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MDPI

Data Descriptor

High-Resolution Magnetic Susceptibility Dataset from Borehole Samples from the "Rudnik" Mine Tailings, Republic of Serbia

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Abstract

In 2024, high-resolution (10 cm resolution) magnetic susceptibility (MS) data acquisition and subsequent sample preparation and laboratory measurements were conducted at the "Rudnik" mine tailing site in the Republic of Serbia. The dataset consists of 1010 measurements obtained from 7 boreholes, with the largest borehole containing 218 continuously measured MS samples and the smallest containing 103 measured values. The dataset includes mass magnetic susceptibility data from seven boreholes, accompanied by lithological descriptions of the respective samples and measured sample mass data. High-resolution MS data were obtained during the characterization phase of flotation tailings, as the MS technique is established as an effective proxy for detecting heavy metals in tailings, while also being cost-effective, straightforward, and rapid. Consequently, researchers can acquire extensive data which is correlated with heavy metal concentrations while reserving costly and time-intensive chemical analyses only for the most relevant samples obtained by the analysis of MS values. The significance of such datasets resides in their ability to foster transparency and collaboration, thereby facilitating cross-disciplinary research that may enhance the methodology of the MS technique. In addition to its direct geophysical applications, the dataset fosters transparency and interdisciplinary collaboration, allowing geoscientists, statisticians, and data scientists to evaluate and refine methodologies that could improve the efficiency of the MS technique in the future.

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Keywords: geophysical data; lithological data; high- resolution magnetic susceptibility data; open data; borehole data

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1. Summary

Magnetic susceptibility (MS) is a rapid and cost-effective geophysical technique used to measure and map the distribution of magnetic susceptibility values in surface and subsurface materials. The technique has found wide applicability beyond pure geophysics, including environmental research [1], palaeoclimatology [2], pedology [3], archeology [4], volcanology [5] and marine geophysics [6]. The MS technique demonstrates a strong association with heavy metal concentrations [7–14], which is supported by prior exploratory research conducted at the Rudnik mine tailing site [15], validating the use of MS as a reliable proxy for the rapid estimation of heavy metal distribution.

The MS technique also offers the benefit of minimal sample preparation, as the samples only need to be dried and hand ground prior to measurement. Additionally, the samples are left unaltered after MS measurements, allowing them to be reused for other measurements, such as geochemical or mineralogical measurements.

The MS method was implemented at the "Rudnik" mine tailings in the Republic of Serbia, under the "Characterization and technological procedures for recycling and reusing of the Rudnik mine flotation tailings (REASONING)" project, which was funded by the Science Fund of the Republic of Serbia. During 2024, a total of seven exploratory boreholes were drilled, and a total of 1010 samples were collected from these boreholes for high-resolution (10 cm resolution) MS measurements. The measurements and standard sample preparation (drying and grinding) were performed in the latter half of 2024 and early 2025. The final database was prepared, which included depth information, lithological descriptions and the mass magnetic susceptibility values for each borehole. The sample measurements were conducted using the Bartington MS3 and MS2B (low-frequency) magnetic susceptibility meters.

The primary benefits of sharing MS datasets and lithological data are that it not only promotes collaboration, transparency, open science, and data sharing practices, but also contributes a large and high-resolution dataset of MS measurements that can be used to develop novel methods that can provide additional information from the MS data itself, potentially increasing the efficiency of the MS technique i.e., methodological development. The data was collected with the potential for future methodological developments, and as such, it is not only intended for geophysicists, geologists, and geoscientists, but also for data analysts, statisticians, and data scientists. The open sharing of this type of data further encourages cross-disciplinary applied research, which has the potential to provide significant benefits to a broader range of researchers in increasing the efficiency of the MS technique. Additionally, the methods section outlines all relevant details of data acquisition, sample preparation, and measurements in a systematic framework, serving as a reference for future MS measurements on mine tailing material.

2. Data Description

A Microsoft Excel file (.xlsx) containing three worksheets, "MS_data", "lithological_data" and "Mass_data" contains mass MS data (Table 1), lithological data (Table 2) and measured sample mass data (Table 3), respectively. The MS data is structured in a manner that each column represents a distinct borehole (from borehole RJ-1 to RJ-7), with one column reserved for the depth column (in meters), which spans from 0.1 m to 21.8 m, indicating the maximum depth of a borehole in the entire dataset.

Table 1. Explanation of column names contained in the magnetic susceptibility dataset; MMS- Mass-specific Magnetic Susceptibility; Coordinate system- WGS 84.

Column Name	Description	Longitude [°E]	Latitude [°N]
depth [m]	Depth column in meters. Values range from 0.1 to 21.8 m in 0.1 m increments	Not applicable	
RJ_1_MMS [m^3/kg]	MMS for borehole RJ-1 in kg/m^3	20.4945167	44.1103192
RJ_2_MMS [m^3/kg]	MMS for borehole RJ-2 in kg/m^3	20.4941121	44.1103754
RJ_3_MMS [m^3/kg]	MMS for borehole RJ-3 in kg/m^3	20.4936550	44.1100375
RJ_4_MMS [m^3/kg]	MMS for borehole RJ-4 in kg/m^3	20.4932213	44.1097107
RJ_5_MMS [m^3/kg]	MMS for borehole RJ-5 in kg/m^3	20.4927673	44.1093670
RJ_6_MMS [m^3/kg]	MMS for borehole RJ-6 in kg/m^3	20.4923094	44.1090218
RJ_7_MMS [m^3/kg]	MMS for borehole RJ-7 in kg/m^3	20.4920447	44.1088184

Table 2. Explanation of column names contained in the lithology dataset.

Column Name	Description
borehole_ID	Identification code of the borehole (e.g., RJ-1, RJ-2, RJ-3 etc.)
start_depth [m]	Depth from which the given lithological unit starts in meters
end_depth [m]	Depth to which the given lithological unit goes in meters
lithology	Description of the lithology

Table 3. Explanation of column names contained in the sample mass dataset.

Column Name	Description
depth [m]	Depth column in meters. Values range from 0.1 to 21.8 m in 0.1 m increments
RJ_1_mass [g]	Mass measured in grams for samples from borehole RJ-1
RJ_2_mass [g]	Mass measured in grams for samples from borehole RJ-2
RJ_3_mass [g]	Mass measured in grams for samples from borehole RJ-3
RJ_4_mass [g]	Mass measured in grams for samples from borehole RJ-4
RJ_5_mass [g]	Mass measured in grams for samples from borehole RJ-5
RJ_6_mass [g]	Mass measured in grams for samples from borehole RJ-6
RJ_7_mass [g]	Mass measured in grams for samples from borehole RJ-7

The lithological data (Table 2) is organized in the following manner: the borehole identification code is provided in one column (ranging from RJ-1 to RJ-7), the start and end depths are specified in meters in individual columns, and the lithological description is located in the lithology column of the "lithological_data" worksheet.

The sample mass is organized in a manner similar to the MS data (Table 3), wherein a depth column is provided, and each borehole has its own column, with each sample corresponding to a specific borehole and depth. The sample mass is expressed in grams. All previously mentioned worksheets provided in Microsoft Excel (.xlsx) format are also available individually in .csv format to offer a non-proprietary option for researchers who do not utilize Microsoft Excel.

A total of 1010 data points from 7 boreholes are included in the MS measurements (Table 4), with borehole RJ-1 having the lowest value at 103 data points and borehole RJ-5 having the highest value at 218 data points. Borehole RJ-1 displays a total of 17 missing observations, concentrated in a total of four groups, the largest of which ranges from the surface to the depth of 1.2 m. Boreholes RJ-2 and RJ-3 displayed a low number of missing observations which are due to data quality i.e., data points that were not consistent across repeated measurements. Due to core loss, borehole RJ-4 shows 46 missing observations in total across three groups. The largest continuous sample of MS data in borehole RJ-4 consists of samples from the surface to the depth of 10 m i.e., a total of 100 continuous, measured samples. The missing observations in borehole RJ-4 are concentrated from depth of 10.1 m to 12.8 m, one single sample at the depth of 13.4 m, and a third group from the depth of 13.7 m to the depth of 15.3 m.

The lithological data comprises 14 distinct lithological categories, the majority of which are variations in the color of the sand or clayey sand (grayish-red sand, gray clayey sand, red sand, gray sand, etc.). Additionally, one label is designated as core loss (for borehole RJ-4) and one lithological unit is entirely clay.

Table 4. Description of missing observations in mass magnetic susceptibility data.

Borehole	Number of Data Points [/]	Start Depth [m]	End Depth [m]	Number of Missing Observations [/]	Groups of Missing Observations [/]
RJ-1	103	1.3	12	17	4
RJ-2	109	0.1	11.1	2	2
RJ-3	142	0.1	14.6	5	4
RJ-4	116	0.1	16.2	46	3
RJ-5	218	0.1	21.8	0	0
RJ-6	168	0.1	16.8	0	0
RJ-7	155	0.1	15.5	0	0

Figure 1 illustrates an example of magnetic susceptibility measurements obtained from boreholes at the "Rudnik" mine tailings. Figure 1 indicates that, for borehole RJ-2 magnetic susceptibility values remain relatively constant up to a depth of 10 m, with the exception of two data points at approximately 5 m depth. The remaining boreholes exhibit significant variation, with all three showing elevated MS near the surface and reduced MS towards the ends of the boreholes. Furthermore, Figure 1 effectively illustrates the variation in magnetic susceptibility of mine tailings, as the measurements were conducted with high resolution, allowing for the easy detection of subtle variations.

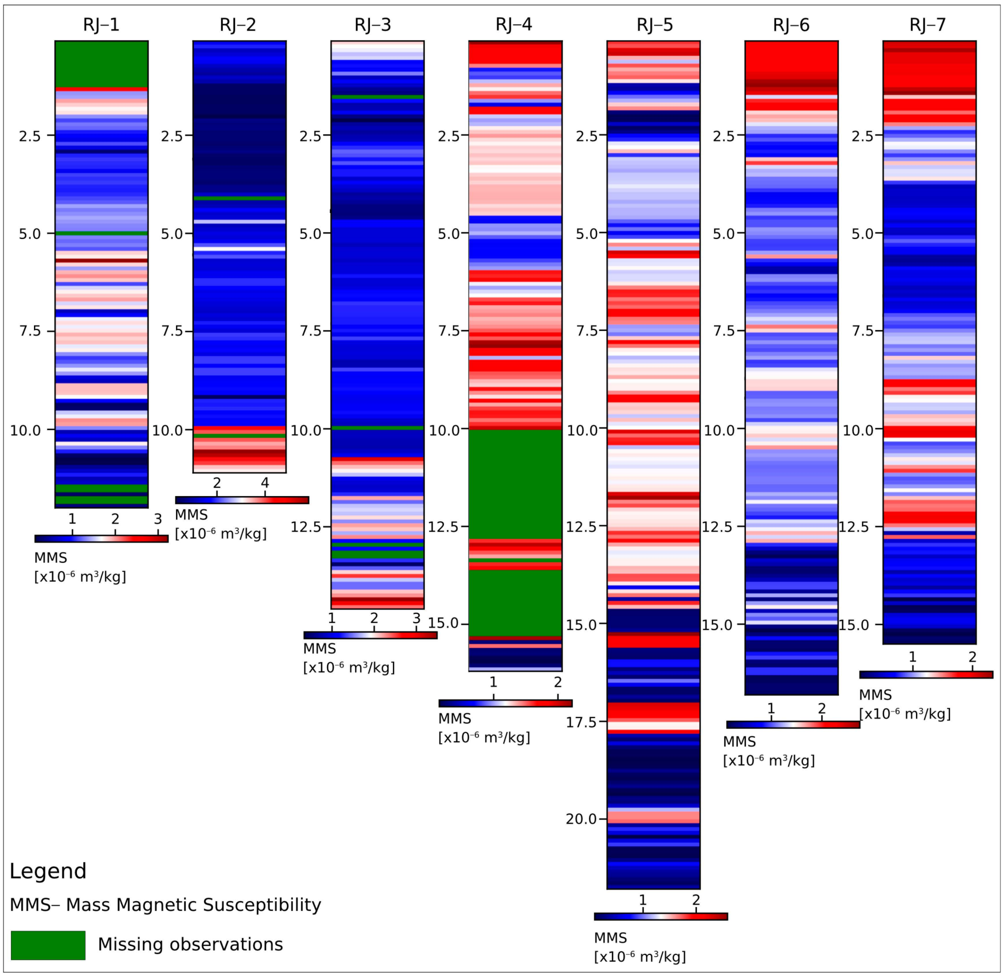

Figure 1. Magnetic susceptibility measured in borehole samples from the Rudnik mine tailings, Republic of Serbia.

3. Methods

The dataset acquisition methodology commenced with exploratory borehole drilling at the site of the "Rudnik" mine tailings in 2024. After each core segment was retrieved the sampling of the tailing material was done in increments of 10 cm. The samples were gathered in plastic bags and labeled with the borehole name and the corresponding depth of collection. Upon completion of the drilling and initial sample collection, the samples were transported to the laboratory and subjected to air drying for several weeks under ambient laboratory conditions (~22–25 °C, ambient humidity). Upon confirming the samples were dry- through continuous visual inspection during the drying process, when they appeared dry visually, felt dry by touch, and exhibited no visible condensation in the plastic bags- they were subsequently packed into 12 cm^3 Bartington MS2B sample bottles for further processing. If the samples were in larger pieces, the process of manual grinding was conducted. Following the packaging of the samples, the mass of each sample was measured using the Radwag AS 220.R2 Plus laboratory scale to facilitate mass MS measurements. The MS measurements were conducted using the Bartington MS2B sensor alongside the Bartington MS3.The Bartington MS3 system, equipped with the MS2B sensor, is a standard instrument for measuring the MS of sediment samples, soils, and rock samples. Due to the unconsolidated nature of mine tailing material, direct in situ measurements using portable instruments like the Terraplus KT-10 are unfeasible. Consequently, the material must be stored in suitable sample containers and measured under laboratory conditions. The MS2B sensor offers a resolution of up to 2×10^{-6} SI and a maximum measurement range of 26 SI, rendering it suitable for MS assessments of unconsolidated mine tailing samples.

To solely measure the MS of the sample, rather than the MS values of the sample bottles along with the MS of the sample, 10 randomly selected empty bottles were measured, and their MS values were averaged to yield a singular value for data pre-processing. The MS value of the empty bottle was deducted from the raw output MS value, after which the final mass MS was computed by multiplying with the manufacturer's coefficient equation [16].

Validation of quantitative measurements, specifically data quality, was conducted by evaluating the calibration sample at every tenth measurement (i.e., every 1 m), with subsequent analysis for potential discrepancies. The variances between the remeasured calibration sample and the manufacturer's specifications across all seven boreholes are approximately 1%, which is deemed acceptable for subsequent processing and analysis. Data points that were deemed to be of insufficient data quality were disregarded from the MS database.

Additional precautions considered during the sample preparation phase encompassed the prevention of sample leakage and contamination; specifically, the laboratory environment was maintained in a clean setting, the preparation table was sanitized after each sample, and all tools employed in the sample preparation were thoroughly cleaned.

Additionally, the laboratory for MS measurements was configured to ensure a stable magnetic field, with all furniture devoid of metallic objects, such as metal chairs or tables. The placement of the instrument was deliberately arranged to avoid proximity to heat sources or direct sunlight.

Furthermore, the employment of non-magnetic materials, such as plastic spoons, was maintained throughout the sample preparation process. The individual who prepared the samples ensured that all metal objects were kept away from them to prevent any magnetic particles from contaminating the samples.

Throughout the drilling procedure, water was not utilized to cool the drilling equipment, causing samples that were damp due to only pore water in the upper strata and groundwater in the deeper layers.

These precautionary measures taken during sample acquisition, preparation and measurement to minimize both environmental and human error sources, ensuring high data quality with an error margin not expected to exceed 1%.

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References

1. Degvekar, J.V.; Gadekar, E.U.; Darshana, O.; Chand, J.; Amrish, V.N.; Jose, J.; Priya, K.; Prabhu, S.; Warrier, A.K. Tracking soil health and potentially toxic elements (PTEs) across land-use types using physico-chemical, magnetic, and geochemical proxies: A case study from Manipal, Southwestern India. *Environ. Geochem Health* **2025**, *47*, 397. [CrossRef]
2. Hu, S.; Goddu, S.R.; Appel, E.; Verosub, K.; Yang, X.; Wang, S. Palaeoclimatic changes over the past 1 million years derived from lacustrine sediments of Heqing basin (Yunnan, China). *Quat. Int.* **2005**, *136*, 123–129. [CrossRef]
3. Szuszkiewicz, M.; Łukasik, A.; Magiera, T.; Mendakiewicz, M. Combination of geo-pedo-and technogenic magnetic and geochemical signals in soil profiles–diversification and its interpretation: A new approach. *Environ. Pollut.* **2016**, *214*, 464–477. [CrossRef]
4. Bondar, K.M.; Fassbinder, J.W.E.; Didenko, S.V.; Hahn, S.E. Rock magnetic study of grave infill as a key to understanding magnetic anomalies on burial ground. *Archaeol. Prospect.* **2022**, *29*, 139–156. [CrossRef]
5. Díaz Michelena, M.; Kilian, R.; Rivero, M.Á.; Fernández Romero, S.; Ríos, F.; Mesa, J.L.; Oyarzún, A. Magnetometric Surveys for the Non-Invasive Surface and Subsurface Interpretation of Volcanic Structures in Planetary Exploration, a Case Study of Several Volcanoes in the Iberian Peninsula. *Remote Sens.* **2022**, *14*, 2039. [CrossRef]
6. Barone, A.; Milano, M.; Fedi, M. Inhomogeneous magnetization of Tyrrhenian seamounts revealed from gravity and magnetic correlation analysis. *J. Geophys. Res. Solid Earth* **2024**, *129*, e2024JB028977. [CrossRef]
7. Karimi, R.; Ayoubi, S.; Jalalian, A.; Sheikh-Hosseini, A.R.; Afyuni, M. Relationships between magnetic susceptibility and heavy metals in urban topsoils in the arid region of Isfahan, central Iran. *J. Appl. Geophys.* **2011**, *74*, 1–7. [CrossRef]
8. Wang, X.S. Assessment of heavy metal pollution in Xuzhou urban topsoils by magnetic susceptibility measurements. *J. Appl. Geophys.* **2013**, *92*, 76–83. [CrossRef]
9. Brempong, F.; Mariam, Q.; Preko, K. The use of magnetic susceptibility measurements to determine pollution of agricultural soils in road proximity. *Afr. J. Environ. Sci. Technol.* **2016**, *10*, 263–271. [CrossRef]
10. Oudeika, M.S.; Altinoglu, F.F.; Akbay, F.; Aydin, A. The use of magnetic susceptibility and chemical analysis data for characterizing heavy metal contamination of topsoil in Denizli city, Turkey. *J. Appl. Geophys.* **2020**, *183*, 104208. [CrossRef]
11. Salehi, M.H.; Jorkesh, S.; Mohajer, R. Relationship between Magnetic Susceptibility and Heavy Metals Concentration in Polluted Soils of Lenjanat Region, Isfahan. In *E3S Web Conferences*; EDP Sciences: Les Ulis, France, 2013; Volume 1, p. 04003. [CrossRef]
12. Zawadzki, J.; Fabijańczyk, P.; Magiera, T.; Rachwał, M. Geostatistical microscale study of magnetic susceptibility in soil profile and magnetic indicators of potential soil pollution. *Water Air Soil Pollut.* **2015**, *226*, 142. [CrossRef] [PubMed]
13. Jaffar, S.T.A.; Chen, L.-Z.; Younas, H.; Ahmad, N. Heavy metals pollution assessment in correlation with magnetic susceptibility in topsoils of Shanghai. *Environ. Earth Sci.* **2017**, *76*, 277. [CrossRef]
14. Vasiliev, A.; Gorokhova, S.; Razinsky, M. Technogenic magnetic particles in soils and Ecological–Geochemical Assessment of the soil cover of an industrial city in the Ural, Russia. *Geosciences* **2020**, *10*, 443. [CrossRef]

15. Abramović, F.; Cvetkov, V.; Ilić, A.; Životić, D. Correlation of Magnetic Susceptibility and Content of Metal in Flotation Tailings. In *Book of Abstracts of the 18th Serbian Geological Congress "Geology Solves the Problems"*; The Serbian Geological Society: Belgrade, Serbia, 2022; p. 24.
16. Bartington Instruments Ltd. Operation Manual for MS2 Magnetic Susceptibility System. 2008. Available online: https://gmw.com/wp-content/uploads/2019/03/MS2-OM0408.pdf (accessed on 25 July 2025).