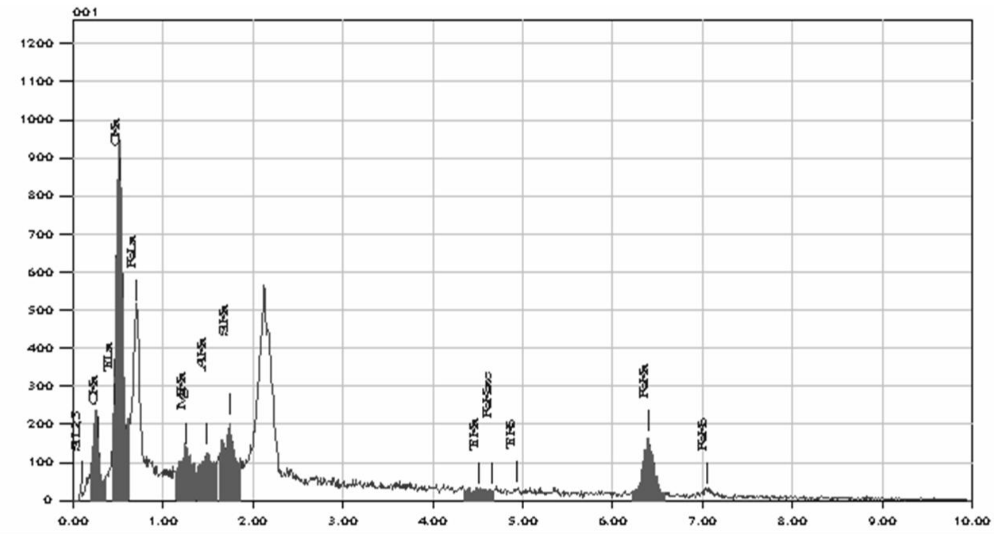


Figure 6 Typical magnetic mineral grains from Lake Bedali (a & b) and Lake Matano (c & d). (a) Detrital magnetic grains with sharp edges, originated from weathered igneous rocks in the volcanic area. (b) Octahedral magnetite with cracks in all parts of the surface (c) BSE image showing the domination of rounded grains; brighter grains indicate higher Fe content (d) A grain with quite significant concentrations of FeO and Chromite (Cr_2O_3).

In almost all samples, the morphology of magnetic grains is predominantly tetrahedral dipyramids or octahedral crystals, which has been recognized as titanomagnetite [19], or magnetite [20]. EDX analyses of selected magnetic grain show high content of FeO and small but variable concentrations of TiO, suggesting largely magnetite or Ti-poor titanomagnetite (Figure 7). The results show that some of the magnetic mineral grains are partially clay-coated, as indicated by the presence of Al, Si, Mg, and other elements in or on the magnetic grains.



Element	(keV)	mass%	Error%	At%	Compound		mass%	Cation	K
C K	0.277	5.94	0.07	27.11	C	5.94	0.00	15.9979	
O		23.02							
Mg K	1.253	1.04	0.31	2.34	MgO	1.72	0.71	4.4683	
Al K	1.486	0.90	0.37	0.92	Al2O3	1.70	0.56	4.4582	
Si K	1.739	1.72	0.45	3.35	SiO2	3.67	1.02	9.8296	
Ti K *	4.508	0.72	1.31	0.83	TiO2	1.20	0.25	4.5067	
Fe K	6.398	66.67	3.88	65.46	FeO	85.77	19.91	393.6757	
Total		100.00		100.00		100.00	22.45		

Figure 7 EDX analyses of selected magnetic grain on Lake Matano show high content of FeO and small concentrations of TiO, suggesting largely magnetite or Ti-poor titanomagnetite.

In upper section of core sediment of Lake Bedali, the magnetic grains have sharp edges indicating short pathways of transport, compatible with the small crater rim of this lake. These grains are very likely to be magnetite or Ti-poor titanomagnetite that originated from detrital particles around the crater. Similar to the upper section, the lower section of core sediment of Lake Bedali is also dominated by magnetite grains. However, the magnetic grains seem to be cracked or even destroyed in certain parts. In this section, a pure carbon particle (C 100%) that almost certainly charred terrestrial material (*i.e.* charcoal) was also identified.

The morphology of magnetic minerals from the upper section of Lake Matano is dominated by grains with rounded edges, indicating fluvial transport, but similar to Lake Bedali, octahedral crystals were also found quite a lot in this sequence. Based on EDX analysis, most of the magnetic grains in the lower section have high FeO content and low TiO content. In the lower section, a grain with quite significant concentrations of Chromite (Cr_2O_3) was also identified. This corresponds to the soils around Lake Matano that contain quite a lot of Cr. On the hand, the presences of Cr in lake sediment mineral could also possibly occur from authigenic or endogenic processes [21].

5.3 Discussion

Rock magnetic investigations of Indonesian lakes sediment using the S-ratio demonstrates that the mineralogy of sediment from Lakes Lading, Bedali, and Matano is relatively dominated by similar magnetic minerals, *i.e.*, magnetite (Fe_3O_4). This finding is confirmed by the range of χ_{LF} values of whole samples. The χ_{LF} values of more than 10 x 10^{-8} m^3 kg^{-1} indicate the predominance of ferrimagnetic minerals [22]. χ_{LF} values of our measured sediment equal or greatly exceed these, indicating that the magnetic properties of these lakes' sediments are dominated by ferrimagnetic minerals such as magnetite or maghemite. This interpretation is also in accord with SEM observations and EDX analyses showing the abundance of octahedral grains enriched in FeO.

However, the results of EDX analysis on the selected magnetic grains also showed that magnetite in the maar lake (Lake Bedali) tend to contain Ti while in Matano grains are almost free of Ti. This suggests that the magnetic minerals in Lake Bedali originate primarily from detrital titanomagnetite derived from the catchment area (surrounding crater), which is dominated by volcanic rock and tephra. The morphology of the grains confirms their transport pathway, in that the grains with sharp edges from Lake Bedali indicate the short transport distance from their source while the rounded grains on Lake Matano indicate longer alluvial transport pathway in this much larger lake and catchment area.

To estimate the magnetic grain size for grain size distributions dominated by magnetite, a scatter plot of volume specific ARM susceptibility versus low frequency susceptibility, often referred to informally as King's plot [11], estimates a grain size distribution of the mineral within the sediments [23]. The King's plot of LLS, LBS, and LMS is shown in Figure 8. Changes in slope in this plot indicate changes in magnetic grain size, while changes along a line of constant slope indicate changes in the concentration of magnetic minerals. It seems that the magnetic grains in all cores show small variations in grain-size, ranging from around 1 μm to about 5 μm. The graph also shows that magnetic grains from LMS are larger than that from LLS, and the grains from LLS are larger than that from LBS.

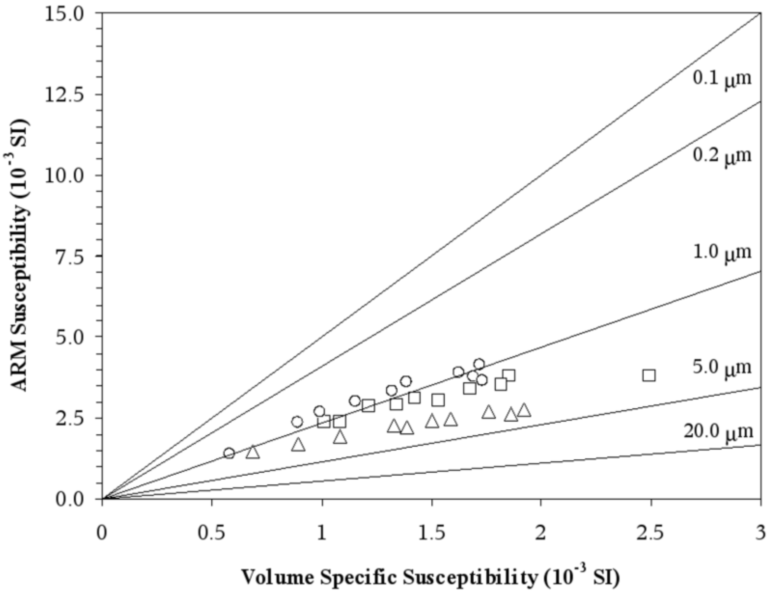


Figure 8 Estimation of magnetite grains size using King's plot (□ : LLS, O: LBS, Δ: LMS).

In contrast, the mean value of χ_{FD} shows that magnetic grains from Lake Matano also have higher superparamagnetic (SP) content compared to Lakes Lading and Bedali. The value of χ_{FD} of 2% to 10% shows that the magnetic mineral grains are a mixture between the fine, SP grains and coarser grains [22]. The similar value of χ_{FD} in sediment of Lake Matano and in adjacent soils (STM-1, STM-2) suggests that the SP grains in this lake originated from soils around the lake (Figure 5). Furthermore, χ_{FD} can also reflect the SP mineral grain size. Assuming, based on our results, that the dominant magnetic mineral is magnetite, the SP grain size can be estimated at 0.025 – 0.035 μm [22, 23]. The value of 7.5% < χ_{FD} < 9.2 can also be associated with very-fine grain particles, 0.0125 – 0.015 μm.

As the predominant magnetic mineral is magnetite, the magnetic domain can be inferred from a plot developed earlier [24]. Based on the MDF value for each lakes' sediments, it is clear that the magnetic domain of these grains is pseudo-single domain (PSD). Magnetic domain can also be identified based on the grain size distribution, because domain state depends on magnetic mineral grain size. The size distribution of magnetite grains shown in Figure 7 can be classified as PSD [13], confirming the results of our MDF analysis. Conversely, the MDF value can be used to estimate the magnetite grain size. As the effects of AF demagnetization for ARM play a similar role to effect of temperature for TRM [24], we can use ARM as an analogue to TRM. Based on the ARM decay curves (Figure 4), the value of MDF of LLS, LBS, and LMS is associated with grain size around to 1 μm. This result in agreement with the results obtained using the King plot.

Based on evidence that there are no major variations in either magnetic mineralogy or grain size, it is very likely that the susceptibility variations in Lakes Lading, Bedali, and Matano are basically controlled by concentration or abundance of magnetic minerals. This is also supported by a good correlation between the concentration dependent parameters such as χ_{LF}, ARM, and SIRM. This correlation is expected in samples with high concentration of ferrimagnetic. While increasing values of magnetic susceptibility with depth in the upper sections of the sediments in each lake, followed by a rather stable value at greater depth, suggests that the variation of magnetic susceptibility in surficial sediments in each core is related to sediment compaction, smaller scale variations as well as variations in deeper sediment cores could be interpreted to reflect environmental changes.

The SIRM value can also be used as an estimate of the concentration of magnetic minerals in the sample [18]. Higher intensity of SIRM means higher concentration of magnetic minerals, and vice versa. SIRM values are correlated well with χ_{LF}, and indicate that the concentration of magnetic minerals in maar lakes (Lakes Bedali and Lading) is generally higher than in the tectonic lake (Lake Matano).

Homogeneity of magnetic minerals in the three sites could support the utilization of rock magnetic parameters as proxy indicators of paleoclimate. Thus, below the zone of sediment compaction, paleoclimatic variation should be reflected by the variation of magnetic mineral abundance in these lakes' sediments. Magnetic susceptibility could be used as the easiest, cheapest, and most non-destructive methods for this purpose. The process of erosion usually occurs in the rainy season, producing more eroded materials that are transported to the lakes [11]. Thus a period with predominantly longer rainy seasons will have higher susceptibility values compared to a period of prolonged drought. For the existing cores, due to the effects of compaction possible climatic variations could be distinguished only as small peaks at depth of 12 cm and 30 cm at Lake Lading. It has been shown that variations in magnetic susceptibility in the maar lake Klindungan in Eastern Java correspond to the SOI (Southern Oscillation Index) [25], with higher susceptibility during wet, La Niña years. Therefore, the peaks on magnetic susceptibility profile of Lake Lading might be associated to climatic event during period of higher erosion on the catchments area or longer rainy season. More broadly, our findings confirm the process underlying this correlation, and show that these magnetic tools should be more broadly applicable to lake sediments in other maars and in large tectonic basins.

Assuming that the peaks in magnetic susceptibility in Lake Lading represent precipitation anomalies, it is curious that these events did not cause magnetic susceptibility changes in Lake Bedali sediments, as the two lakes are located quite close to each other. However, radiocarbon dating of sediment cores from Lakes Lading and Bedali have shown that sediments accumulate nearly 5 times more quickly in Lake Bedali than in Lake Lading [26]. It seems likely that our cores from Lake Bedali do not extend back far enough in time to record the precipitation changes indicated by the susceptibility variations in Lading.

On the other hand, there are several limitations to deriving clear interpretations about climatic events on these sites. Firstly, the sediments in these lakes are very magnetic. Any climatic signals could therefore be masked by the high background concentrations of magnetic signals. More detailed magnetic studies are required to delineate the climatic influences on magnetic signals from the natural ones. Secondly, the sediment cores examined in this study are relatively short (36 cm for Lake Lading, 30 cm for Lake Bedali, and 53 cm for Lake Matano), so the amplitude of climatic events recorded by these cores is small relative to the long-term climate changes in the region. Thirdly, there is a need to determine the absolute ages of these cores so that the presence or the absence of climatic events could be verified. Lastly, although there are no clear ash layers in these sediment cores, inputs of volcanic ash from air fall could increase sediment magnetic susceptibility and mimic the signals of positive rainfall events. Future work will address these issues through sediment dating, analysis of the magnetic properties of ash, and analysis of longer cores.

6 Conclusion

After magnetic measurement and analyses of sediment cores from Lakes Lading, Bedali, and Matano, complimented by SEM survey, the following conclusions can be drawn:

The predominant magnetic mineral in sediment from Lakes Lading, Bedali, and Matano is pseudo-single domain magnetite (Fe_3O_4). EDX analysis on selected grains shows that generally the magnetite both from maar lakes and from tectonic lakes has little TiO, although titanomagnetite is more abundant in Lake Bedali than Matano.

The main source of magnetic minerals to Lakes Lading, Bedali, and Matano is erosion of rocks and soils around the lakes. This is shown by the shape of magnetic grains, the similarity of χ_{FD} value between the sediment and adjacent soils of Lake Matano, and the correspondence between grain shape and length of transport path (euhedral in Lake Bedali, rounded grains in Lake Matano) in these lakes.

The sediment from maar lakes is more magnetic than the sediment from the tectonic lake. The values of magnetic susceptibility and artificial magnetic remanence on sediment of Lakes Lading and Bedali are relatively higher than that of Lake Matano. This likely reflects the proximity of these lakes to sources of highly magnetic volcanic rock and tephra relative to Matano.

Variations of susceptibility in Lakes Lading, Bedali, and Matano are controlled by the concentration of magnetic minerals. The magnetic susceptibility profile on Lakes Bedali and Matano shows an increasing trend with depth in the upper section and a rather stable in the lower sections, suggesting the accumulation of magnetic minerals during sediment compaction.

Climatic events should be recorded as variation in magnetic susceptibility values in these lakes' sediment. The magnetic susceptibility peaks in the profile from Lake Lading probably correspond to climatic events, such as prolonged rain seasons, that cause higher erosion in the catchments area.

The magnetic properties, especially magnetic susceptibility, of sediments from Lakes Lading, Bedali, and Matano can be used as proxy recorders of paleoclimate. Homogeneity of magnetic minerals in the three lakes sediment would allow that the paleoclimate proxy be based on variation of their magnetic susceptibility.

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