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Geochemical and magnetic characteristics of placer gold deposits from Central Kalimantan, Indonesia

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Gusfrimanuel Nahan[1]; **Satria Bijaksana**[2]; **Putu Billy Suryanata**[3]; **Khalil Ibrahim**[4]

[1] *Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jalan Ganesa 10, Bandung 40132, Indonesia. https://orcid.org/0000-0002-9892-2067*

[2] *Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jalan Ganesa 10, Bandung 40132, Indonesia. https://orcid.org/0000-0001-6374-4128*

[3] *Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jalan Ganesa 10, Bandung 40132, Indonesia. https://orcid.org/0000-0001-6701-2311*

[4] *Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jalan Ganesa 10, Bandung 40132, Indonesia. https://orcid.org/0000-0002-7108-5457*

Abstract

Massive tailings have resulted from the extensive use of placer deposits in Central Kalimantan, Indonesia, by artisanal and small-scale gold mining (ASGM) activities. Recently, the placer deposits and their tailings have been exploited for heavy minerals. In this study, geochemical and magnetic analyses were carried out on these deposits to identify the prospect of REE (rare earth element) exploration in the materials already collected by ASGM activities. Samples were collected from ten different locations. For each location, two different fractions were prepared for analyses, i.e. the heavy mineral (HM) fraction and the panned (M60) fraction. All HM and M60 samples were subjected to magnetic susceptibility measurements, but only representative samples were subjected to x-ray fluorescence (XRF) measurements (for Si, Ti, Fe, Zr, and Al) and to inductively coupled plasma-emission spectroscopy (ICP-OES) measurements (for Eu, Tb, Dy, and Sc). The results showed that the concentrations of major elements (Ti, Fe, Zr, and Al) vary significantly from deposits along one river to another, while the concentration of Si is rather similar. Compared to M60 samples, the HM samples have higher concentrations of Ti, Fe, Zr, Al, and Sc, implying that the sluice-box separation enhances the concentration of valuable minerals. Magnetic susceptibility is found to be correlated with Fe and Sc concentrations, confirming the potential use of magnetic measurements as a complementary tool for Fe and Sc exploitation in placer deposits. It is believed that both the source rocks and the sedimentary settings of these deposits determine whether certain elements (Sc, Fe, and Zr) are present or absent in Central Kalimantan placer deposits. The prospect of exploring and exploiting Sc in these placer deposits might augment the ASGM activities in Central Kalimantan.

Keywords:
ASGM; REE; magnetic susceptibility; placer deposits; Central Kalimantan

1. Introduction

Rare earth elements (REEs) are seen as strategic resources because they are in high demand for new technologies (**Balaram, 2019; Mancheri et al., 2019**). Therefore, governments in various countries, including Indonesia, are trying to explore these resources. A preliminary report by the Geological Agency of the Republic of Indonesia hinted that placer minerals associated with tin deposits on Bangka Island might contain REEs (**PSDMBP, 2019**). In nearby Malaysia, **Fauzi et al. (2019)** and **Setiady and Aryanto (2009)** identified REE prospects in placer deposits derived from granitic source rocks. Similar studies have been carried out on placer deposits in other areas, such as Kazakhstan (**Suiekpayev et al., 2021**), Sri Lanka (**Batapola et al., 2020**), China (**Van Gosen et al., 2019**), Turkey (***Öztürk* et al., 2019**), Greece (**Papadopoulos et al., 2019),** the USA (**Bern et al., 2016**), and Europe (**Goodenough et al., 2016**). In the southwestern part of Indonesian Kalimantan, the granitoid igneous rocks as well as the metamorphic rocks of the Schwaner Mountains are believed to be the source of placer deposits in the Central Kalimantan Province (**Herman, 2007**). These placer deposits have been exploited for decades by local people for artisanal and small-scale gold mining (ASGM). In the last ten years, the heavy minerals, especially zircons, that were in the waste from these ASGM activities have been reprocessed. Heavy mineral tailings are sold by local miners to local companies that will continue to process and refine these heavy minerals.

The main goal of this study is to find out if there is any chance of REE exploration in materials that have already

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Corresponding author: Satria Bijaksana
e-mail address: satria@fi.itb.ac.id

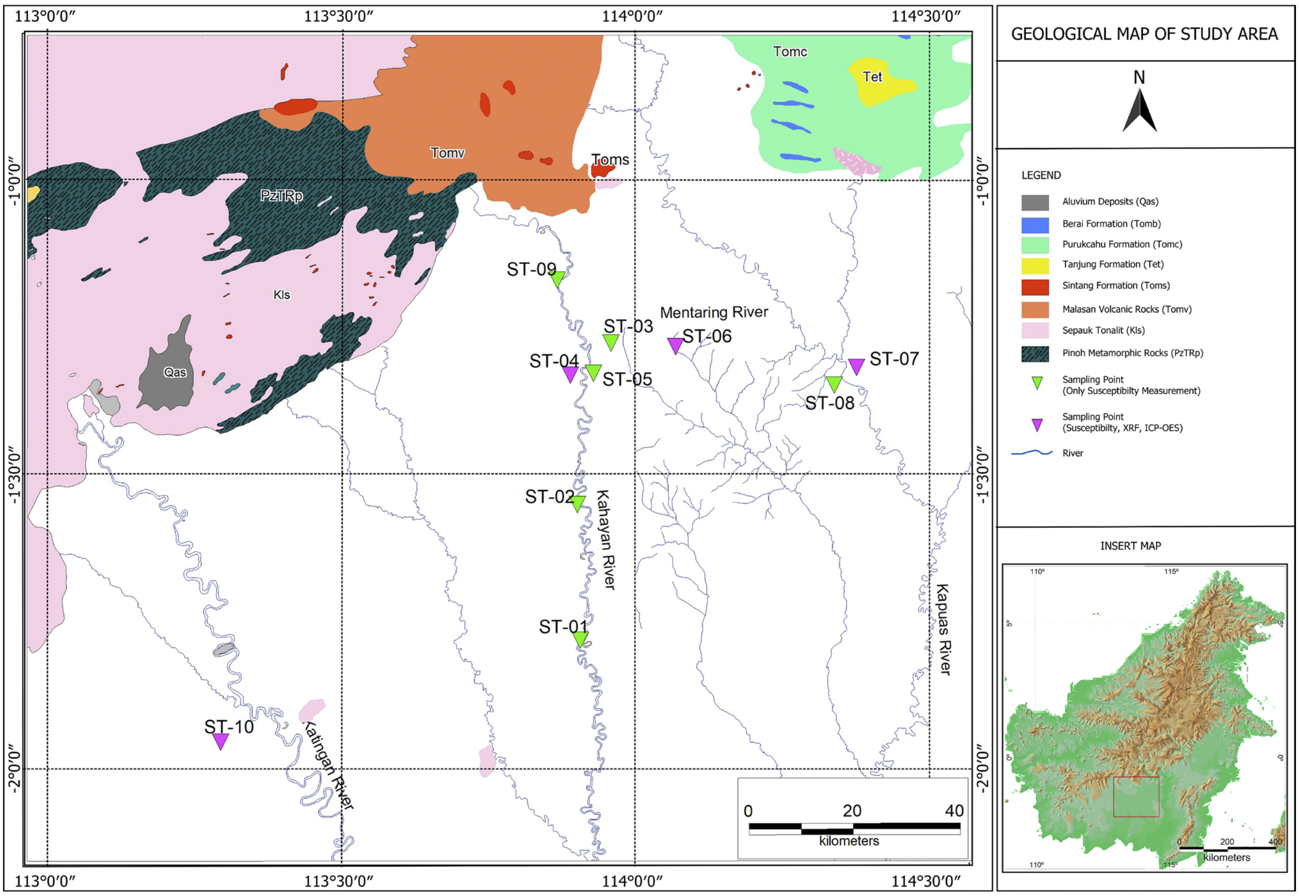

Figure 1: A geological map of the study area (modified from **Sumartadipura and Margono, 1996**), where the green inverted triangle represents the sampling point tested for magnetic properties and the magenta inverted triangle represents the sampling points tested for magnetic properties as well as geochemistry.

been collected by artisanal heavy mineral mining in Central Kalimantan Province. The other goal is to find out if there is a link between REEs and how magnetic these placer deposits are. **Sudarningsih et al. (2017)** as well as **Wang and Qin (2005)** have shown that magnetic susceptibility values correlate well with certain heavy elements. Such correlation is important for REE exploration, as magnetic susceptibility measurements are much simpler, easier, cheaper, and can be measured in situ than geochemical analyses. To achieve these objectives, magnetic susceptibility analyses were performed on samples collected from placer deposits in the ASGM area. Based on the magnetic analysis results, selected samples were also subjected to ICP-OES measurements to obtain REEs data and selected major elements (Fe, Ti, Zr, Al, and Si) from XRF measurements.

2. Materials and Methods

Figure 1 shows the alluvial plain in the Central Kalimantan Province of Indonesia. The source rocks of the alluvial deposits consist of Malasan volcanic rocks, Sepauk tonalite, and Pinoh metamorphic rocks (**Sumartadipura and Margono, 1996**). The samples were collected from ten different locations along four different rivers (Kahayan, Kapuas, Mentaring, and Katingan) in the Central Kalimantan Province (see **Figure 1**). Six locations (ST-01, ST-02, ST-03, ST-04, ST-05, and ST-09) are along the main river (Kahayan), two locations (ST-07 and ST-08) are along the Kapuas River, and one location is respectively along the Mentaring (ST-06) and Katingan (ST-10) rivers. The samples were collected from the alluvial deposits that have been exploited by artisanal gold mines (see **Figure 2**). The HM samples were extracted using panning methods as well as a by-product of ASGM (artisanal small-scale gold mining) activities from placer deposits. About 10 kg of HM were obtained from the ASGM area in each location. Apart from the extracted HM, about 5 kg of bulk placer deposits from each location were also collected and sieved with a 60-mesh (fraction less than 250 microns) screen to obtain fine sand (M60 samples).

The HM and M60 samples were then subjected to magnetic parameter measurements in accordance with the procedures outlined by **Yunginger et al. (2018)**. Three specimens were prepared for each of the HM and M60 samples. The preparation process for magnetic susceptibility is carried out as in **Santoso et al. (2017)**. In this investigation, a dual-frequency MS2B sensor that operates at both 470 Hz and 4700 Hz was utilised with a

Figure 2: Sampling locations: (a) placer deposit from Kahayan River (ST-04); (b) placer deposit from Katingan River (ST-10); (c) HM panning process on placer deposit from Mentaring River (ST-6); (d) placer deposit from Kapuas River (ST-07). Note that the ASGM miners hire heavy equipment, such as excavators, for land clearing, so that the mining area is quite extensive.

Bartington MS3 magnetic susceptibility system (Bartington Instruments Ltd., Witney, UK) to measure the mass-specific low-frequency and high-frequency magnetic susceptibilities, termed χ_{LF} and χ_{HF}, respectively. The frequency-dependent magnetic susceptibility ($\chi_{FD\%}$) could be calculated using the following equation: $\chi_{FD\%} = 100\% \, (\chi_{LF} - \chi_{HF})/\chi_{LF}$. These magnetic measurements were made in a facility at the Institut Teknologi Bandung. Since magnetite and hematite are ferromagnetic mineral phases, the parameter χ_{LF} is frequently used as a proxy indicator of the concentration of magnetic minerals (**Dearing, 1994; Dearing, 1999; Sudarningsih et al., 2017; Yunginger et al., 2018**). Meanwhile, higher values of $\chi_{FD\%}$ indicate higher concentrations of superparamagnetic (SP) fine grains and vice versa (**Dearing, 1999**). Superparamagnetic is a fine magnetic grain that has a strong but unstable magnetization behaviour due to thermal energies counteracting induced magnetization very quickly after a magnetic field is removed. This behaviour is similar to paramagnetism but with a much greater susceptibility (**Dearing, 1999**).

Unlike magnetic susceptibility measurements, XRF and ICP-OES measurements use a few selected samples. Selected HM and M60 samples from four locations (ST-04, ST-06, ST-07, and ST-10) representing each river were subjected to XRF (X-ray fluorescence) analyses using an XRF Thermo Scientific type ARL 9900 (Thermo Fisher Scientific, Waltham, MA, USA) to obtain major element (Si, Ti, Fe, Zr, Al) and to inductively coupled plasma atomic-optical emission spectrometry (ICP-OES) analyses using a ProdigyPlus ICP-OES (Teledyne Leeman Labs, Mason, OH, USA) to obtain seventeen REE elements (Y, Pm, Er, Yb, Tm, Lu, Ho, Sc, Gd, Dy, Sm, Ce, Eu, La, Tb, Pr and Nd). XRF samples were prepared using fused beads made from fine powder mixing (200-mesh size, or < 75µm). The fused beads are 3 mm thick, and the mass of each sample is about 10 g. The XRF analyses were carried out at the Central Laboratory of the Indonesian Geological Survey in Bandung. The ICP-OES analyses were carried out at the Nuclear Minerals Technology Laboratory (Laboratorium Teknologi Bahan Galian Nuklir) of BRIN (Badan Riset dan Inovasi Nasional, or National Research and Innovation Agency) in Serpong. As solid samples cannot be introduced into the plasma directly, they have to be dissolved using acid digestion. The QA/QC protocol for both analyses was carried out by professional technicians in the respective laboratories.

3. Results

Table 1 shows the concentration of selected elements (Fe, Ti, Zr, Al, and Si) in HM and M60 samples from ST-04, ST-06, ST-07, and S-10 locations. The Si concen-

Table 1: Selected Major Elements based on XRF measurement from a selected sample in each river

Rivers	Sample Code	Major Elements (wt. %)				
		Si	Ti	Fe	Zr	Al
KAHAYAN	ST-04-HM	19.57	14.63	7.72	7.22	4.74
MENTARING	ST-06-HM	17.54	3.19	1.98	34.70	2.38
KAPUAS	ST-07-HM	27.63	9.65	4.79	4.17	3.89
KATINGAN	ST-10-HM	28.08	14.07	2.92	2.44	2.46
Max		28.08	14.63	7.72	34.70	4.74
Min		17.54	3.19	1.98	2.44	2.38
Average		23.21	10.39	4.35	12.13	3.37
KAHAYAN	ST-04-M60	42.08	1.94	1.41	0.70	1.27
MENTARING	ST-06-M60	45.43	0.16	0.71	0.19	0.18
KAPUAS	ST-07-M60	42.73	1.94	1.17	0.42	0.88
KATINGAN	ST-10-M60	43.16	1.86	0.94	0.19	0.98
Max		45.43	1.94	1.41	0.70	1.27
Min		42.08	0.16	0.71	0.19	0.18
Average		43.35	1.47	1.06	0.38	0.83

Table 2: Rare Earth Elements based on ICP-OES measurement from a selected sample in each river

Rivers	Sample Code	Rare Earth Elements (ppm)			
		Eu	Tb	Dy	Sc
KAHAYAN	ST-04-HM	7.80	7.30	n.d.	51.30
MENTARING	ST-06-HM	7.40	6.70	5.10	n.d.
KAPUAS	ST-07-HM	7.10	5.60	2.10	40.90
KATINGAN	ST-10-HM	6.70	7.10	7.50	n.d.
Max		7.80	7.30	7.50	51.30
Min		6.70	5.60	n.d.	n.d.
Average		7.25	6.68	4.90	46.10
KAHAYAN	ST-04-M60	8.00	8.00	0.90	7.30
MENTARING	ST-06-M60	6.90	7.10	7.90	n.d.
KAPUAS	ST-07-M60	7.70	7.60	12.80	6.40
KATINGAN	ST-10-M60	6.80	6.50	5.80	4.20
Max		8.00	8.00	12.80	7.30
Min		6.80	6.50	0.90	n.d.
Average		7.35	7.30	6.85	5.97

n.d.: not detected.

tration in HM samples is generally lower than that in M60 samples, inferring that the separation by panning or sluice boxes tends to eliminate Si. The Si concentrations in all M60 samples are rather similar, averaging 43.35 wt.%. On the other hand, the concentration of other major elements (Ti, Fe, Zr, and Al) in HM samples is higher than that in M60 samples, inferring that the separation by sluice boxes tends to enhance the concentrations of these elements. The Zr concentration in the Mentaring River HM sample ST-06 is unusually high.

Table 2 shows the concentration of selected REEs (Eu, Tb, Dy, and Sc) for HM and M60 samples from ST-04, ST-06, ST-07, and ST-10 locations. Seventeen REEs were measured using ICP-OES, but most elements, except Eu, Tb, Dy and Sc could not be detected in all samples. The element Sc in the periodic table belongs to the transition metals. However, Sc is considered a rare-earth element because it tends to occur in the same ore deposits as the lanthanides and exhibits similar chemical properties but has different electronic and magnetic properties (**Klimpel et al., 2021**). In this study, except for that of Sc, the concentration of REEs in HM samples is rather similar to that of M60 samples, inferring that the separation panning methods do not enhance the concentration of REEs. However, separation by panning methods apparently enhanced the concentration of Sc in HM samples from ST-04 and ST-07. The concentration of Sc in these samples is significantly higher than that in the respective M60 samples. The Sc concentration in the HM and M60 samples from ST-06 was not detected. For ST-10, the Sc concentration is not detected in the HM sample, even though it is detected at 4.20 ppm in the M60 sample. The inconsistency of the ST-06 sample for the Sc element is probably caused by the difference in the sample batches used for the HM and M60 samples.

The values of χ_{LF} in HM samples are higher than those in M60 samples (see **Table 3**), inferring that the separation by sluice boxes tends to enhance the concentrations of magnetic minerals. As shown earlier, the separation by sluice boxes also enhances the concentration of Fe in HM samples. The values of χ_{LF} vary greatly between locations, even along the same river. The M60 sample of ST-06 (Mentaring River) has a negative χ_{LF} value. Assuming that the values of χ_{LF} depend on the concentration of Fe, the distribution of χ_{LF} values in **Table 3** infers that the Fe concentration also varies greatly, supporting the data in **Table 1**. The $\chi_{FD\%}$ values in HM samples are generally smaller than those in M60 samples (see **Table 3**), indicating that the separation by sluice boxes reduces the concentration of SP grains. With few exceptions (ST-02 and ST-06), the $\chi_{FD\%}$ values of HM samples are between 2 and 10%, implying, magnetically, the admixture of SP and coarser non-SP grains or SP grains < 0.005 µm (**Dearing, 1999**).

4. Discussion

The results showed that the concentrations of major elements and REEs in the four rivers varied. For example, the Zr content in the Mentaring River is much higher than the content in the other three rivers. Meanwhile, the Fe content in the Kahayan and Kapuas rivers was higher than the content in the other two rivers. Except for the Mentaring River, all rivers contained Sc. The variation of major elements is summarised in **Figure 3**, while **Figure 4** summarises the variation of REE. The source rocks of each river influence the variety of major

Table 3: Magnetic susceptibility values of all samples

Rivers	Sample Code	χ_{LF} (10^{-8} m^3/kg)		% χ_{FD}	
		M60	HM	M60	HM
KAHAYAN	ST-01	195.10 ± 4.45	978.67 ± 61.56	3.6	2.6
	ST-02	141.26 ± 19.62	727.32 ± 124.19	2	1.5
	ST-03	1.12 ± 0.29	42.41 ± 3.95	7.1	3.8
	ST-04	13.72 ± 2.08	111.89 ± 8.43	4.4	3.5
	ST-05	257.94 ± 8.04	1581.7 ± 54.09	4	2.4
	ST-09	4.57 ± 0.09	96.84 ± 1.03	6.4	6.3
KAPUAS	ST-07	3.74 ± 0.32	30.48 ± 0.28	12.6	5.6
	ST-08	3.24 ± 0.15	32.76 ± 0.66	3.5	3.9
KATINGAN	ST-10	0.37 ± 0.43	9.92 ± 1.03	1.5	2.2
MENTARING	ST-06	-	23.13 ± 0.96	-	1
MIN		-0.29	9.92	0	1
MAX		257.94	1581.7	12.6	6.3

elements and REEs. The common source rocks of the Kahayan and Kapuas rivers are the Malasan volcanic rocks as well as Sepauk tonalite (see **Figure 1**). The Kahayan River also passes through Pinoh metamorphic rocks. The similarity of Sc concentrations in ST-04 and ST-07 infers that it is very likely that Sc originated from Sepauk tonalite. An earlier study on Cornucopia tonalite from Oregon, USA, shows the presence of Sc (**Johnson et al., 1997**). Even though the Katingan River has the same source rock as the Kahayan River, the ST-10 sampling location is relatively far from the source, causing a low concentration of Fe in the sample. On the other hand, the Fe and Sc content in the Mentaring River was relatively lower compared to other locations. This can be caused because the Mentaring River is a tributary of the Kapuas River and does not originate in mountainous areas. The deposits along the Mentaring River are reworkings of placer deposits that are older than the Kapuas River. This can also explain why the Zr content in the Mentaring River is much higher compared to other rivers. In other sedimentary environments, Zr is associated with Ti (**Mehedi Hasan et al., 2022**), but in the reworked alluvial deposits of the Mentaring River, high Zr content is not accompanied by high Ti content.

The REE content, especially Sc, in placer deposits in Central Kalimantan is comparable to the Sc content in other deposits, for example, alkali-carbonatite deposits in Brazil, which have a range of Sc_2O_3 values in the

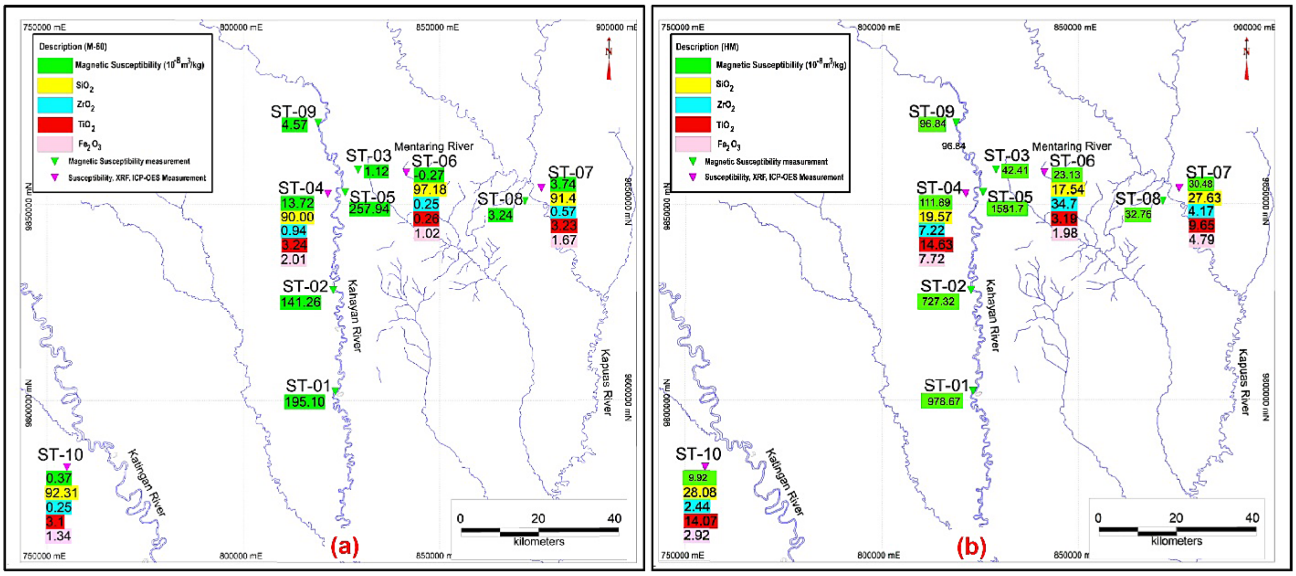

Figure 3: Distribution of magnetic properties and major elements from XRF measurements in each river
(a) Concentration of magnetic properties and selected major elements in M60 samples
(b) Concentration of magnetic properties and selected major elements in HM samples.

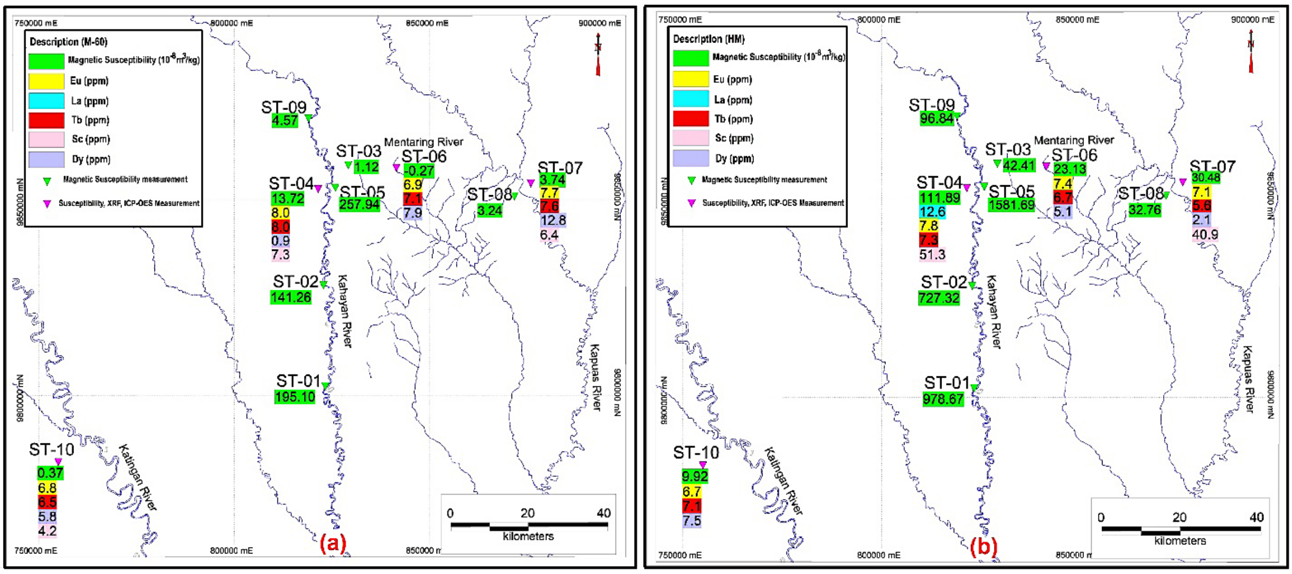

Figure 4: Distribution of magnetic properties and REE from ICP-OES measurements in each river
(a) Concentration of magnetic properties and REE in M60 samples
(b) Concentration of magnetic properties and REE in HM samples.

Table 4: Correlation of REEs with Magnetic Susceptibility (χ_{LF}) for HM and M60 samples. Bold numbers indicate significant correlations (> 0.6).

PARAMETER	Si	Ti	Fe	Zr	Al	Eu	Tb	Dy	Sc
χ_{LF}	-0.66	**0.67**	**0.93**	0.19	**0.84**	0.44	0.02	-0.63	**0.84**
Si		-0.68	-0.71	-0.71	-0.84	-0.10	0.32	0.45	-0.47
Ti			**0.85**	-0.01	**0.85**	-0.08	-0.19	-0.39	**0.62**
Fe				0.09	**0.95**	0.24	-0.22	-0.62	**0.91**
Zr					0.27	0.13	-0.20	-0.15	-0.08
Al						0.19	-0.36	-0.64	**0.84**
Eu							0.59	-0.32	0.33
Tb								0.15	-0.30
Dy									-0.63

range of 8–435 ppm (**Antoniassi et al., 2020**), although it is still lower than the Sc concentration in the Bear Lodge deposit (165 ppm) in the United States (**Cui and Anderson, 2017**). In the world of mining, the concentration of minerals sought is not the only important parameter. Ease of processing is the basis for other considerations (**Botelho Junior et al., 2021**). The presence of Sc in the tailings from ASGM makes the exploitation of Sc in Central Kalimantan an attractive option.

A report by the **World Gold Council (2022)** explains that 20% of world gold production is produced by ASGM activities. The same report also states that around the world, no less than 20 million people depend on ASGM activities and provide for 100 million people. Although ASGM activities have potential hazards, such as environmental pollution due to the use of mercury, there have been efforts to reduce or eliminate the use of mercury in ASGM activities (**UNEP, 2012**). In Central Kalimantan, Indonesia, ASGM activities are also related to regulatory uncertainty and overlapping authorizations, so ASGM activities take place intermittently (**Lombah et al., 2021**). For artisanal miners in Central Kalimantan, HM exploration from waste or tailings is an option. The prospect of the existence of Sc in two locations is one of the possibilities for adding economic value from tailings, which can then improve the welfare of local communities. The economic value of Sc is far greater than that of other REEs (**Botelho Junior et al., 2021**).

Table 4 shows the results of the correlation between magnetic susceptibility and the concentrations of the main elements and REEs. Although the number of samples is limited ($N = 8$), **Table 4** shows that the χ_{LF} value is significantly correlated with the concentrations of Fe, Al, and Sc. This indicates that it is possible to use magnetic susceptibility (χ_{LF}) as a proxy indicator to detect Sc, but that one still uses geochemical data to perform geochemistry. Also, the measurement of magnetic susceptibility is simpler, easier, and cheaper. Unlike geochemical measurements, it can be measured in situ. A significant correlation between χ_{LF} and Sc has been previously reported by **Wang and Qin (2005)**, who conducted a study of urban topsoil in China. On the other hand, the correlation between Fe and Sc also shows that the HM separation process will increase the concentration of Sc. The mineral association between Fe and Sc has been documented in lateritic soils where Sc is present with goethite and hematite (**Santoro et al., 2022**). The correlation between Sc and Al_2O_3 has also been reported by **Teitler et al. (2022)**.

5. Conclusion

Geochemical measurements on placer deposits from Central Kalimantan, Indonesia, reveal that certain deposits contain REEs, in particular Sc. The deposits along the larger Kahayan and Kapuas rivers contain a sizable concentration of Sc. The concentrations of other REEs (Eu, Tb, and Dy) are rather similar in the four rivers, and their values are lower than those of Sc from the Kahayan and Kapuas rivers. The results show that placer deposits along a particular river might have different characteristics and mineral compositions, implying that systematic mapping is required for future exploration and exploitation of Sc or any other valuable elements. In general, the HM samples have higher concentrations of Ti, Fe, and Zr, as expected by the local miners who extracted the HM samples using sluice boxes. The availability of HM samples from local miners is an attractive proposition for Sc exploration and exploitation in these placer deposits. As χ_{LF} value correlates well with Fe and Sc concentration, it might be possible to use magnetic measurements as a complementary tool for Fe and Sc exploration in placer deposits.

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SAŽETAK

Geokemijske i magnetne karakteristike nanosnih ležišta zlata u središnjem Kalimantanu, Indonezija

Ogromne količine jalovine rezultat su prekomjerne eksploatacije nanosnih ležišta u središnjem Kalimantanu, Indonezija,zanatskim rudarenjem zlata malih razmjera (ASGM). U novije vrijeme iz tih ležišta i njihove jalovine eksploatirani su i teški minerali. U ovom istraživanju, provedene su geokemijske i magnetne analize uzoraka nanosnih ležišta kako bi se utvrdile mogućnosti istraživanja REE (elemenata rijetkih zemalja) u materijalima koji su već prikupljeni ASGM aktivnostima. Uzorci su prikupljeni s deset različitih lokacija. Sa svake lokacije za analizu su pripremljene dvije različite frakcije, tj. frakcija teških minerala (HM) i šlih (M60). Svi uzorci i njihove frakcije (HM i M60) su podvrgnuti mjerenju magnetne susceptibilnosti, dok su samo reprezentativni uzorci analizirani rendgenskom fluorescencijom-XRF (Si, Ti, Fe, Zr i Al) i induktivno spregnutom plazmom-emisijskom spektroskopijom-ICP-OES (Eu, Tb, Dy i Sc). Rezultati su pokazali da koncentracije glavnih elemenata (Ti, Fe, Zr i Al) značajno variraju u ležištimarazličitih rijeka, dok je koncentracija Si vrlo slična. U usporedbi s uzorcima M60, uzorci HM imaju više koncentracije Ti, Fe, Zr, Al i Sc, što upućuje na to da separacija na uređaju za ispiranje zlata povećava koncentraciju vrijednih minerala. Utvrđeno je da je magnetna susceptibilnost u korelaciji s koncentracijama Fe i Sc, što potvrđuje potencijalnu upotrebu magnetnih mjerenja kao komplementarnog alata za eksploataciju Fe i Sc u nanosnim ležištima. Vjeruje se da izvorišne stijene kao i sedimentni dijelovi ovih ležišta određuju jesu li određeni elementi (Sc, Fe i Zr) prisutni ili odsutni u nanosnim ležištima središnjeg Kalimantana. Perspektivnost istraživanja i eksploatacije Sc u nanosnim ležištima mogli bi povećati ASGM aktivnosti u središnjem Kalimantanu.

Ključne riječi:
ASGM, REE, magnetna susceptibilnost, nanosna ležišta, središnji Kalimantan

Author's contribution

Gusfrimanuel Nahan (1) (M.Eng., Geological Engineering with expertise in mineral exploration) performed the field work and sample data collection, magnetic data measurements and processing, provided the data interpretation, composed the original draft and editing and project administration. **Satria Bijaksana (2)** (Ph.D., Professor, expert on rock magnetism) performed the field work and sample data collection, provided the rock magnetism data interpretation, editing draft, held funding acquisition, supervision, and project administration. **Putu Billy Suryanata (3)** (M.Eng., Geophysical Engineering with expertise in rock magnetism for volcanoes) performed the field work and sample data collection, provided the data interpretation, editing draft and project administration. **Khalil Ibrahim (4)** (M.Eng., Geophysical Engineering with expertise in geophysical exploration) provided the data interpretation and draft editing.