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Geochemistry and rock magnetic analysis on surface sediment in Lampenisu River: a quest for Mg source to Lake Towuti, Indonesia

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Abstract

Sediment from Lake Towuti has been extensively studied to reconstruct past climate and environmental changes. One of the remaining questions is the source of magnesium (Mg) and calcium (Ca) in the northern part of Lake Towuti. In this study, the source of high Mg and Ca content is examined by analysing surface sediment from the Lampenisu River (LR) and Mahalona River (MR) that merge before entering Lake Towuti. Twelve surface sediments from MR, LR, and the confluence of the two rivers (LMR) were subjected to geochemical (XRF), mineralogical (XRD), and rock magnetic (susceptibility and hysteresis parameter) analyses. The result shows that the Mg and Ca content in LR samples are higher than in MR samples. LR samples have a higher susceptibility and a lower frequency dependent susceptibility than MR samples. XRD analyses on extracted magnetic grains show the presence of minerals with a sodalite crystal structure, possibly valleyite in LR but not in MR samples. If valleyite indeed occurs in LR samples, it may contribute to their relatively high Ca content. At the same time, the high content of Mg in LR samples is likely due to the serpentinized peridotite rocks. LR is thereby considered to be the source of high Mg and Ca content in the northern portion of Lake Towuti. This study shows the importance of sediment-source identification in big lakes such as Lake Towuti, where the influx could come from several rivers around the lake.

Keywords:

Lake Towuti; Lampenisu River; magnesium; rock magnetism; geochemistry

1. Introduction

Located in the Indo-Pacific Warm Pool, Lake Towuti in Sulawesi, Indonesia has been the focus of numerous studies in the last decade, especially after the completion of the Towuti Drilling Program (TDP) in 2015 (**Vogel et al., 2015; Russell et al., 2016; Ulfers et al., 2021**). Sediments from Lake Towuti have been intensively studied, especially in reconstructing past climate and environmental changes in the Western Pacific region of Lake Towuti. These studies were not simple and straightforward as the sediments of Lake Towuti are quite complex due to the high concentration of iron, chromium, and other metals released by the ophiolite rocks in the surrounding area. Such metals catalyse biogeochemical activity by a unique and diverse microbial community (**Russell et al., 2020; Vuillemin et al., 2020; Friese et al., 2021; Morlock et al., 2021; Ageli et al., 2022; Vuillemin et al., 2022**). **Tamuntuan et al. (2015)** reported that the magnetic minerals in the sediments experienced diagenetic processes that were linked to the climate of the region.

During the TDP, participating scientists also collected and studied the surface sediments of Lake Towuti (**Hasberg et al., 2019; Morlock et al., 2019**). Based on geochemical analyses, **Morlock et al. (2019)** reported that the surface sediments in the northern part of the lake were supplied by the Mahalona River, connecting Lake Towuti with Lake Mahalona and Lake Matano further upstream. **Morlock et al. (2019)** showed that these sur-

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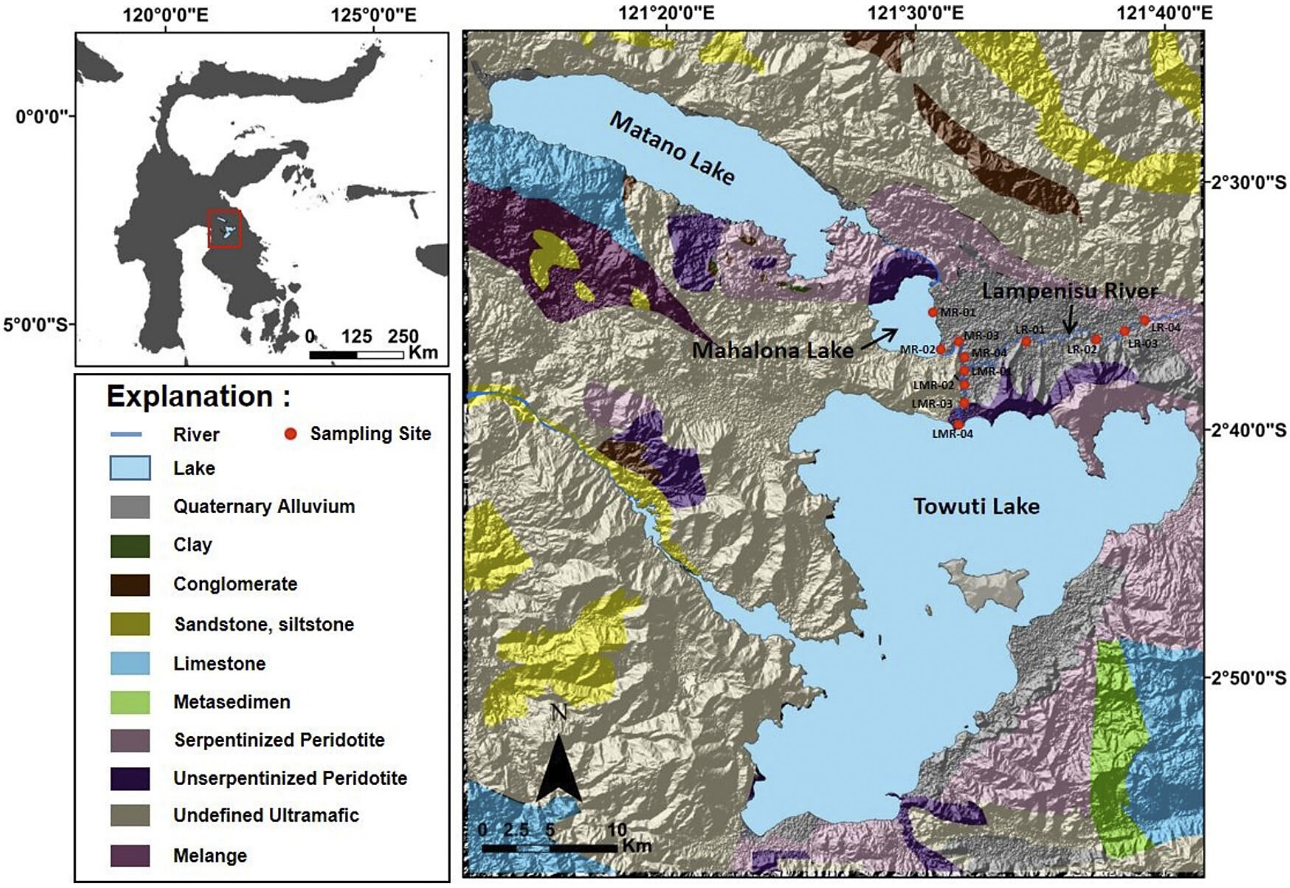

Figure 1: Geological map of the study area around Lake Matano, Lake Mahalona, and Lake Towuti. Rock units of the geological map are taken from **Costa et al. (2015)**.

face sediments are characterized by their high concentration of magnesium (Mg) and low concentration of aluminium (Al), potassium (K), and titanium (Ti). **Hasberg et al. (2019)** confirmed the high concentration of Mg and reported a high concentration of calcium (Ca) in the sediments from the northern part of Lake Towuti. The high concentration of Mg and Ca in these sediments is surprising in the pristine environmental setting of Lake Towuti. The high concentrations of Mg and Ca are often found in lakes affected by anthropogenic impacts such as human settlements and agricultural land (**Potasznik and Szymczyk, 2015**). Other studies, however, showed that the presence of Mg might also be associated with ultramafic or serpentinite rock (**Van Moort, 1973; Teitler et al., 2019; Yang et al., 2022**).

In this study, the source of the high concentration of Mg and Ca in the northern part of Lake Towuti is investigated by conducting geochemical and magnetic analyses on surface sediments from the Mahalona River (MR), the Lampenisu River (LR), and the confluence of these two rivers (MLR) before entering Lake Towuti. Magnetic analyses were carried out to support the results of geochemical analyses. Several studies have shown that magnetic characteristics, such as magnetic susceptibility as well as magnetic hysteresis parameters, are associated with metal content (**Jordanova et al., 2004; Franke et al., 2009; Delbecque et al., 2022; Grison et al., 2021; Lu et al., 2022**). The goals of this study are to identify the source(s) of high Mg and Ca concentrations in Lake Towuti sediments and to look for a correlation between Mg content and magnetic susceptibility in these sediments.

2. Material and Methods

Administratively, the research location is in the Towuti District in East Luwu Regency, South Sulawesi Province, Indonesia. Twelve river and lake surface sediments (see **Figure 1**) were collected. One sample (MR-01) was from the shore of Lake Mahalona, one sample (MR-02) was obtained from the outflow of Lake Mahalona towards the Mahalona River, and two others (MR-03 and MR-04) were obtained from the Mahalona River before it meets the Lampenisu River. Four samples (LR-01 to LR-04) were obtained along the Lampenisu River before it meets the Mahalona River. The remaining four samples were obtained fromthe confluence of the Mahalona and Lampenisu Rivers (LMR-01 to LMR-04). To obtain homogeneous clay particles, the surface sediments were sieved with a 325-mesh size (44 µm in diameter). Sample preparations were carried out following the steps described earlier in detail by **Sudarningsih et al. (2017)**.

Table 1: Summary of magnetic parameters on surface sediment samples from MR, LR, and LMR.

Location	Sample ID	Mass (gr)	χ_{LF} (10^{-8} m^3/kg)	χ_{HF} (10^{-8} m^3/kg)	χ_{FD} (%)	H_c (mT)	H_{cr} (mT)	M_s (emu/g)	M_{rs} (emu/g)	H_{cr}/H_c	M_{rs}/M_s
MR	MR-01	12.40	310.97	301.93	2.91	NM	NM	NM	NM	NM	NM
	MR-02	13.99	121.07	117.47	2.97	25.92	65.80	30.95	9.70	2.54	0.31
	MR-03	13.61	135.03	124.90	7.50	22.26	50.30	26.40	9.02	2.26	0.34
	MR-04	12.06	306.07	286.53	6.51	NM	NM	NM	NM	NM	NM
	Mean	13.02	218.29	207.71	4.94	24.09	58.05	28.68	9.36	2.4	0.33
	SD	0.93	104.37	100.15	2.38	1.83	7.75	2.28	0.34	0.14	0.02
LR	LR-01	13.14	510.63	500.70	1.95	24.40	52.80	48.68	10.41	2.16	0.21
	LR-02	12.71	560.23	556.43	0.68	NM	NM	NM	NM	NM	NM
	LR-03	11.25	494.13	494.13	0.65	NM	NM	NM	NM	NM	NM
	LR-04	13.12	523.73	523.73	2.32	NM	NM	NM	NM	NM	NM
	Mean	12.55	518.75	518.75	1.40	24.40	52.80	48.68	10.41	2.16	0.21
	SD	0.89	27.82	28.15	0.86	NM	NM	NM	NM	NM	NM
LMR	LMR-01	14.20	139.03	135.37	2.64	25.32	64.84	15.95	4.17	2.56	0.26
	LMR-02	12.59	346.93	340.67	1.81	24.31	53.64	44.07	10.87	2.21	0.25
	LMR-03	13.91	230.97	227.90	1.33	NM	NM	NM	NM	NM	NM
	LMR-04	13.37	218.93	213.53	2.47	NM	NM	NM	NM	NM	NM
	Mean	13.52	233.97	229.37	2.06	24.82	59.24	30.01	7.52	2.39	0.26
	SD	0.71	85.65	84.61	0.61	0.51	5.6	14.06	3.35	0.10	0.01

Notes: NM means Not Measured and SD means Standard Deviation.

Magnetic analyses consist of measurements of magnetic susceptibilities and measurements of magnetic hysteresis parameters. First, samples were subjected to measurements of mass-specific magnetic susceptibility at two different frequencies (a low frequency at 470 Hz and a high frequency at 4700 Hz). The results are termed a low-frequency mass-specific susceptibility χ_{LF} and a high-frequency mass-specific susceptibility χ_{HF}. The frequency-dependent magnetic susceptibility $\chi_{FD\%}$ was calculated as 100% × $(\chi_{LF}-\chi_{HF})/\chi_{LF}$. Measurements of magnetic susceptibility were carried out using a Bartington MS-2 magnetic susceptibility system (Bartington Ltd., Oxford, UK) at Institut Teknologi Bandung. Representative samples (MR-02, MR-03, LR-01, LMR-01, and LMR-02) were also subjected to measurements of magnetic hysteresis parameters using a Vibrating Sample Magnetometer, or VSM, using a 1.2 H/CT/HT VSM system (Oxford Instrument, Oxfordshire, UK) at the National Research and Innovation Agency in Serpong, Banten, Indonesia. The four measured hysteresis parameters are H_c (coercive force), H_{cr} (coercivity of remanent), M_s (saturation magnetization), and M_{rs} (magnetic saturation remanent). Based on the plot introduced by **Day et al. (1977)**, the plots of M_{rs}/M_s versus H_{cr}/H_c might infer the predominant magnetic domain of the samples. Moreover, the plots of M_{rs}/M_s versus H_c could be used to qualitatively estimate the type of magnetic minerals (**Wang and Van der Voo, 2004**). Samples were also subjected to geochemical analyses to identify their major elements as well as trace elements using a Rigaku Supermini 200 XRF (X-Ray Fluorescence) system (Rigaku Corp., Tokyo, Japan). Magnetic extraction was also performed on representative samples, as described in **Novala et al. (2019)**. The magnetic grains were then examined with a Rigaku Smartlab XRD (X-Ray Diffraction) (Rigaku Corp., Tokyo, Japan). Both XRF and XRD analyses were carried out at Institut Teknologi Bandung.

3. Result

Table 1 shows the results of magnetic susceptibility measurements, showing that the LR samples have stronger magnetic susceptibilities compared to the MR samples. The average χ_{LF} value in LR samples is (518.8 ± 27.8) × 10^{-8} m^3/kg, while the average value in MR samples is (218.3 ± 104.4) × 10^{-8} m^3/kg. The LR samples, however, have lower $\chi_{FD\%}$ values, averaging only 1.40 ± 0.86%, while in MR samples $\chi_{FD\%}$ is 4.94 ± 2.23%. **Figure 2** shows the plots of $\chi_{FD\%}$ versus χ_{LF} values for the twelve samples. The LR samples could be seen to be distinctively grouped from the MR samples. These discrepancies in magnetic susceptibility values infer that the MR samples and LR samples indeed have different affinities. As shown in **Table 1**, the LMR samples are magnetically stronger than the MR samples, but they are not as strong as LR samples. **Figure 2** shows that LMR samples are also distinctively grouped from MR and LR samples.

Table 1 also shows the ratios of M_{rs}/M_s and H_{cr}/H_c for the five representative samples. **Figure 3a** shows the plots of these ratios in a diagram similar to that prescribed by **Day et al. (1977)**. Assuming that the predom-

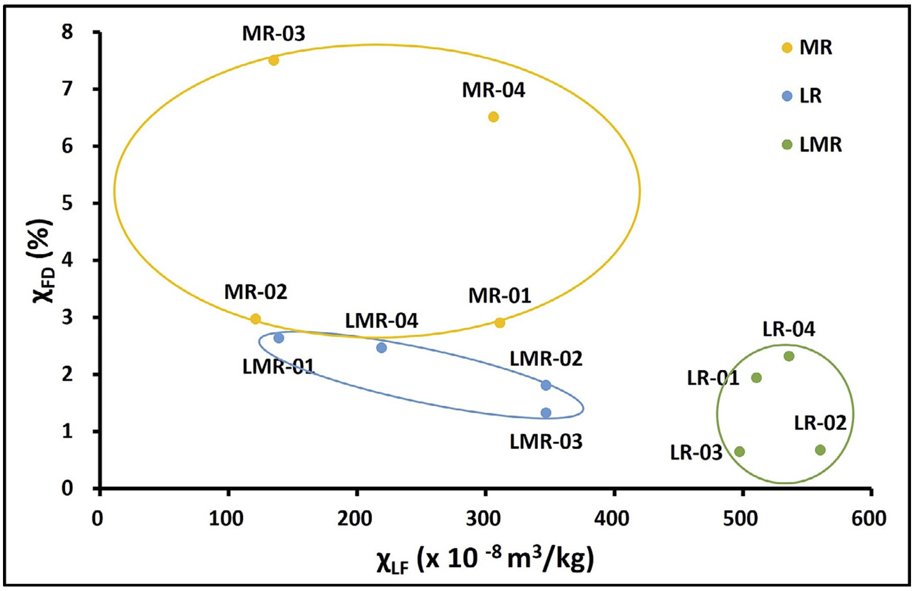

Figure 2: Distribution of magnetic susceptibility for MR, LR, and LMR. Circle or oval groups are samples from each river.

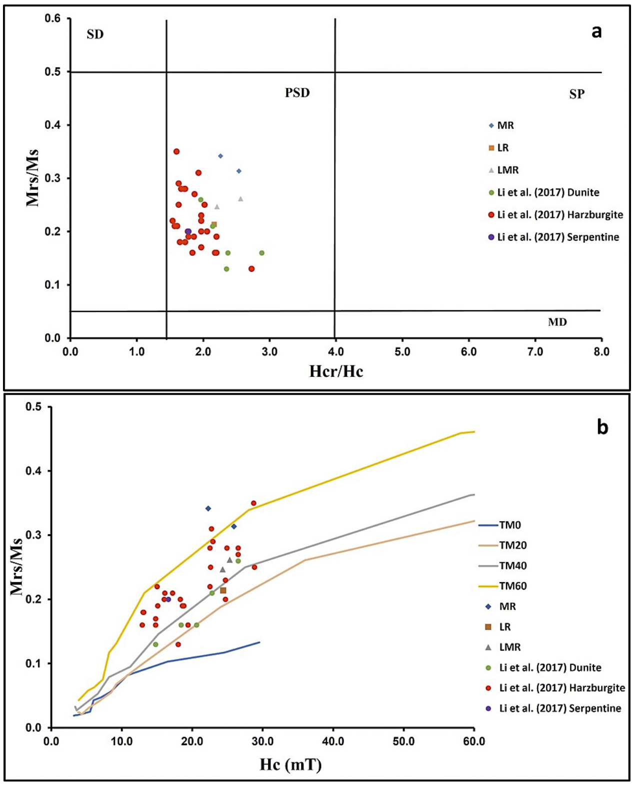

Figure 3: (a) The Day diagram showing the magnetic particles from the sample are dominated by PSD grain and (b) M_{rs}/M_s vs H_c proposed by **Wang and Van der Voo (2004)** to estimate the type of magnetic mineral. Other symbols represent the following: SD for Single Domain, PSD for Pseudo Single Domain, MD for Multi Domain, SP for Super Paramagnetic, TM0, TM20, TM40, TM60 for a content of 0%, 20%, 40%, and 60% of the maximum total Ti contained in a magnetic mineral, respectively.

inant magnetic mineral in the sediment samples is magnetite (Fe_3O_4), **Figure 3** infers that the magnetic minerals predominantly belong to a pseudo-single domain (PSD). In **Figure 3**, the plots of our data are placed and compared with data of samples from Dongbo ophiolite in SW Tibet published by **Li et al. (2017)**. **Figure 3b** shows the plots of M_{rs}/M_s versus H_c of our data in the diagram prescribed by **Wang and van der Voo (2004)**. **Figure 3b** also contains the curves of natural titanomagnetites (TM) with varying content of Ti. As the general formula of the TM series is $Fe_{3-x}Ti_xO_4$, then TM0 is for x = 0, TM20 is for x =0.2, TM40 is for x = 0.4 and TM60 is for x = 0.6. **Figure 3b** shows that our data are in the same range as Dongbo ophiolite (**Li et al., 2017**). **Figure 3b** suggests that MR samples have different magnetic characteristics as they resemble TM60 while the LR and LMR samples resemble TM40.

The results of XRF analyses for the twelve sediments are listed in **Table 2**. The Mg, Ca, and K contents in LR samples are significantly higher than those in MR samples. The average Mg content in LR samples is 13.28 ± 1.68% while the average Mg content in MR samples is only 3.45 ± 1.59%. In contrast, the Fe, Al, Mn, and Pb contents in MR samples are higher than those in LR samples. The average Fe content in MR samples is 20.07 ± 5.04%, while in LR samples, it is only 8.48 ± 1.96%. The discrepancies in Mg, Ca, K, Fe, Al, Mn, and Pb contents in LR and MR samples imply that LR samples and MR samples originated from different sources. **Figure 4** shows the X-Ray diffractograms for magnetic grains extracted from representative samples. The main magnetic mineral in these samples is shown to be magnetite. Representing MR samples, the extracted magnetic minerals from MR-02 show the presence of bixbyite, a manganese iron oxide mineral with a chemical formula of $(Mn, Fe)_2O_3$. In contrast, the diffractograms for the extracted magnetic minerals from LR-01 show the presence of sodalite, a non-magnetic tectosilicate mineral with the formula $Na_8(Al_6Si_6O_{24})Cl_2$.

Table 2: Measured content of major and minor elements in the samples of this study.

Location	Sample ID	Fe (%)	Al (%)	Si (%)	Ca (%)	Mg (%)	K (%)	Ti (%)	Mn (%)	Pb (%)
MR	MR-01	13.98	6.04	15.18	1.06	3.60	0.11	0.18	0.53	0.0010
	MR-02	17.86	3.68	14.55	0.85	3.99	0.15	0.12	0.44	0.0015
	MR-03	23.99	5.96	12.43	0.14	1.23	0.13	0.25	0.22	0.0014
	MR-04	24.43	2.72	11.69	0.57	4.97	0.05	0.13	0.46	0.0015
	Mean	20.07	4.60	13.46	0.66	3.45	0.11	0.17	0.41	0.0014
	SD	5.04	1.66	1.67	0.40	1.59	0.04	0.06	0.13	0.0002
LR	LR-01	9.86	3.17	17.80	0.80	12.24	0.23	0.14	0.18	0.0011
	LR-02	7.09	2.73	18.16	1.13	14.83	0.34	0.11	0.14	0.0007
	LR-03	6.52	2.88	18.16	1.04	14.57	0.38	0.12	0.16	0.0011
	LR-04	10.44	3.28	17.18	0.57	11.46	0.32	0.13	0.23	0.0012
	Mean	8.48	3.02	17.83	0.89	13.28	0.32	0.13	0.18	0.0010
	SD	1.96	0.25	0.46	0.25	1.68	0.06	0.01	0.04	0.0002
LMR	LMR-01	13.41	4.01	18.28	0.83	4.09	0.09	0.18	0.09	0.0011
	LMR-02	10.17	3.71	18.05	0.71	9.76	0.23	0.15	0.18	0.0010
	LMR-03	11.94	3.81	18.00	0.63	8.00	0.20	0.17	0.23	0.0012
	LMR-04	11.79	3.79	18.01	0.65	8.40	0.22	0.16	0.21	0.0011
	Mean	11.83	3.83	18.09	0.71	7.56	0.19	0.17	0.18	0.0011
	SD	1.32	0.13	0.13	0.09	2.43	0.06	0.01	0.06	0.0001

Note: SD means Standard Deviation.

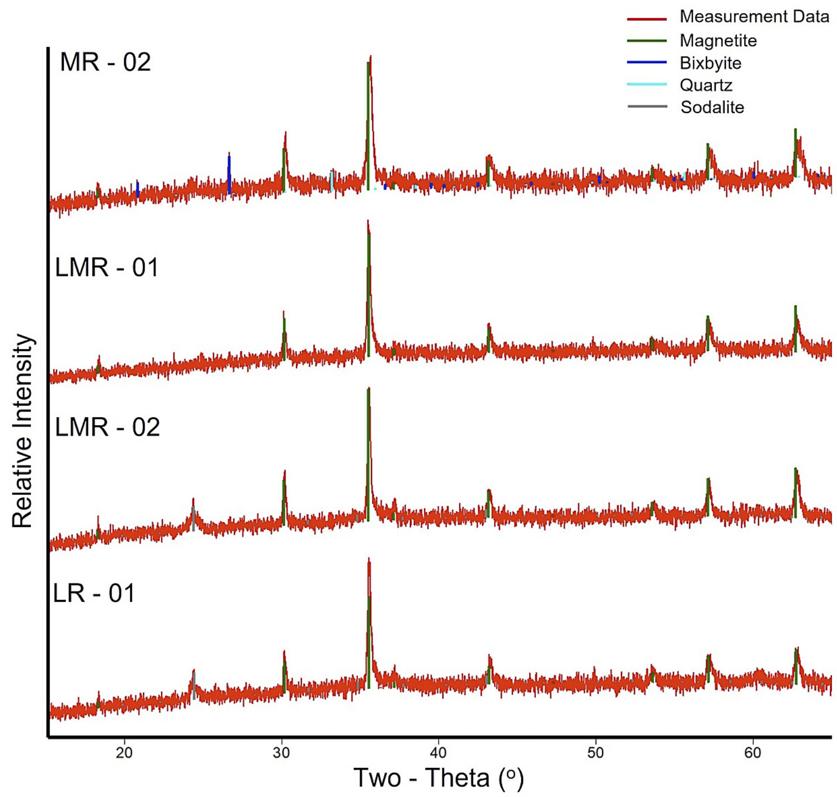

Figure 4: XRD measurement result for this study's result. There are differences in mineral content for each sample. MR – 02 is composed of the magnetite, bixbyite, and quartz minerals. LMR-01 only contains magnetite minerals, LMR-02 and LR-01 consist of magnetite and sodalite minerals.

4. Discussion

This study is one of the few studies on the magnetic characteristics of river sediments in ultramafic areas. **Figure 3a** and **Figure 3b** show that the magnetic hysteresis parameters of the samples in this study fall between the parameters of samples from Dongbo ophiolite in SW Tibet (**Li et al., 2017**), indicating that the magnetic minerals in these samples originated mainly from ultramafic rocks. The variation of magnetic hysteresis parameters

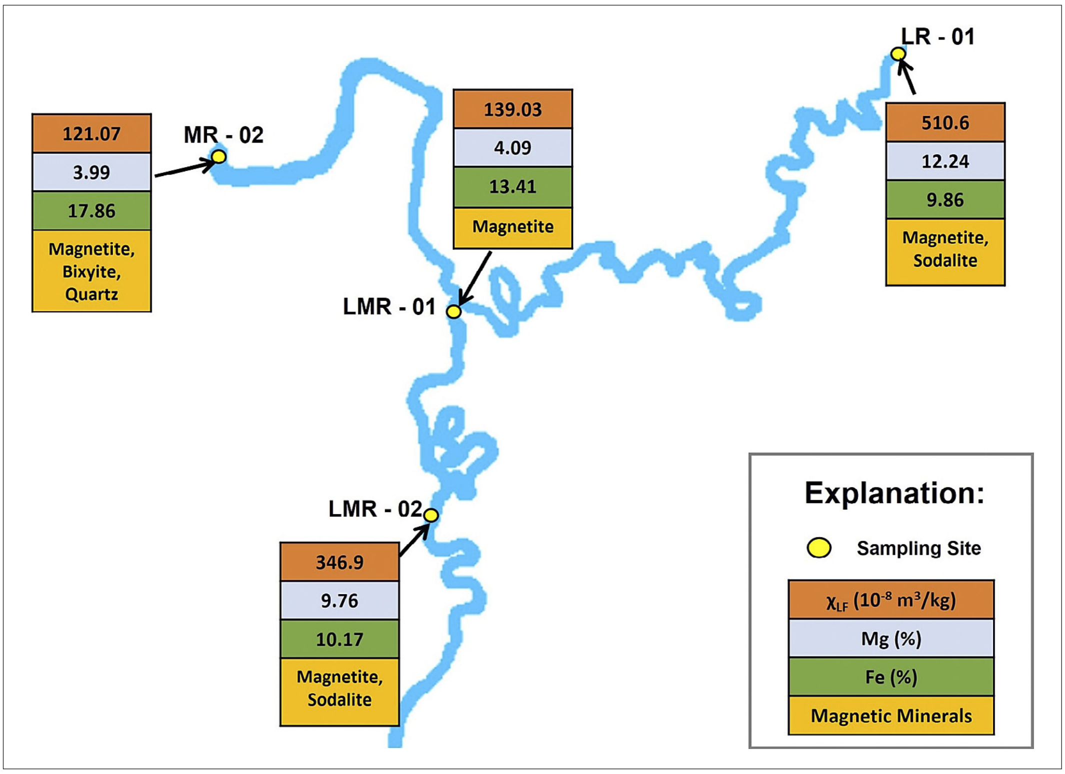

Figure 5: The schematic of the important parameters/characters (the average χ_{LF} values, the average Mg and Fe content, as well as the predominant minerals after magnetic extraction) of the LR and MR sediments before and after the two rivers converge prior to entering Lake Towuti.

in samples of **Li et al. (2017)** is partly due to the variation in rock types, i.e. dunnite, harzburgite, and serpentinite. **Costa et al. (2015)** also described the area around Lake Mahalona as being dominated by dunnite and harzburgite.

Apart from the obvious magnetite, the extracted magnetic grains show the presence of other minerals, namely bixbyite (in MR-02) and sodalite (in LR-01). Depending on the Fe content and its structure, bixbyite might be magnetic but not as magnetic as magnetite (**Cockayne et al., 2013; Roth et al., 2019**). As bixbyite contains Mn, the presence of bixbyite in MR sediments might contribute to the high Mn content in these sediments. So how can the non-magnetic sodalite be magnetically extracted? One possible explanation is the presence of magnetic minerals with a sodalite structure. The most likely candidate is valleyite ($Ca_4(Fe, Al)_6O_{13}$), a mineral discovered in 2017 (**Hålenius et al., 2017**). **Lee et al. (2019)** studied the magnetic properties of valleyite from the late Pleistocene basaltic scoria of the Menan Volcanic Complex in the USA. Interestingly, valleyite could only be identified by synchrotron X-ray Diffraction and not by conventional XRD (**Xu et al., 2020**). Valleyite has also been found to be associated with esseneite, a mineral of the pyroxene group with a formula of $CaFe^{3+}[AlSiO_6]$. **Cosca and Peacor (1987)** identified esseneite as a product of pyrometamorphism that occurred in both natural and anthropogenic coal-fire sites. **Lee et al. (2019)** have also successfully created a synthetic valleyite by placing powdered nontronite in a furnace at 850°C for two days. At least three implications follow if valleyite is indeed found in LR samples: first, valleyite might contribute to the high magnetic susceptibility of LR samples. Second, valleyite might also contribute to the relatively high Ca content in LR samples. Third, valleyite might have originated from anthropogenic sources such as man-made fires in the human settlements along LR. Further research on the presence of valleyite in LR is required.

Results of magnetic and geochemical analyses show that LR samples have a lower content of Fe but higher magnetic susceptibility compared to MR samples. Intuitively, one might think that higher Fe content is associated with higher magnetic susceptibility. **Costa et al. (2015)** described that LR originated from the zone of serpentinized peridotite. An earlier study by **Liu et al. (2012)** showed that serpentinized peridotite has high magnetic susceptibility. Later, **Li et al. (2017)** suggested that, depending on its degree, serpentinization might produce highly magnetized magnetite. The higher M_s value in the LR sample supports this possibility. Compared to MR samples, the M_s value of the LR sample is significantly higher (see **Table 1**). The value of M_s indicates the maximum possible magnetization of ferromagnetic material. A higher M_s value indicates stronger magnetic properties. Thus, the smaller amount of magnetite in LR samples might have a stronger magnetic susceptibility compared to that in MR samples. Moreover, serpentinite minerals have been known to have high Mg content (**Moody, 1976, de Obeso and Kelemen, 2020**).

Figure 5 summarizes the important parameters/characters of the LR and MR sediments before and after the two rivers converge prior to entering Lake Towuti. The key parameters are the average χ_{LF} values, the average Mg and Fe content, as well as the predominant minerals after magnetic extraction. This type of representation shows that magnetic characteristics together with geochemical analyses could be used to differentiate the source of river sediments or monitor the changes that have occurred in the sediments. Earlier, **Jordanova et al. (2004)** used the same approach to delineate the anthropogenic magnetic phases in the sediment along the Bulgarian part of the Danube River. Later, **Franke et al. (2009)** used magnetic and geochemical signatures to monitor the anthropogenic components in the Seine River, France. **Sudarningsih et al. (2017)** used the same methodology to monitor the sediments of the Citarum River and its seven tributaries near Bandung, Indonesia. As the Citarum River originated in the volcanic areas, the unpolluted sediments have higher χ_{LF} values compared to those of the polluted sediments downstream. **Sudarningsih et al. (2017)** concluded that applying magnetic methods for monitoring river pollution in the tropics or volcanic areas should be carefully analysed and interpreted**.**

Lake Towuti has at least three identifiable and isolated basins (**Russell et al., 2016**); one of them is located in the southern part of the lake. Much of the work, including the TDP drilling, is concentrated in the northern part of the lake. Thus, the transportation and sedimentation processes in the southern part of Lake Towuti are not well studied. **Costa et al. (2015)** have identified several rivers in the southern part of the lake originating from areas that have different lithology compared to the northern part of the lake. Information provided by **Costa et al. (2015)** could serve as a starting point for future studies using combined magnetic and geochemical analyses similar to this study.

5. Conclusion

This study shows the importance of sediment-source identification in big lakes such as Lake Towuti, where the influx could come from several rivers around the lake. The predominant magnetic mineral in the surface sediments of this study is PSD magnetite. However, LR and MR samples have different magnetic and geochemical characteristics. LR samples have a high average χ_{LF} value, a low average $\chi_{FD\%}$, and high Mg content compared to MR samples. These differences are likely due to the differences in their respective lithologies. LR samples originate from serpentinized peridotite rocks with high Mg content. LR samples might also contain a magnetic mineral with a sodalite structure, suspected to be Ca-rich valleyite, that might be generated by anthropogenic activities. These findings infer that LR samples might be responsible for the high Mg and Ca content in the northern part of Lake Towuti. The presence of valleyite, however, needs to be confirmed and validated further.

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SAŽETAK

Geokemija i magnetska analiza stijena površinskoga sedimenta rijeke Lampenisu: potraga za izvorom magnezija u jezeru Towuti, Indonezija

Sediment iz jezera Towuti opsežno je istraživan kako bi se rekonstruirale klimatske i okolišne promjene u prošlosti. Jedno od preostalih pitanja jest izvor magnezija (Mg) i kalcija (Ca) u sjevernome dijelu jezera Towuti. U ovome istraživanju izvor visokoga sadržaja Mg i Ca ispitan je analizama površinskoga sedimenta iz rijeke Lampenisu (LR) i rijeke Mahalona (MR) koje se spajaju prije ulaska u jezero Towuti. Dvanaest površinskih sedimenata iz MR, LR i ušća dviju rijeka (LMR) podvrgnuto je geokemijskoj (XRF), mineraloškoj (XRD) i magnetskoj analizi stijena (susceptibilnost i parametar histereze). Rezultat pokazuje da je sadržaj Mg i Ca u LR uzorcima veći nego u MR uzorcima. LR uzorci imaju veću susceptibilnost i manju susceptibilnost ovisnu o frekvenciji od MR uzoraka. XRD analize ekstrahiranih magnetskih zrnaca pokazale su prisutnost minerala s kristalnom strukturom sodalita, moguće valleyita u LR, ali ne i u MR uzorcima. Ako se valleyit doista pojavljuje u LR uzorcima, to može pridonijeti njihovu relativno visokom sadržaju Ca. Istodobno, visok sadržaj Mg u uzorcima LR vjerojatno je posljedica serpentiniziranih stijena peridotita. S obzirom na navedeno, LR se smatra izvorom visokoga sadržaja Mg i Ca u sjevernome dijelu jezera Towuti. Ovo istraživanje pokazalo je važnost identifikacije izvora sedimenta u velikim jezerima kao što je jezero Towuti, gdje donos materijala može dolaziti iz nekoliko rijeka oko samoga jezera.

Ključne riječi:
jezero Towuti, rijeka Lampenisu, magnezij, magnetizam stijena, geokemija

Author's contribution

Silvia Jannatul Fajar (1) (M.Eng., Lecturer, with a research interest in rock magnetism, especially in lake sediments) performed the surface sediment sample data collection, magnetic and geochemistry measurements and processing, performed data interpretation, composed the original and final manuscripts, and performed project administration. **Putu Billy Suryanata (2)** (M.Eng., Ph.D. student) performed visualisation as well as composed the original and final manuscript. **Wahidah Wahidah (3)** (M.Eng. Lecturer, with a research interest in rock magnetism, especially in lake sediments) performed the surface sediment sample data collection, magnetic and geochemistry data measurements and processing, provided the data interpretation, and composed the original and final manuscripts. **Abd. Hafidz (4)** (M.Eng., Ph.D. student) performed the surface sediment sample data collection and figure visualisation and composed the original and final manuscripts. **Satria Bijaksana (5)** (Ph.D., Professor in Rock Magnetism) provided rock magnetic interpretation and composed the original and final manuscripts. **Darharta Dahrin (6)** (Ph.D., Associate Professor in Geophysics) provided statistical analysis of the data and their interpretation and composed the original and final manuscripts. **Irwan Iskandar (7)** (Ph.D., Associate Professor in Mining Hydrology) provided interpretation of geochemistry data and composed the original and final manuscripts.