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Environmental assessment of lake sediments using magnetic susceptibility and hysteresis parameters: A case study of Lake Tondano, Indonesia

Vistarani Arini Tiwow[1*], Meytij Jeanne Rampe[2], Ishak Pawarangan[1], Dolfie Paulus Pandara[3], Muhammad Arsyad[4], Sayenne Givenshe Pungus[1], Gita Gratia Patris Nangka[1]

[1] Department of Physics, Universitas Negeri Manado, Jl. Kampus Unima 95618 Tondano, North Sulawesi, Indonesia
[2] Department of Chemistry, Universitas Negeri Manado, Jl. Kampus Unima 95618 Tondano, North Sulawesi, Indonesia
[3] Department of Physics, Universitas Sam Ratulangi, Bahu, Malalayang, 95115 Manado, North Sulawesi, Indonesia
[4] Department of Physics, Universitas Negeri Makassar, Kampus UNM Parangtambung Jl. Daeng Tata 90224 Makassar, South Sulawesi, Indonesia
* Corresponding author's e-mail: vistaranitiwow@unima.ac.id

ABSTRACT

Lake Tondano is experiencing increasing environmental pressures from erosion, sedimentation, and land-use changes within its catchment area. However, information on the spatial variability of sediment magnetic properties remains limited. This study aimed to characterize the magnetic properties of Lake Tondano sediments using environmental magnetic parameters and to evaluate their spatial distribution across the lake. Surface sediment samples were collected from 30 locations and analyzed for low-frequency magnetic susceptibility (χ_{LF}), frequency-dependent susceptibility (χ_{FD}%), and hysteresis parameters (Ms, Mrs, Hc, and Hcr). The magnetic susceptibility data were further processed using spatial interpolation to examine the distribution of magnetic properties. The χ_{LF} values exhibit considerable spatial variability, indicating differences in magnetic mineral concentrations among sampling locations. Relatively high χ_{LF} values were observed in the western and central-western parts of the lake, suggesting enhanced accumulation of magnetic minerals in these areas. The generally low χ_{FD}% values (<5%) suggest a predominance of coarse-grained magnetic particles and a limited contribution from superparamagnetic grains. Hysteresis and Day plot analyses of two representative samples indicate the presence of low-coercivity ferrimagnetic minerals with pseudo-single-domain to multi-domain magnetic behavior, consistent with magnetite-dominated magnetic assemblages. These magnetic characteristics suggest that the sedimentary magnetic fraction is predominantly derived from detrital material associated with the surrounding volcanic catchment. Overall, this study provided the first spatially distributed environmental magnetic dataset for the Lake Tondano sediments and baseline information on the variability of magnetic susceptibility and magnetic mineral characteristics across the lake. The results demonstrate the usefulness of environmental magnetic parameters for characterizing sediment magnetic properties in tropical volcanic lake environments.

Keywords: lake Tondano, magnetic susceptibility, lake sediment, magnetic minerals, hysteresis parameters.

INTRODUCTION

Lakes are aquatic ecosystems that are sensitive to environmental changes, both from natural processes and anthropogenic activities in their catchment areas (Sulastriningsih et al., 2021). Lake sediments serve as natural archives, recording various environmental processes, such as climate change, volcanic activity, erosion, and the impact of human activities on the surrounding area (Li et al., 2025). Therefore, lake sediment analysis is an important approach to understanding long-term environmental dynamics. Over the past few decades, environmental magnetic methods have become valuable approaches for assessing aquatic environmental conditions based on the properties of magnetic minerals preserved in sediments (Matondang et al., 2025). Magnetic properties, including magnetic susceptibility and hysteresis parameters, can reveal information about the concentration, grain size, and origin of magnetic minerals within lake sediments (Rong et al., 2023). This method is also known for its rapid, non-destructive, and relatively economical nature in monitoring environmental quality (Deng et al., 2024).

Lake sediments are recognized as archives of environmental change caused by human activities, such as urban development, industrial growth, and agricultural practices, as reflected in differences in the levels of magnetic minerals and heavy metals (Harlianti et al., 2026; Noya et al., 2024). Various studies have shown that increases in magnetic susceptibility values in sediments are often associated with increased ferrimagnetic particle content resulting from anthropogenic activities such as fossil fuel combustion and industrial activity (Tiwow et al., 2026a). Therefore, environmental magnetism has been widely used as an indicator of environmental pollution and as a tool for reconstructing the environmental history of lake sediments. Studies in various lakes worldwide have shown that magnetic parameters can effectively record changes in lake environmental quality both temporally and spatially (Fu et al., 2024; Yang et al., 2025). Furthermore, magnetic parameters are also sensitive to variations in sediment sources and changes in deposition processes in the lake environment (Li et al., 2025).

Previous studies have demonstrated that magnetic sediment characteristics can influence long-term environmental changes. Research in the Songnen Plain, China, demonstrated variations in magnetic parameters in lake sediments accumulated with regional climate change and human activity since the mid-20th century (Fu et al., 2024). These findings indicate that magnetic minerals in sediments can function as significant indicators of environmental and human-induced changes. Another study in Lake Chaohu, China, used an environmental magnetism approach combined with heavy-metal analysis to determine the pollution levels in lake sediments. The findings of this study demonstrate a strong correlation between magnetic parameters and the levels of heavy metals, including Cr, Ni, and Zn, suggesting that magnetic methods can be utilized as rapid indicators of aquatic environmental pollution (Deng et al., 2024).

In Indonesian research, environmental magnetic methods have also been used to analyze lake sediments and other water bodies. Numerous studies have demonstrated that magnetic parameters can distinguish the sources of magnetic minerals derived from both natural processes and anthropogenic activities in aquatic environments. Research in Ambon Bay indicates that sediment magnetic susceptibility values accumulate with heavy metals such as Cr, Co, and Ni originating from human activities in coastal areas (Noya et al., 2024). These research results demonstrate that the magnetic approach can serve as a rapid indicator for monitoring aquatic environmental pollution (Harlianti et al., 2026). This method has also been used to characterize magnetic minerals in volcanic lake sediments in Indonesia (Prasetyo et al., 2022).

Several environmental magnetic studies of lakes in Indonesia have been conducted in recent years. A study of sediments from Lake Batur revealed the dominance of magnetite and titanomagnetite minerals originating from the weathering of volcanic rocks surrounding the lake (Harlianti et al., 2026). Furthermore, research on sediments from Lake Ranu Klakah (East Java) identified the presence of pseudo-single-domain magnetic minerals associated with volcanic material sources in the lake's catchment area (Matondang et al., 2025). Other studies on lake and river sediments in Indonesia have also shown that variations in magnetic susceptibility can be used to identify magnetic mineral sources and the influence of human activities on aquatic environments (Rong et al., 2023; Yusupova et al., 2024). These studies demonstrate the significant potential of environmental magnetic methods for analyzing lake sediments in Indonesia.

Furthermore, environmental magnetic studies have been conducted on several aquatic systems in Indonesia, such as river and lake sediments in urban and agricultural areas. The findings suggest that variations in magnetic parameters can be applied to differentiate magnetic mineral sources associated with natural processes, including rock erosion and volcanic activity, from those related to anthropogenic activities, such as industrial operations and transportation (Fajar et al., 2022; Sudarningsih et al., 2023). Studies of sediments from the

Tallo River in Makassar have shown that the magnetic susceptibility values correlate with the grain size of magnetic minerals and with human activity in the river basin. This suggests that magnetic approaches can be used as indicators of environmental change in tropical waters (Rong et al., 2023).

Lake Tondano is one of the largest volcanic lakes in North Sulawesi, Indonesia, formed by volcanic activity in the Tondano caldera during the Quaternary period. The lake plays a vital role as a source of water, fisheries, agriculture, and hydroelectric power for the surrounding community. Geologically, the area around Lake Tondano is dominated by tuff and volcanic rock deposits derived from volcanic activity in the Minahasa region (Moningkey et al., 2022). This volcanic material is the primary source of sediment that accumulates on the lakebed through erosion and sediment transport from the catchment area. In addition to geological factors, human activities such as agriculture, settlements, and fisheries also contribute to increased sedimentation and changes in the lake's environmental quality (Matondang et al., 2025).

Several previous studies on Lake Tondano have primarily concentrated on water quality, lake morphometry, and the physical and chemical properties of the sediments (Sulastriningsih et al., 2021). The results indicate that Lake Tondano's sediments are predominantly silty clay with a relatively high organic matter and nutrient content. This condition indicates that anthropogenic activities influence sedimentation in the lake's catchment. Furthermore, changes in lake morphometry and depth indicate significant sedimentation over the past few decades. This emphasizes the importance of lake sediment studies for a more comprehensive understanding of Lake Tondano's environmental dynamics (Moningkey et al., 2022).

Although several studies have examined the physicochemical characteristics, water quality, morphometry, and sedimentation of Lake Tondano (Sulastriningsih et al., 2021; Moningkey et al., 2022; Mamangkey et al., 2026), environmental magnetic investigations of its sediments remain very limited. Consequently, information on the spatial variability of sediment magnetic properties and magnetic mineral characteristics across the lake remains scarce. Environmental magnetic parameters, particularly magnetic susceptibility, have been widely used to assess magnetic mineral concentrations and investigate sediment sources, transport processes, and environmental changes in lacustrine environments (Fu et al., 2024; Li et al., 2025; Yang et al., 2025). However, the application of these approaches to tropical volcanic lake systems remains relatively limited, particularly in Indonesia. As one of the largest volcanic lakes in Indonesia, Lake Tondano represents an important lacustrine environment for investigating the spatial distribution of magnetic properties and magnetic mineral assemblages in sediments. This study provides an integrated environmental magnetic characterization of the Lake Tondano sediments and establishes baseline information on the spatial variability of sediment magnetic properties across the lake.

The primary focus of this study was the spatial variability of magnetic susceptibility in the Lake Tondano sediments. Hysteresis measurements were conducted only on selected high-susceptibility samples and, therefore, are intended to provide supplementary information on magnetic mineral characteristics rather than a comprehensive characterization of all lake sediments. Nevertheless, hysteresis parameters remain useful for identifying magnetic domain states and dominant magnetic mineral assemblages (Paterson et al., 2024; Cych et al., 2024; Williams et al., 2024).

This study integrated spatial magnetic susceptibility analysis and hysteresis measurements on selected samples to investigate the magnetic characteristics of the Lake Tondano sediments. The objectives were to determine the spatial distribution of magnetic susceptibility, characterize the magnetic properties of selected high-susceptibility sediments, and evaluate spatial variations in sediment characteristics across the lake. The results are expected to enhance understanding of sediment heterogeneity and the spatial variability of magnetic properties in Lake Tondano.

METHOD

Study area

This research was conducted at Lake Tondano, the largest volcanic lake in North Sulawesi Province, Indonesia. Minahasa highlands contains the lake, which is located at approximately 1°15′–1°20′ N and 124°50′–124°55′ E, at an altitude of about 600 meters above sea level. The lake spans about 46 km² and reaches a maximum depth of 20–30 m.(Moningkey et al., 2022). Lake Tondano receives water and sediment from several rivers originating in the surrounding catchment, including agricultural, residential, and forested areas (Mamangkey et al., 2026).

Lake Tondano formed on the eastern edge of the Tondano Caldera. Several volcanoes, such as Mount Soputan, Lokon-Empung, Mahawu, and Sempu, surround the caldera. Stratigraphic studies of Quaternary deposits in the Lake Tondano area indicate the presence of six depositional facies: Tondano tuff, young volcanic eruptions, lakes, lake sandstones, tidal deposits, and swamp deposits (Patria et al., 2025). These changes in depositional environments are controlled by tectonic activity, including the activity of the main Sonder fault, which is recorded in each Sedimentary Facies Unit.

The volcanic rocks surrounding Lake Tondano can be categorized into several major groups according to their modes of formation, which are directly related to the type of volcanic eruption. Effusive rocks (lava flows) include andesite, basalt, and obsidian. Proclastic rocks (products of explosive eruptions) include tuff and ignimbrite, lapilli, and pyroclastic breccia. Hydrovolcanic rocks (the interaction of magma and water) include datrem and hyalotuff breccia. Porous (vesicular) rocks include pumice.

Geologically, the Lake Tondano area is dominated by volcanic rocks originating from past volcanic activity in the Minahasa region. This past volcanic activity produced various volcanic rock products, such as andesitic and pyroclastic lava, which then underwent weathering and erosion (Mamangkey et al., 2026). The weathering process of these volcanic rocks produced various magnetic minerals, such as magnetite and titanomagnetite, which were then transported into the lake through erosion and river flow. In addition to geological factors, human activities such as agriculture, fish farming using floating net cages, and the expansion of residential areas around the lake also have the potential to affect the characteristics of sediments deposited on the lake floor (Mukti et al., 2022; Soehaimi et al., 2024).

Sediment sampling

Sampling was conducted in Lake Tondano, North Sulawesi, Indonesia (Figure 1). Sediment sampling was conducted at points along the perimeter of Lake Tondano. These points represent different environmental conditions, including river inlets, river outlets, and areas affected by anthropogenic activities. Sampling sites were selected using a purposive sampling approach, accounting for sediment flow patterns and the distribution of human activities around the lake (Tiwow et al., 2026a). Surface sediment samples were collected using a grab sampler or a similar sediment collection tool. The upper sediment layer, approximately 0–5 cm deep, was collected as it is considered most representative of recent environmental conditions (Yang et al., 2025).

The location of each sampling site was documented using a Global Positioning System (GPS) to support spatial analysis. Sediment samples were then placed in non-magnetic plastic bags, labeled and coded by sampling location, and the samples were then taken to the laboratory for preparation

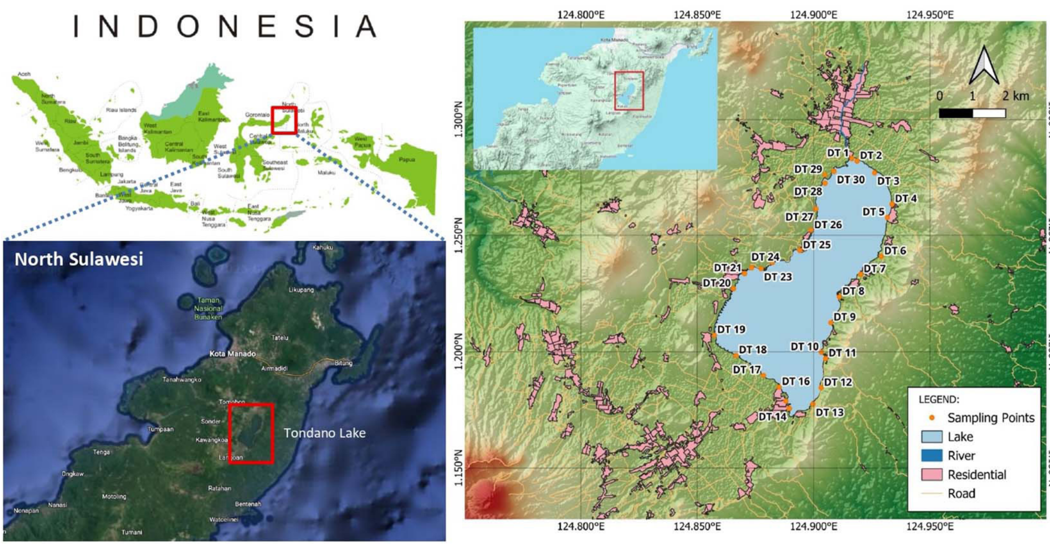

Figure 1. Location map of Lake Tondano and design of sampling points

and further analysis. Sample preparation involved drying, grinding, and sieving using a 100-mesh sieve. Each prepared sample was then weighed to 15 g prior to testing (Tiwow et al., 2025). This procedure is used in lake sediment research to maintain sample integrity and minimize contamination during transportation and storage (Liu et al., 2025).

Magnetic susceptibility measurement

Sediment sample preparation was conducted by drying the sediment at room temperature until it reached an air-dry state. The sample was then gently ground and sieved through a 100-mesh sieve to ensure a consistent, reliable grain-size distribution. After homogenization, the sediment was placed in a non-magnetic container or a special plastic clip for magnetic property measurement (Liu et al., 2025).

Magnetic susceptibility was determined using a Bartington MS2B Susceptibility Meter, which functions at two measurement frequencies: a low frequency (χ_{LF}) of 470 Hz and a high frequency (χ_{HF}) of 4700 Hz (Tiwow et al., 2025). Prior to measurements, the instrument was calibrated using standard reference materials to ensure accuracy. These two parameters are utilized to determine the frequency-dependent susceptibility (χ_{FD}%), which can be applied to detect ultrafine magnetic particles, particularly superparamagnetic grains. The χ_{FD}% value was calculated using the equation:

$$\chi_{FD}(\%) = \frac{\chi_{LF} - \chi_{HF}}{\chi_{LF}} \times 100 \quad (1)$$

where: χ_{LF} – magnetic susceptibility at low frequencies, χ_{HF} – magnetic susceptibility at high frequencies, χ_{FD} – frequency-dependent magnetic susceptibility.

Magnetic susceptibility measurements were performed using a Bartington MS2B sensor with a measurement precision of 1.0×10^{-8} SI. Prior to measurement, the instrument was calibrated according to the manufacturer’s standard procedures. To assess measurement reproducibility and analytical precision, each sediment sample was measured three times, and the mean value was used for subsequent analysis. The standard deviation of repeated measurements was calculated for each sample as an estimate of analytical uncertainty.

Magnetic susceptibility parameters play an important role in evaluating the relative concentration of magnetic minerals within sediments and serve as indicators of sediment source, whether from natural or human influences (Wang et al., 2024). Magnetic parameter data obtained from magnetic susceptibility measurements were analyzed using descriptive statistics. This analysis involved determining the minimum, maximum, average, standard deviation, and coefficient of variation for each magnetic parameter (Tiwow et al., 2026a).

The spatial distribution of sediment magnetic parameters was analyzed using QGIS (Tamuntuan et al., 2023). The GPS coordinates of sampling locations were combined with magnetic parameter values to generate a spatial distribution map of magnetic susceptibility in Lake Tondano. Spatial distribution maps of magnetic susceptibility were generated using the inverse distance weighting (IDW) interpolation method implemented in QGIS version 3.38.3-Grenoble. The IDW method was selected because it assumes that sample points closer to an unsampled location exert greater influence on the predicted value than those farther away. Magnetic susceptibility values measured at sampling locations were interpolated using a distance coefficient (power) of 2, which applies an inverse square distance weighting scheme to estimate values across the study area. The interpolation was performed within the spatial extent of the study area using geographic coordinates referenced to the WGS 84 coordinate system (EPSG:4326). The output raster was generated with a pixel size of 0.000656° × 0.000656°, corresponding to approximately 72–73 m near the equator, providing sufficient spatial detail for lake-scale analysis. The interpolated surface was exported in the GeoTIFF format and subsequently used to produce the spatial distribution maps of magnetic susceptibility. Processing was carried out using QGIS 3.38.3 with GDAL 3.9.2, GEOS 3.12.2, PROJ 9.4.0, and Python 3.12.6.

Hysteresis analysis

Magnetic hysteresis parameter analysis was conducted using a Quantum Design PPMS VersaLab Cryogen-free 3 Tesla Physical Properties Measurement System/Vibrating Sample Magnetometer to obtain magnetic hysteresis curves. Several important parameters were derived from these curves, including saturation magnetization (Ms), saturation remanent magnetization (Mrs), coercivity (Hc), and remanent coercivity (Hcr).

These parameters serve as essential indicators for characterizing the magnetic properties of minerals in sediments (Wang et al., 2024).

These parameters were applied to identify the dominant types of magnetic minerals and the magnetic domain sizes within the sediments. In addition, magnetic parameter ratios, including Mrs/Ms and Hcr/Hc, were utilized to evaluate magnetic domain characteristics through a Day plot analysis (Moidaki et al., 2025; Xu et al., 2020). This diagram is utilized to determine magnetic domain states, such as single-domain (SD), pseudo-single-domain (PSD), and multi-domain (MD), which are associated with the grain size of magnetic minerals in sediments (Liu et al., 2025).

Hysteresis measurements were performed on two representative sediment samples using a vibrating sample magnetometer (VSM). The selected samples were chosen to represent contrasting magnetic susceptibility characteristics observed across the study area, thereby providing preliminary information on the magnetic domain state of the Lake Tondano sediments. Due to instrument availability and measurement time constraints, hysteresis analyses were limited to these two representative samples. Hysteresis measurements were conducted once for each sample using a calibrated instrument. Owing to the high precision and stability of the instrument, a single measurement was deemed adequate for determining the magnetic hysteresis parameters.

RESULTS AND DISCUSSION

Characteristics of magnetic susceptibility

Table 1 presents a statistical overview of the magnetic susceptibility values of the sediment samples collected from Lake Tondano. Meanwhile, complete data on the magnetic susceptibility of the Lake Tondano sediments are shown in Table 2. The sediment χ_{LF} values ranged from 44.4×10^{-8} m³/kg to 4800.2×10^{-8} m³/kg (Tiwow et al., 2026b). Figure 2 illustrates the magnetic susceptibility values of samples 1 through 30. The reliability of the magnetic susceptibility measurements was evaluated by repeating the measurements. The repeated measurements demonstrated high analytical reproducibility. For all samples, the standard deviation of the three measurements was less than 1 ($\times 10^{-8}$ SI), indicating excellent measurement precision relative to the observed range of magnetic susceptibility values.

This range of values suggests considerable variation in the concentration of magnetic minerals within the sediment. The minimum value of 44.4×10^{-8} m³/kg indicates a very low magnetic mineral content, possibly caused by the predominance of diamagnetic or paramagnetic minerals, such as quartz, carbonates, and organic material. Conversely, the maximum value of 4800.2×10^{-8} m³/kg indicates a relatively high accumulation of magnetic minerals. In many lake systems, high χ_{LF} values are generally associated with increased input of detrital material from rock erosion in iron-rich catchments (Li et al., 2025; Ortega-Guerrero et al., 2026). In general, increased χ_{LF} values indicate increased concentrations of ferrimagnetic minerals, including magnetite and titanomagnetite, contained within the sediment, while low χ_{LF} values indicate a predominance of non-magnetic materials or a reduced contribution of magnetic minerals from the catchment area (Yu et al., 2026).

A simple calculation of this range reveals an average χ_{LF} value of approximately 2422×10^{-8} m³/kg, indicating that the sediment generally has moderate to relatively high concentrations of magnetic minerals. This variation reflects the heterogeneity of sediment sources and differences in depositional conditions within the lake system. Environmental magnetism studies indicate that changes in χ_{LF} values are often associated with variations in sediment supply, climatic conditions, and anthropogenic activities in the catchment area

Table 1. Statistical description of magnetic susceptibility values in the Lake Tondano sediment samples (n=30) (Tiwow et al., 2026b)

Variable	Unit	Descriptive statistics					
		Minimum	Maximum	Range	Mean	SD	CV (%)
χ_{LF}	x 10^{-8} m³/kg	44.4	4800.2	4755.8	597.9	1189.3	198.9
χ_{HF}	x 10^{-8} m³/kg	44.3	4770.3	4726	589.3	1179.4	200.1
χ_{FD}	%	0.23	4.95	4.72	2.58	2.84	109.9

that impact erosion and the movement of sediment into the lake (Fu et al., 2024; Yu et al., 2026).

Differences in magnetic susceptibility values between sediment sampling locations can indicate spatial variations in the distribution of magnetic minerals. The locations close to sediment sources, such as river mouths or inflow areas, commonly exhibit higher χ_{LF} values owing to the direct influx of detrital material from the catchment area. Conversely, the locations in the central or calmer depositional zones tend to exhibit lower χ_{LF} values due to hydrodynamic selection processes during sediment transport. This process causes coarser, more magnetic-rich particles to be deposited closer to their source, while finer particles can be transported farther before being finally deposited (Ortega-Guerrero et al., 2026; Yang et al., 2025).

Moreover, variations in χ_{LF} values are strongly associated with the level of magnetic minerals in the sediments. Ferrimagnetic minerals, particularly magnetite and maghemite, generally make the greatest contribution to magnetic susceptibility (Rath et al., 2025; Venkateshwarlu & Babu, 2022). Several studies have shown that these minerals generally originate from weathered rocks within the catchment area and are subsequently carried into the lake through erosion and surface runoff. Therefore, changes in χ_{LF} values can serve as an indicator of changes in the supply of detrital sediment from land to the lake environment (Li et al., 2025).

Table 2. Complete data on magnetic susceptibility values of the Lake Tondano sediments

Sample code	Latitude	Longitude	χ_{LF} (x 10^{-8} m^3/kg)	χ_{HF} (x 10^{-8} m^3/kg)	χ_{FD} (%)
DT 1	1.283262°N	124.916416°E	141.9	137.3	3.24
DT 2	1.282171°N	124.91868°E	67.0	64.2	4.18
DT 3	1.277136°N	124.926176°E	272.7	265.4	2.68
DT 4	1.263645°N	124.93371°E	169.1	161.1	4.73
DT 5	1.257902°N	124.931722°E	586.7	576.2	1.79
DT 6	1.240866°N	124.929073°E	88.9	86.3	2.92
DT 7	1.233213°N	124.92028°E	144.9	141.9	2.14
DT 8	1.223524°N	124.911083°E	79.1	76.7	3.03
DT 9	1.212394°N	124.907404°E	319.1	312.7	2.01
DT 10	1.199721°N	124.903365°E	212.3	201.8	4.95
DT 11	1.196942°N	124.905137°E	490.6	480.2	2.12
DT 12	1.184402°N	124.903255°E	163.3	155.4	4.84
DT 13	1.177366°N	124.89969°E	829.8	818.2	1.4
DT 14	1.175553°N	124.889575°E	181.6	174.9	3.69
DT 15	1.178702°N	124.888113°E	359.4	349.2	2.84
DT 16	1.184738°N	124.885152°E	508.5	500.8	1.51
DT 17	1.170551°N	124.85776°E	119.5	116.7	2.34
DT 18	1.188869°N	124.881693°E	120.6	115.1	4.56
DT 19	1.206985°N	124.857333°E	428.6	417.2	2.66
DT 20	1.2269983°N	124.8655701°E	304.6	299.8	1.58
DT 21	1.233511°N	124.870317°E	204.5	202.4	1.03
DT 22	1.235999°N	124.873421°E	1668.8	1653.8	0.9
DT 23	1.235573°N	124.87745°E	3162.0	3135	0.85
DT 24	1.238243°N	124.882274°E	1039.2	1016.6	2.17
DT 25	1.243429°N	124.894116°E	4800.2	4770.3	0.62
DT 26	1.252262°N	124.898948°E	1112.1	1101.1	0.99
DT 27	1.261657°N	124.901072°E	44.4	44.3	0.23
DT 28	1.272642°N	124.904925°E	105.9	100.9	4.72
DT 29	1.276233°N	124.904925°E	104.5	102.4	2.01
DT 30	1.283222°N	124.910368°E	106.4	101.3	4.79

χ_{FD}% values, ranging from 0.23% to 4.95%, provide additional insight into the grain size of magnetic minerals contained in the sediments. The χ_{FD}% parameter is particularly sensitive to the presence of ultrafine magnetic minerals within the superparamagnetic (SP) domain. Relatively low χ_{FD}% values (<5%) suggest that the SP fraction in the sediments is limited, indicating that the magnetic minerals are predominantly composed of coarser grains, such as pseudo-single-domain (PSD) or multi-domain (MD) particles (Tiwow et al., 2026a). This condition commonly implies that the magnetic minerals in the sediments are sourced from detrital materials, rather than from the pedogenic processes that produce large amounts of SP particles (Hamdan et al., 2025; Ouallali et al., 2025).

Variations in χ_{LF} and χ_{FD}% values in sediments provide an initial insight into the abundance of magnetic minerals and the dynamics of sedimentation processes within the lake. The wide range of χ_{LF} values indicates differences in magnetic mineral concentrations, likely influenced by variations in material sources, catchment geological conditions, and sediment transport processes (Harlianti et al., 2026; Matondang et al., 2025). Meanwhile, the relatively low χ_{FD}% value indicates the dominance of relatively coarse-grained detrital magnetic minerals. Therefore, the interpretation of magnetic susceptibility parameters can serve as an initial indicator of sediment sources, material transport processes, and sediment deposition conditions in lake systems (Fu et al., 2024; Ortega-Guerrero et al., 2026; Yu et al., 2026).

Spatial distribution of magnetic susceptibility

The spatial distribution of χ_{LF} of Lake Tondano sediment is shown in Figure 3. Clear variations are evident among sampling points scattered along the lake's edges and in its center. Based on the interpolation map, χ_{LF} values range from approximately 300 to over 4000 × 10^{-8} m^3/kg, indicating heterogeneity in magnetic mineral concentrations in the sediment. This variation reflects differences in sediment source material, lake hydrodynamic conditions, and deposition processes occurring at various sampling locations. In environmental magnetism studies, the spatial distribution of χ_{LF} is often used to identify the areas with high magnetic-mineral accumulation rates and to explore the relationships between sedimentation processes and environmental conditions in the catchment (Fu et al., 2024; Yu et al., 2026).

In the northern part of the lake, defined by points DT1, DT2, DT3, DT28, DT29, and DT30, magnetic susceptibility values are generally relatively low to moderate, ranging from approximately 300–800 × 10^{-8} m^3/kg. This zone is shown by blue to dark blue colors on the distribution map. These comparatively low values imply that the abundance of magnetic minerals in the sediments from the northern region of the lake is relatively low. This indicated that calmer hydrodynamic conditions and the dominance of fine-grained sediments that undergo long-distance transport before deposition were related. Several studies have shown that the central part or areas farther from the inflow source typically have

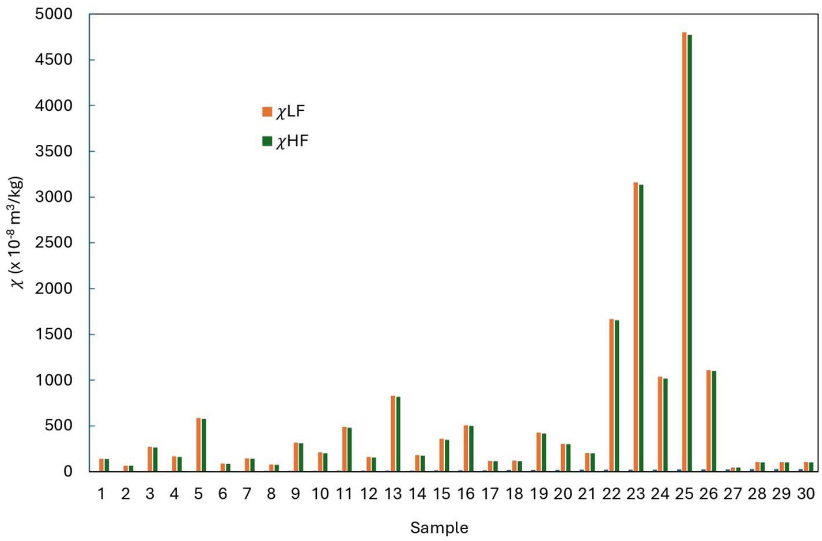

Figure 2. Magnetic susceptibility of sediments of Lake Tondano

lower magnetic-mineral concentrations due to hydrodynamic selection during sediment transport (García-Ávila et al., 2022; Zhang et al., 2025).

In the eastern part of the lake, including points DT4, DT5, DT6, DT7, DT8, and DT9, χ_{LF} values also show a relatively low-to-moderate range. Most points in this zone fall within the range of 400–1000 × 10^{-8} m³/kg, indicating a moderate magnetic mineral concentration. This distribution indicates that it was influenced by the geomorphological conditions in the eastern part of the lake, which has a relatively steep slope, allowing incoming sediment to be transported directly to the lake's center. Furthermore, the low χ_{LF} values in this area may also reflect the dominance of non-magnetic minerals or the high organic matter content in the sediment (Fu et al., 2024; Yang et al., 2025).

Higher magnetic susceptibility values begin to appear in the western part of the lake, particularly around points DT20, DT21, DT24, DT25, and DT26. This area shows a significant increase in χ_{LF} values, ranging from approximately 1500 to 4000 × 10^{-8} m³/kg. Point DT25 has the highest value, indicated by the red color on the distribution map. The very high values in this area indicate the presence of large concentrations of magnetic minerals in the sediment. This condition indicates that it was related to the influx of iron-rich detrital sediment from the catchment area through the river system or surface runoff that empties into the western part of the lake (Fu et al., 2024; Wang et al., 2025).

In the southwest and south of the lake, represented by points DT14, DT15, DT16, DT17, DT18, and DT19, the χ_{LF} values decreased again and generally ranged from 300–800 × 10^{-8} m³/kg. This pattern indicates that the concentration of magnetic minerals in the sediments in these areas is relatively low compared to the central-western zone. This may be due to more stable hydrodynamic conditions, leading to a predominance of fine-grained material with lower magnetic mineral content. Furthermore, dilution by non-magnetic materials such as silicate minerals or organic matter may also have occurred (Yu et al., 2026; Zhang et al., 2025).

In addition to natural factors, the distribution of magnetic susceptibility values around the sampling points is also influenced by human activities in the lake. Several sampling points located near residential areas or transportation routes, such as those in the west and southwest of the lake, showed higher χ_{LF} values than other areas. Anthropogenic activities such as agriculture, infrastructure development, and runoff from residential areas can introduce metal particles or iron-rich materials into the lake, increasing the concentration of magnetic minerals in the sediment (Yang et al., 2025; Yu et al., 2026).

Meanwhile, the spatial distribution of χ_{FD} in the Lake Tondano sediments is shown in Figure 4. The distribution of fine magnetic particles appears uneven, indicating that it was influenced by material sources, transport processes, and human activities. High χ_{FD} values in coastal areas indicate

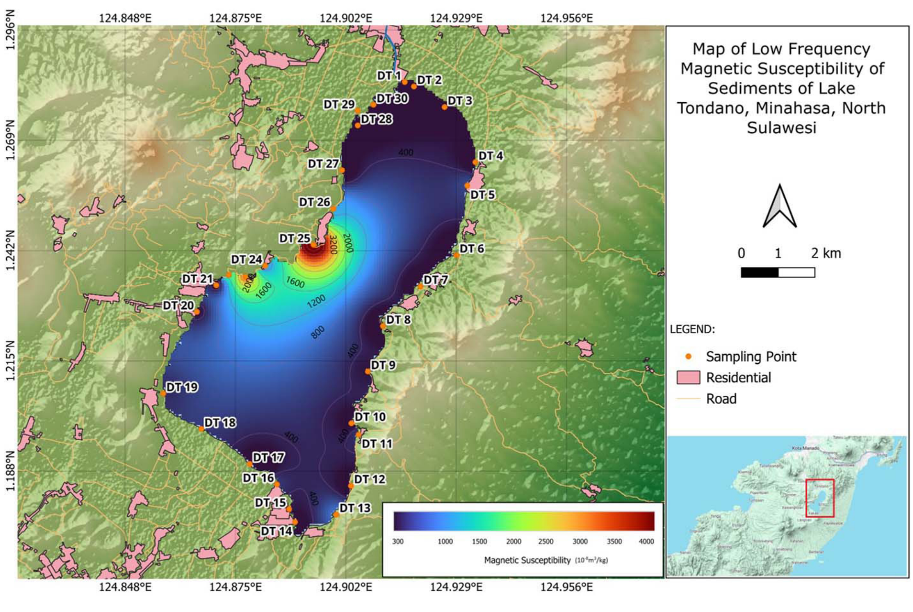

Figure 3. Spatial distribution map of low-frequency magnetic susceptibility (χ_{LF}) of the Lake Tondano sediments

a contribution from pedogenesis and land erosion, while low values in the central area reflect the dominance of detrital volcanic material. Therefore, the χ_{FD} parameter can serve as an important indicator for evaluating interactions among geomorphological processes, the environment, and anthropogenic activities in the Lake Tondano system.

Meanwhile, the distribution pattern of magnetic susceptibility based on sampling points DT1–DT30 indicates that the western and central-western parts of the lake are the zones with the highest magnetic mineral accumulation. In contrast, the northern, eastern, and southern parts are relatively dominated by lower χ_{FD} values. This pattern indicates the combined influence of sediment sources in the catchment area, the lake basin geomorphology, the inflow hydrological system, and human activities around the lake. Therefore, analyzing the spatial distribution of magnetic susceptibility can provide important insights into sedimentation dynamics and potential environmental changes within the Lake Tondano system (Fu et al., 2024; Ortega-Guerrero et al., 2026; Yu et al., 2026).

Hysteresis parameter characteristics of lake sediments

The hysteresis parameters of the Lake Tondano sediments are presented in Table 3. The results show that sample DT23 has a Ms of 1.266 emu, a Mrs of 0.0143 emu, a Hc of 3 mT, and a Hcr of 55 mT (Figure 5). The Ms value reflects the concentration of ferrimagnetic minerals within the sediment, which are commonly dominated by magnetite or titanomagnetite (Cych et al., 2024; Moidaki et al., 2025; Paterson et al., 2024). The Ms value observed in DT23 suggests the presence of a moderate concentration of magnetic minerals.

The Mrs value of 0.0143 emu indicates the ability of magnetic particles to retain magnetization after the removal of an external magnetic field. The relatively low Mrs compared to Ms suggests the dominance of relatively coarse magnetic grains or magnetic particles with less stable domain states. In natural sediments, low Mrs/Ms ratios are commonly associated with PSD-to-MD magnetic particles (Nikolaisen et al., 2022; Paterson et al., 2024).

The coercivity value of approximately 3 mT indicates that the dominant magnetic minerals are magnetically soft. Such low coercivity values are generally characteristic of ferrimagnetic minerals such as magnetite. The higher Hcr value relative to Hc suggests a relatively broad distribution of magnetic grain sizes within the sample. Sample DT25 exhibits a higher saturation magnetization value (Ms ≈ 1.7137 emu), a saturation remanent magnetization (Mrs ≈ 0.0173 emu), a coercivity (Hc ≈ 4.3 mT), and a remanent coercivity (Hcr ≈ 39

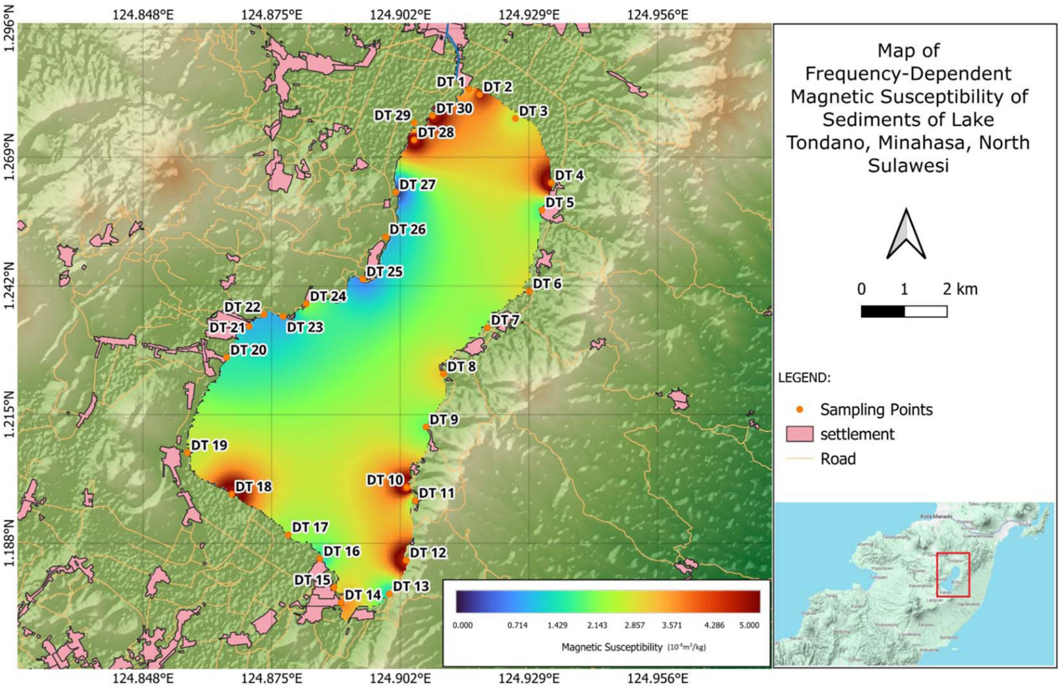

Figure 4. Spatial distribution map of frequency-dependent magnetic susceptibility (χ_{FD}) of the Lake Tondano sediments

Table 3. Hysteresis parameters of the Lake Tondano sediment

Sample	Parameter hysteresis			
	Ms (emu)	Mrs (emu)	Hc (mT)	Hcr (mT)
DT 23	1.266	0.0143	3	55
DT 25	1.7137	0.0173	4.3	39

Note: Ms – saturation magnetization, Mrs – saturation remanent magnetization, Hc – coercivity, Hcr – remanent coercivity.

mT). The higher Ms value compared with DT23 suggests a greater concentration of magnetic minerals in DT25. Differences in magnetic concentration between the two samples may reflect spatial variations in the abundance of magnetic minerals within the lake sediments (Moidaki et al., 2025).

The slightly higher coercivity value in DT25 may suggest differences in magnetic grain-size distributions and/or magnetic mineral assemblages between the two samples. Similar variations in hysteresis parameters have been reported in natural sedimentary environments where magnetic particles of different grain sizes coexist (Nikolaisen et al., 2022; Paterson et al., 2024).

Overall, the hysteresis parameters of DT23 and DT25 indicate the presence of low-coercivity ferrimagnetic minerals and magnetic domain states ranging from pseudo-single-domain to multi-domain. These results provide supplementary information on the magnetic mineral characteristics of the Lake Tondano sediments and are consistent with the magnetic susceptibility data. However, because hysteresis measurements were conducted on only two representative samples selected to reflect contrasting magnetic susceptibility characteristics, the results should be considered preliminary and may not fully represent the spatial variability of magnetic domain states across the entire lake. Future studies incorporating a larger number of hysteresis measurements would enable a more comprehensive characterization of magnetic mineral assemblages and domain-state distributions in the Lake Tondano sediments.

Magnetic domains based on day plots

Magnetic domain analysis of the Lake Tondano sediments was conducted using a Day Plot, which relates the Mrs/Ms and Hcr/Hc ratios to determine the magnetic domain state of ferrimagnetic minerals. Two representative samples (DT23 and DT25) with high magnetic susceptibility values were selected for hysteresis analysis. The Day Plot distinguishes SD, PSD, and MD states, which are associated with magnetic grain size and magnetization characteristics (Sathyanarayanan et al., 2025; Zhao et al., 2017). Based on the hysteresis measurements, sample DT23 yielded Mrs/Ms and Hcr/Hc values of approximately 0.011 and 18.3, respectively, whereas DT25 showed values of approximately 0.010 and 9.1. The very low Mrs/Ms ratios (<0.05) indicate that the magnetic minerals are dominated by relatively coarse magnetic grains in the MD range (Williams et al., 2024).

The Hcr/Hc values further support this interpretation. Both samples exhibit high Hcr/Hc ratios, particularly DT23, indicating the presence of MD grains or a PSD–MD mixture. Such characteristics

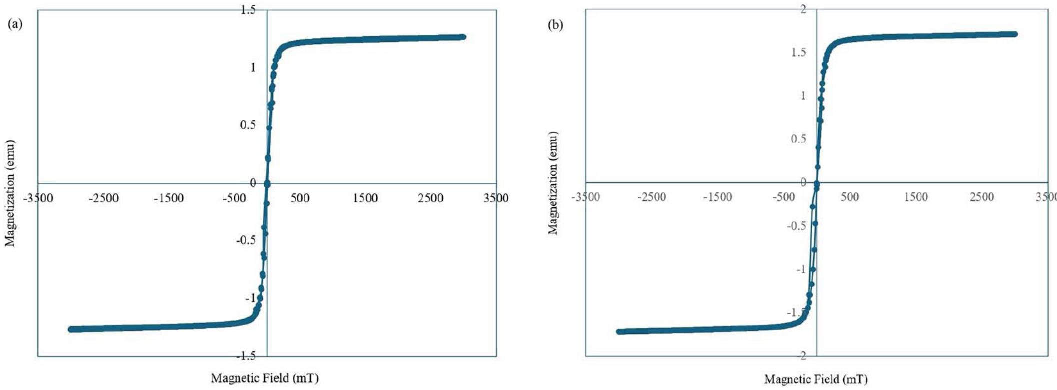

Figure 5. Magnetic hysteresis curve of the Lake Tondano sediment for samples (a) DT 23 and (b) DT 25

are commonly associated with natural sediments containing detrital magnetic minerals with a broad grain-size distribution (Moidaki et al., 2025; Williams et al., 2024). The positions of both samples on the Day Plot (Figure 6) fall within the MD to PSD–MD region, suggesting that the dominant magnetic minerals are likely detrital magnetite derived from the weathering and erosion of volcanic rocks in the Lake Tondano catchment area. Similar magnetic domain distributions have been reported in the lake sediments receiving clastic material transported by fluvial processes (Liu et al., 2025).

The combined χ_{LF}, χ_{FD}%, and hysteresis results indicate that the primary source of magnetic minerals is detrital material derived from volcanic rocks, with possible contributions from pedogenic processes and human activities. These magnetic characteristics suggest that sediment transport and deposition play an important role in controlling the distribution of magnetic minerals within the lake. However, because hysteresis measurements were conducted on only two representative samples, these interpretations should be considered preliminary and may not fully represent the spatial variability of magnetic domain states across the lake.

Evaluation of the environmental conditions of Lake Tondano based on sediment magnetic characteristics

Evaluation of the environmental conditions of Lake Tondano based on sediment magnetic characteristics indicates that the lake system is strongly influenced by volcanic material supplied from the surrounding catchment area. Relatively high χ_{LF} values at several locations indicate the dominance of ferrimagnetic minerals, such as magnetite, derived from the erosion of volcanic rocks (Liu et al., 2025). These magnetic characteristics further indicate substantial detrital sediment input and suggest active erosion, potentially driven by high rainfall, steep topography, and land-use activities around the lake. Therefore, χ_{LF} can serve as a useful indicator of detrital sediment supply to the lake system (Matondang et al., 2025).

In terms of grain size and formation process, the frequency-dependent susceptibility (χ_{FD}%) indicates the presence of superparamagnetic (SP) particles. The observed low to moderate χFD values indicate a relatively limited contribution of pedogenic fine-grained magnetic particles, suggesting that the sediments are predominantly derived from fresh volcanic material (Hamdan et al., 2025; Ouallali et al., 2025). These values further indicate that soil weathering processes in the catchment area are not yet well developed or that weathered materials are rapidly transported into the lake before significant pedogenic enhancement can occur. Consequently, the magnetic characteristics indicate an environmental setting dominated by active erosion and sediment transport rather than stable soil formation and accumulation (Fitriani et al., 2025; Jahidin et al., 2019).

Hysteresis parameters, including Ms, Mrs, and Hc, indicate the dominant magnetic characteristics of the minerals present in the sediments. The observed high Ms values and relatively low Hc values indicate a predominance of primary magnetic minerals with coarse grain sizes, ranging from MD to PSD states (Paterson et al., 2024; Zhao et al., 2017). These magnetic properties further indicate limited mineralogical alteration and suggest that the sediments have not undergone substantial diagenetic processes or chemical weathering. In addition, the hysteresis characteristics indicate that sediment input is largely controlled by local geological sources, particularly the volcanic rocks surrounding Lake Tondano (Mamangkey et al., 2026; Moningkey et al., 2022; Sulastriningsih et al., 2021).

Furthermore, variations in magnetic properties can be used to evaluate potential redox conditions at the lake bottom. A decrease in χ_{LF} values or changes in hysteresis parameter ratios may indicate the development of reducing conditions that promote the dissolution of magnetic minerals (Paterson et al., 2024). These magnetic signatures

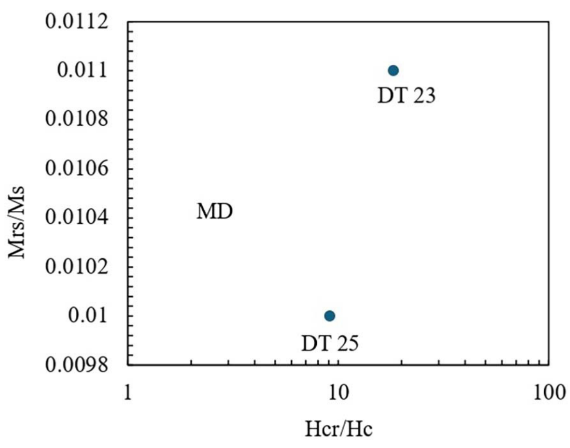

Figure 6. Magnetic hysteresis curve of The Lake Tondano sediment for samples (a) DT 23 and (b) DT 25

may also indicate low dissolved oxygen levels, which are commonly associated with elevated organic matter inputs or eutrophication. Therefore, the observed magnetic characteristics indicate not only variations in sediment sources but may also reflect changes in the geochemical conditions of the aquatic environment (Yang et al., 2025).

This study provided a regional characterization of the magnetic properties of the Lake Tondano sediments. However, interpretations related to ecological processes, redox conditions, and anthropogenic impacts remain preliminary because no independent geochemical, biological, or water-quality analyses were conducted. Future studies integrating environmental magnetic, geochemical, and ecological datasets are needed to verify these interpretations.

CONCLUSIONS

The magnetic properties of the Lake Tondano sediments exhibit considerable spatial variability, as reflected by the wide range of χ_{LF} values observed across the study area. These variations indicate differences in the concentration and distribution of magnetic minerals within the lake sediments. The spatial distribution of χ_{LF} suggests relatively higher magnetic mineral concentrations in the western and central-western parts of the lake compared with other areas. The generally low χ_{FD}% values (<5%) suggest a predominance of coarse-grained magnetic particles and a limited contribution from superparamagnetic grains. These magnetic characteristics are consistent with a predominantly detrital origin of the sedimentary magnetic fraction and may reflect inputs from the surrounding volcanic catchment. Hysteresis and Day plot analyses, conducted on two representative samples, indicate the presence of low-coercivity ferrimagnetic minerals with pseudo-single-domain to multi-domain magnetic behavior. While these measurements provide useful information on the dominant magnetic mineral assemblages, the limited number of hysteresis analyses suggests that caution is needed when extrapolating these results to the entire lake. Overall, the results indicate that environmental magnetic parameters are useful for characterizing the spatial variability of magnetic mineral concentrations and magnetic properties in the Lake Tondano sediments. This study provided baseline environmental magnetic data for Lake Tondano and may serve as a reference for future investigations incorporating more extensive magnetic measurements and complementary geochemical analyses.

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