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RESEARCH PAPER

Fingerprinting of Critical Raw Materials in Lacustrine Systems on Horseshoe Island, Antarctic Peninsula

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Abstract

Modern industry increasingly relies on advanced technologies that require various critical raw materials (CRMs) for their development and functionality. These materials, which are essential for technological innovation and everyday applications, face significant supply risks, hence they are categorized as "critical raw materials". Recent studies have highlighted the ecological and geochemical importance of CRMs in lakes of different geological origin, yet detailed studies on their distribution in polar lacustrine systems remain limited. This study, therefore, aims to address this gap by quantifying concentrations of specific CRMs—boron (B), cerium (Ce), gallium (Ga), germanium (Ge), gadolinium (Gd), lanthanum (La), lithium (Li), nickel (Ni), neodymium (Nd), palladium (Pd), platinum (Pt), titanium (Ti), and yttrium (Y)—in surface waters of nine lacustrine systems sampled during the Türkiye's National Antarctic Scientific Expedition-2024. The analysis revealed measurable values for B, Ga, Nd, Ni and Ti, while the concentrations of Ce, Ge, Gd, La, Li, Pd, Pt and Y remained consistently below the detection limit. Of the lakes analyzed, Clincher Lake had the highest concentrations, with notable values for B (85.2 ppb), Ti (58.1 ppb) and Ni (18.2 ppb). Remarkably, these elevated levels were measured in a lake furthest from shore, highlighting the possible influence of unique environmental or geological factors. These results emphasize the importance of continuously monitoring and comprehensively analyzing the distribution of CRMs in polar lacustrine and marine ecosystems. Such efforts are crucial for assessing the environmental risks associated with CRMs and for understanding their broader ecological impacts.

Introduction

Rapid population growth combined with increasing demand for essential resources has led to accelerated environmental degradation, which is now a critical problem for the world (Radu et al., 2024). This degradation is exacerbated by the unsustainable use of natural resources, which poses a significant threat to ecosystems. At the same time, the global impacts of climate change are intensifying, affecting both socio-economic and natural systems and requiring immediate and proactive solutions (Kar, 2022; Tomescu et al., 2022; Zahra and Badeeb, 2022). In response to these challenges, global industry initiatives now focus on renewable energy, sustainable infrastructure and green transport, which depend on a secure, and sustainable supply of raw materials (Martin et al., 2022). Mining, traditionally associated with significant waste production, has emerged as a potential source for the extraction of valuable secondary raw materials and offers the opportunity to sustainably meet current resource needs (Almeida et al., 2021).

The European Union has recognized the urgency of these issues and has prioritized the sustainable management of critical raw materials (CRMs), which are essential for its economic growth and technological progress. These efforts are reflected in measures such as the European Commission's CRM list and directives to minimize the environmental impact of the extractive industries. The European Commission's list of CRMs includes several metals and metalloids often found as by-elements in metal deposits such as copper, zinc, lead, iron and aluminum (EC, 2020; Domaracka et al., 2022). This list is updated every three years (2011, 2014, 2017, 2020) to reflect the rapid changes in the industry and the growing demand for these materials (EU RMIS, 2024). The management of waste generated in the extractive industries is aligned with EU policies and directives, such as Directive 2006/21/EC, which aims to prevent or minimize adverse effects on the environment, the economy or human health. As the EU's economic growth increasingly depends on non-energy raw materials, including metals and other minerals, these resources are of crucial— importance - even if they have received less critical attention in the past compared to oil and natural gas (Watari et al., 2020; Mejame et al., 2022).

Antarctica has long been at the center of researchers' interest because it provides unique and valuable data that enhances our understanding of the Earth's past and gives us insights into its future (Binish et al., 2024). The continent holds approximately 90% of the world's ice reserves and plays a crucial role in maintaining the Earth's ecosystems by regulating heat distribution across the oceans (Selbesoglu et al., 2023). Although Antarctica is considered the most pristine place on Earth and has been explored for more than a century, knowledge about it remains limited. Most research has focused on coastal waters, sediments, the cryosphere and the composition of the air (Abouchami et al., 2011). The lacustrine systems (land-locked and pro-glacial lakes) serve as a simple natural laboratory for studying the effects of recent and well-documented anthropogenic impact on a "pristine" environment. During the summer months, certain systems in the ice-free regions of Antarctica remain active, offering long-term research opportunities to explore the island's elemental fingerprint (Radu et al., 2024). Previous studies show that the chemical composition of Antarctic lakes varies significantly, ranging from ultra-fresh to highly saline (Green and Lyons, 2009; Priscu and Howkins, 2016; Kakareka et al., 2019). This geochemical diversity plays a critical role in the composition and structure of microbial communities and reflects the patterns observed in aquatic ecosystems worldwide. In Antarctic freshwater lakes, fish are not found; invisible prokaryotic microorganisms (archaea and bacteria) and eukaryotic microorganisms (mainly algae and protozoa) dominate (Nakai et al., 2019). Despite occasional mixing between lakes, those with similar geochemical properties (e.g. conductivity and nutrient levels) tend to support comparable microbial communities, even in geographically distant systems (Chown et al., 2015). In addition, significant differences in water composition have been found between lakes located at similar distances from the sea, further highlighting these ecosystems' complexity (Abollino et al., 2012; Conca et al., 2017; Chown et al., 2022). Understanding such variations is essential for assessing the distribution of CRMs in lacustrine systems.

Although Antarctica is perceived as the last pristine continent on Earth with limited interaction with environmental pollutants, studies have identified regions impacted by anthropogenic activities, such as research stations and logistics hubs. While the limited impact of some natural sources (e.g., animal excrement, volcanism) is recognized, fuel and waste combustion, as well as accidental oil spills, are considered among the primary sources of heavy metal pollutants in Antarctica (Koppel et al., 2017; Chu et al., 2019). Limited studies have confirmed this hypothesis in the lacustrine systems of the Antarctica Peninsula, known for their relative protection from pollution. However, since it is not feasible to study every pollutant or metal in all areas, especially Horseshoe Island, the absence of research specifically addressing CRMs has served as the driving force for this article. This gap in research on CRMs underscores the critical need for further investigation, reinforcing the importance of the present study.

Horseshoe Island, located in the western part of the Antarctic Peninsula (Figure 1), has hosted research stations from various countries for almost a century and receives around 2,500 visitors annually (UK Antarctic Heritage Trust, 2024). It is the third largest island on the Antarctic Peninsula, which is known as one of the fastest warming regions on the continent (Hodgson et al., 2013; Özkan, 2023). The island consists primarily of crystalline rocks, granites of different ages and facies with gabbro, wide exposures of metamorphic rocks, and undifferentiated volcanic rocks. The basement rocks of the island are cut by NS and EW trending systematic acidic and basaltic dykes as detailed and mapped by Matthews (1983). Glaciers or semi-annual ice and snow cover about 66% of the island's surface. Geomorphologically, the southern part of Horseshoe Island is higher and hillier than the northern part and has different landscape features.

The lacustrine systems of Horseshoe Island, where the sampling was carried out, have not been studied previously, making the presence of specific CRMs uncertain. The novelty of this work lies in the fact that it includes the first CRM-related measurements in the area and is therefore the first study of its kind. The aims are to: (1) to quantify the concentrations of CRMs — boron (B), cerium (Ce), gallium (Ga), germanium (Ge), gadolinium (Gd), lanthanum (La), lithium (Li), nickel (Ni), neodymium (Nd), palladium (Pd), platinum (Pt), titanium (Ti) and yttrium (Y); (2) to assess possible sources of these elements with a focus on their distribution patterns in relation to geological formations

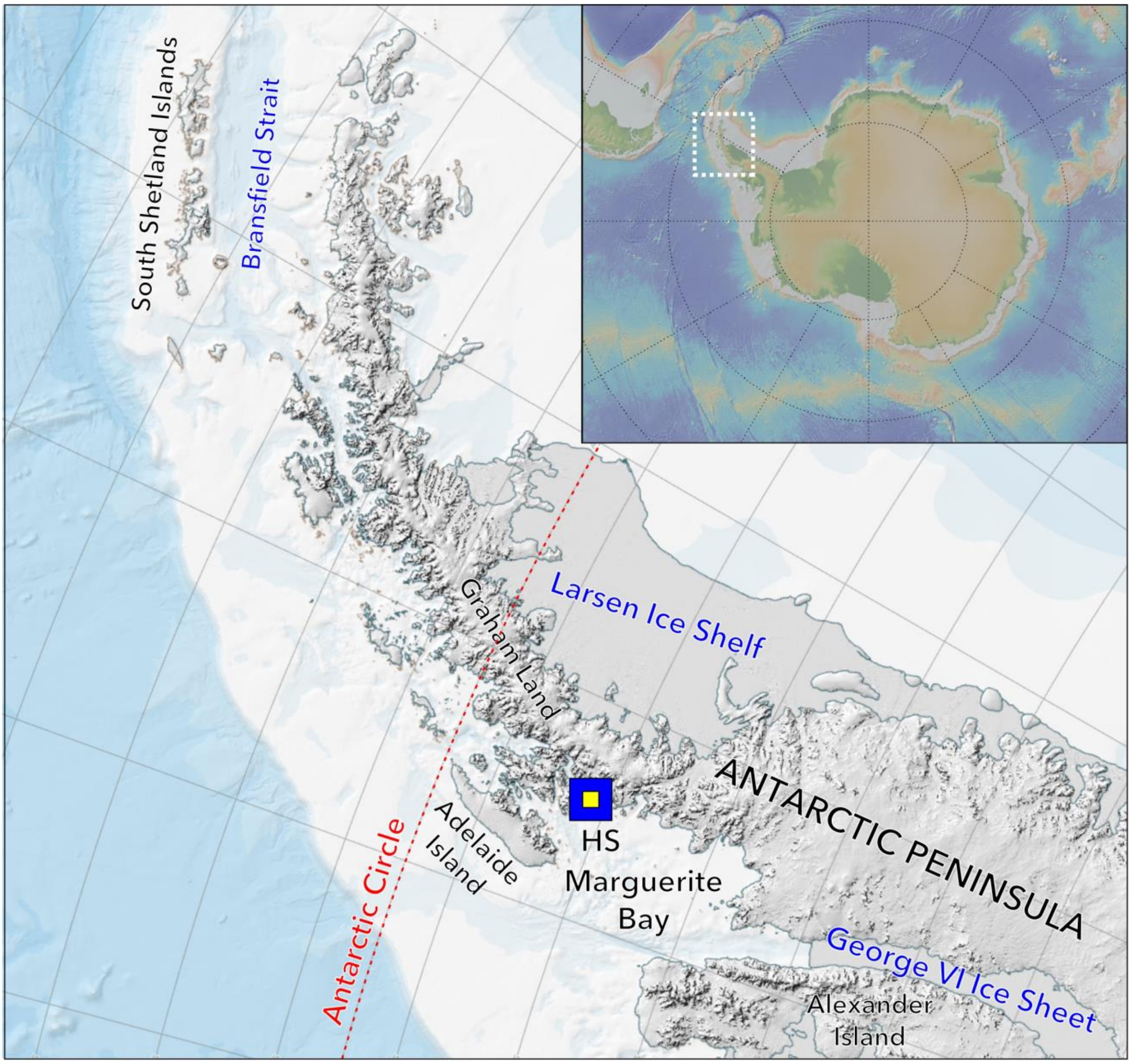

Figure 1. The location map of Horseshoe Island (The yellow square HS: Turkish Scientific Research Station, TARS in the Horseshoe Island) at Antarctica Peninsula (SCAR, 2024).

and local environmental conditions; and (3) to compare similarities between sampling stations. Although further data collection would enrich the findings, the main objective of this study is to provide initial insights into a previously unstudied region and thus lay the foundation for future research on the distribution and environmental impact of CRMs in polar lacustrine systems.

Material & Method

Study Area and Design

The Turkish Scientific Research Station is located on Horseshoe Island, one of the islands in Marguerite Bay on the Antarctic Peninsula (Selbesoglu et al., 2023). The northern and central plateaus of the island are mostly reachable, with ice cover restricted to Mt. Searle and its surrounding areas (Figure 2). In this study, the SCAR Antarctic Digital Database (2024) was utilized to create the basemaps used in Figures 1 through 4 (SCAR, 2024). As part of Türkiye's National Antarctic Scientific Expedition (TAE-VIII), surface water samples were collected from nine lakes on Horseshoe Island, listed in Table 1. The samples were taken in a single trial using pre-cleaned glass bottles, ensuring no contact was made with surrounding areas. During sampling, special care was taken to avoid sediment disturbance, and all samples were strictly taken from the surface water layer of the lakes. Following sample collection, they were stored in cold conditions and transported initially to the research vessel (Betanzos R/V), and subsequently to the laboratory for analysis. The analytical investigations were performed at the MERLAB-IUC.

Instrumental Analysis

A well-known method was selected (Schmidt et al., 2019; Sönmez et al., 2023), and the concentrations of the selected CRMs, "Boron (B), Cerium (Ce), Gallium

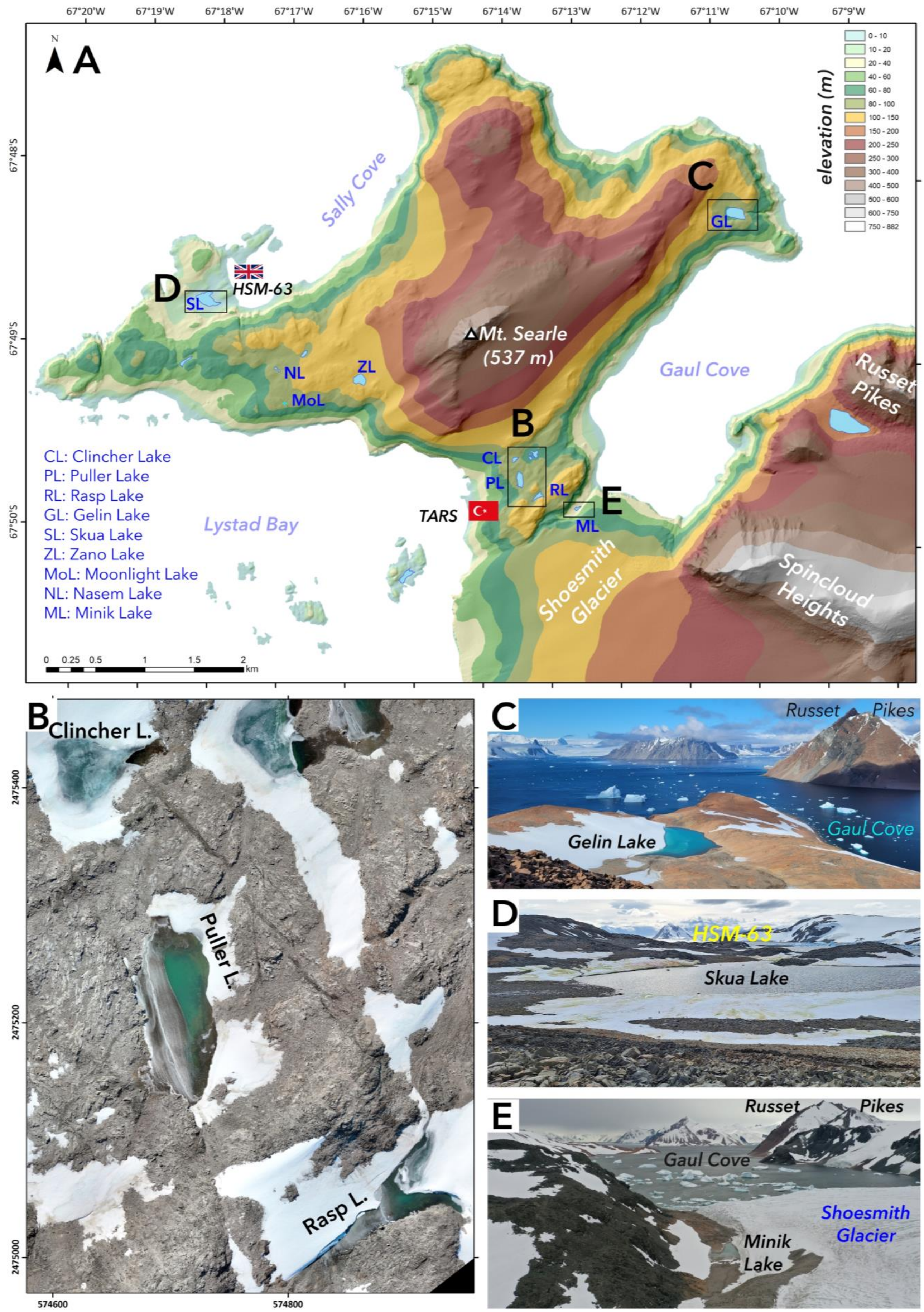

Figure 2. Sampling site locations of lacustrine systems of Horseshoe Island.

(Ga), Germanium (Ge), Gadolinium (Gd), Lanthanum (La), Lithium (Li), Nickel (Ni), Neodymium (Nd), Platinum (Pt), Palladium (Pd), Titanium (Ti), Yttrium (Y)" were carried out by instrumental analysis method using Inductively Coupled Plasma Mass Spectrometry (ICP/MS) (Perkin Elmer Nexion 1000).

In order to ensure the best operating performance of the device before the analyses and to prevent potential interferences caused by oxidation in the analyses such as PrO, CeO, and NdO, the CeO/Ce ratio must be set to a value below 0.025. Therefore, daily performance tests were performed with Nexion Setup Solution containing 1 ppb Be, Ce, Fe, In, Li, Mg, Pb, and U elements.

Before analysis, all lake surface water samples were filtered through 0.22-µm polytetrafluoroethylene (PTFE) filters. Samples taken into disposable polypropylene (PP) falcon tubes were acidified using 65% Merck Suprapure nitric acid with a density of 1.39 kg/L at a volume ratio of 1/20 (v/v). Detection limits were determined for each element measurement and a calibration curve with high linearity of 10, 40, 100, 400, 2000 and 10000 ppt was successfully created for the analysis process for each element.

Results and Discussion

Although various researchers have investigated environmental quality in both the abiotic and biotic components of the Antarctic ecosystem, a systematic approach to understanding the potential impacts and environmental risks posed by different factors has yet to be explored. Robust protocols need to be developed for studies in Antarctica, as protocols commonly used for species at lower latitudes may not be suitable for these regions. For instance, performing a combination of environmental indices with spatial variations laterally and conducting environmental risk assessments, such as the Enrichment Factor, is challenging without understanding all the field conditions (Wallenius & Lehtomäki, 2016; Chown et al. 2022). Normalization typically requires balancing the metal variability arising from the compositional and textural characteristics of sediments. However, in the present study, since the study area consists of volcanic and gneiss formations in the central plateau, and granite and gabbro in the northwest plateau, with a high concentration of alumino-silicates in the weathered sediments, it would not be appropriate to select a single element as the normalizing element. In this study, the lacustrine systems of Horseshoe Island, where sampling was conducted, have not been previously studied. As a result, the specific CRMs that may be detected remain uncertain. The novelty of this work, which includes the first measurements taken in the area and the first CRM-related studies, underscores the significance of the data obtained. While further data production could potentially enrich the study, the main focus was to provide initial insights into an area with no prior research, thus laying the groundwork for future studies in this region.

The results of the study aimed at determining CRM concentrations in surface water samples collected from nine lakes on Horseshoe Island are presented under two main headings. Initially, geological formations and maps from previous studies of the area were considered. Specifically, the geological formations depicted in the map created by Matthews (1983) were referenced to guide this study (Figure 3). The lithological and structural features outlined in this map, along with the elements detectable in the sampled lakes, were documented. In the subsequent stage, CRM analyses were conducted on the surface water samples. However, it was not possible to compare these results with other measurements due to the absence of prior studies in these regions.

Origin Categories of Freshwater Bodies on Horseshoe Island

The freshwater bodies on Horseshoe Island are of three distinct origins. The first group, which constitutes most of the lakes, is located in small-scale depressions on two separate deglaciated plateaus: the central plateau (Clincher, Puller, and Rasp Lakes) and the northwestern plateau (Zano, Nasem, and Moonlight Lakes). These lakes have small catchment areas, with their water budgets primarily sustained by glacial and annual snowmelt during the spring and summer seasons. For most of the year, the surface of these lakes remains frozen, as observed during the TAE-VIII expedition in February, and only thaws for short periods. Thick snow cover accumulates on the lake surfaces during frozen periods. The Antarctic lacustrine system offers comprehensive insights into watershed and

Table 1. Sampling site locations and coordinates on Horseshoe Island

Name of Lake	North (°)	East (°)	Area (m^2)
Clincher Lake	-67.8264	-67.2273	1931.2
Puller Lake	-67.8282	-67.2259	8257.7
Rasp Lake	-67.8297	-67.2214	3496.3
Gelin Lake	-67.8025	-67.1751	17312.2
Skua Lake	-67.8126	-67.3025	19522.0
Zano Lake	-67.8196	-67.2652	10456.9
Moonlight Lake	-67.8219	-67.2831	202.8
Nasem Lake	-67.8188	-67.2854	628.3
Minik Lake	-67.8307	-67.2119	1224.9

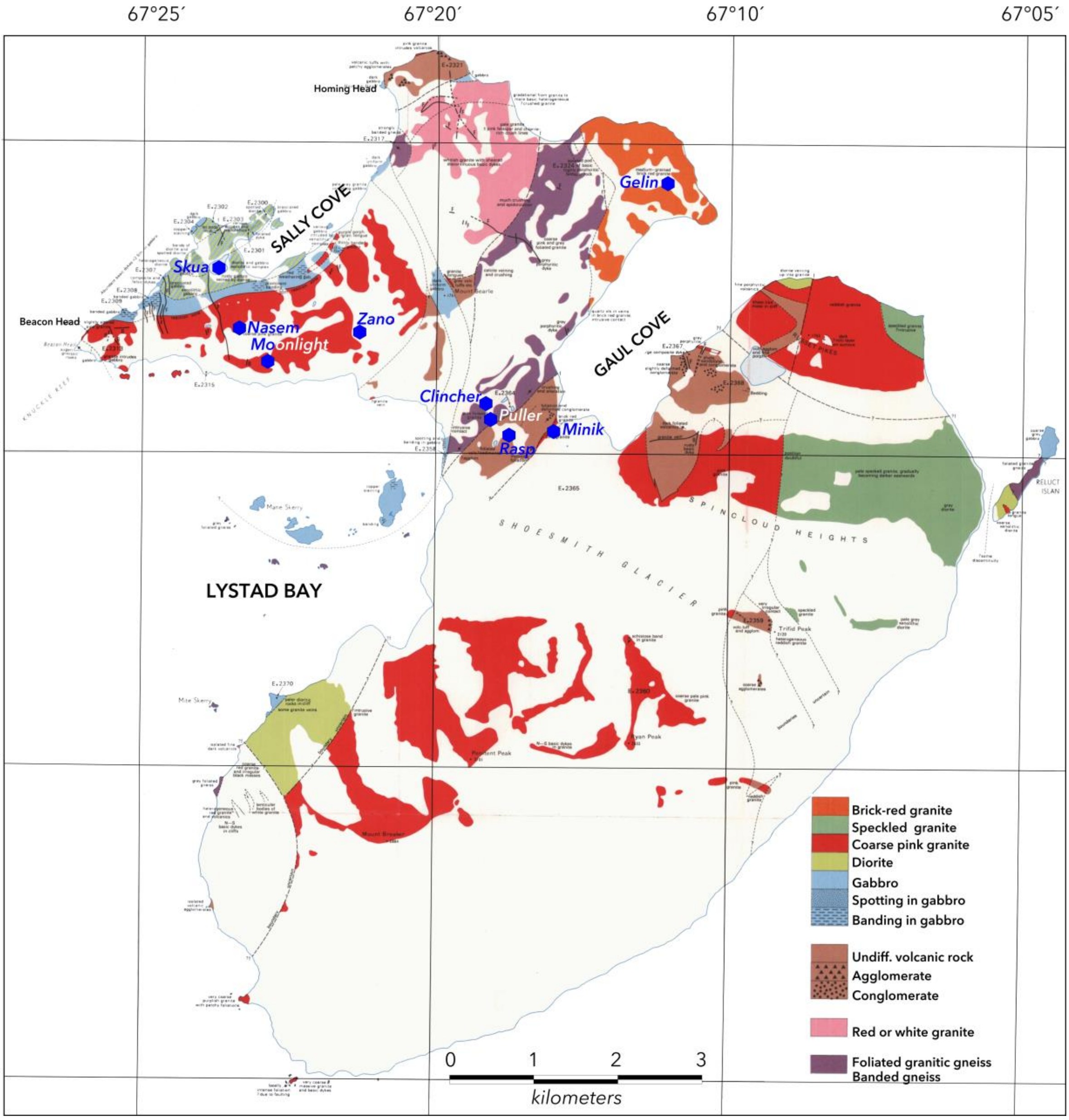

Figure 3. Geological map of Horseshoe Island with positions of studied lakes (adapted from Mathews, 1983).

regional characteristics. Fundamentally, this lake system is abundant in natural resources, encompassing major ions and trace metals. These lakes exhibit unique ecological features on ice-free surfaces situated on the ice-covered continent. Variations in the concentrations of major ions and trace metals within Antarctic lacustrine systems can be ascribed to both natural (geological and aerosol-derived) and anthropogenic factors (Borghini et al., 2008; Borghini et al., 2013; Kim et al., 2020).

Minik Lake, situated in a narrow zone between the basement rocks (Pink Fine Granite) and the lateral moraine of Shoesmith Glacier, has its outlet blocked by ice. The lake's water and sediment supply are supported by both glacial melt and surface runoff. Gelin Lake, located in the northeastern portion of the island, is a moderately sized cirque lake, also fed by annual glacial and snowmelt. Detailed geochemical data on the island's rock structures have not yet been obtained, and analyses of the currently collected samples are ongoing.

Skua Lake has a distinct origin. It was previously part of Sally Cove, functioning as a narrow and shallow extension during the early to late Holocene. Due to the ongoing post-glacial uplift of the island, it became isolated from the sea, transforming into a freshwater lake approximately 3,170 ± 90 years cal BP (Wasell & Håkansson, 1992; Håkansson and Jones, 1994), as indicated by changes in diatom species. Currently, Skua Lake is classified as freshwater, with its sediment and water budget primarily supported by surface runoff (Van de Vijver et al., 2015). Table 2 outlines the geological structures, sediment sources, elevation, and distance details of these lakes. In the light of this information, it is predicted that the hydrological properties and chemical compositions of lakes differing in terms of formation and origin will also show significant differences.

CRM Concentrations in Water Samples

Analyses of CRM concentrations were performed on surface water samples from the lakes. The highest values of the measurement results were detected in Clincher Lake and were determined as B (85.202 ppb), Ga (0.904 ppb), Nd (2.826 ppb), Ti (58.189 ppb), respectively. The lowest values were measured as Zano Lake (82.524 ppb) for B, Minik Lake (0.052 ppb) for Ga, Gelin Lake (0.085 ppb) for Nd, and Minik Lake (30.592 ppb) for Ti. In addition, the highest value for Ni measured belongs to Clincher Lake (18.249 ppb), and the lowest value belongs to Zano Lake (0.432 ppb). To enhance the interpretability of the obtained data, the significance of the detectable elements resulting from the analysis, along with their interactions with other elements, is illustrated in Figure 4. When evaluating the studies conducted by researchers in this field alongside the findings of the current study, several observations can be made under key headings. The distance of the selected stations on Horseshoe Island from the coast is considered a significant factor. Notably, the high concentrations of B (85.2 ppb) and Ti (58.1 ppb) and especially Ni (18.2 ppb) in samples taken from the lake located at the farthest point from the coast, even in what can be classified as the central region, is remarkable.

Table 2. The geological structures, sediment sources, elevation, and distance details of lakes

Name	Altitude (m)	Distance to sea (m)	Geology	Sediment Source	Type
Clincher Lake	80	515	Gneiss	Basement+Till	Closed
Puller Lake	80	475	Gneiss-Metavolcanics	Basement+Till	Closed
Rasp Lake	94	580	Metavolcanics	Basement+Till	Closed
Gelin Lake	95	360	Fine Pink Granite	Basement	Closed
Skua Lake	5	230	Gabro	Basement+Till	Open
Zano Lake	113	370	Coarse Pink Granite	Basement	Closed
Moonlight Lake	84	270	Coarse Pink Granite	Basement+Till	Closed
Nasem Lake	90	605	Coarse Pink Granite	Basement+Till	Closed
Minik Lake	28	280	Fine Pink Granite	Shoesmith Till	Open

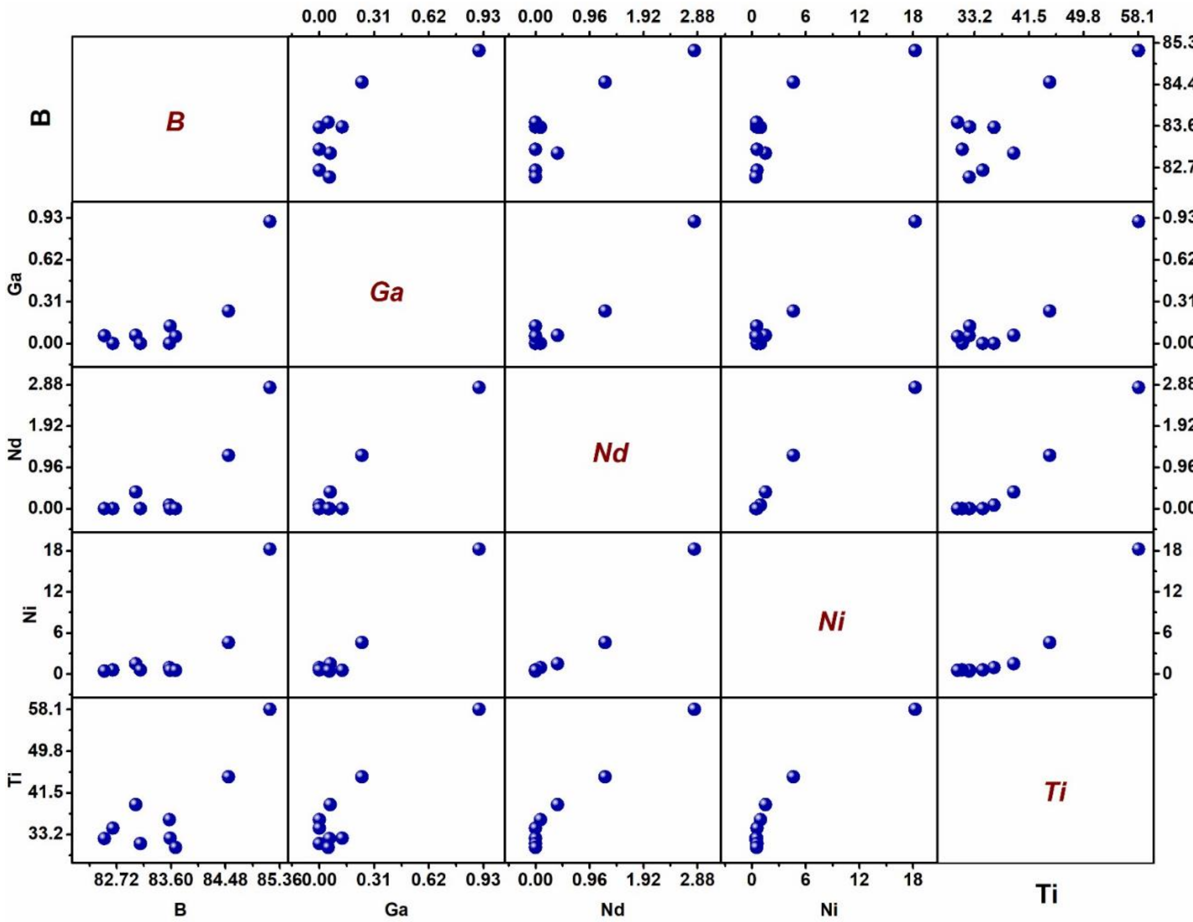

Figure 4. Relationships between CRM concentrations (B, Ga, Nd, Ni, Ti) in lacustrine surface waters (Concentrations are indicated in ppb).

Matthews (1983) highlighted the differences in the rock and sediment structures within the sampling area in his research. These studies also indicate that the variations in freshwater sources are confirmed to have three distinct origins. Also, these details are evident in relation to the measured CRM concentrations. It appears that the primary factor driving these changes is the influence of the local rock and sediment structures.

In unique ecosystems, scatterplot matrices are widely utilized to visualize and analyze the relationships among variables. In this study, this analytical method was employed to investigate the potential effects of anthropogenic and geological sources on the concentrations of critical raw materials (CRMs) in lacustrine surface waters. The analysis provides a visual and statistical basis for distinguishing between natural and human-induced influences. As illustrated in figure 4, each cell within the matrix represents the distribution (scatterplot) between two variables. The diagonal cells, containing the variable names, present the concentrations of B, Ga, Nd, Ni, and Ti, which were above detection limits. These variables are paired along both the horizontal (X-axis) and vertical (Y-axis) dimensions. While predictive models could be developed in future studies for values below the detection limit using related variables, the primary aim of this study is to interpret the concentrations of CRMs that were detected. The results indicate a strong positive relationship between B and Ti. Similarly, a positive linear correlation was observed between Ni and Ti. In contrast, the relationships involving Ga and other variables (particularly Nd and B) were notably weak, suggesting that Ga may function as an independent variable in this context.

Coastal surface winds in Antarctica play a crucial role in influencing ice-sheet stability, sea ice dynamics, and local ecosystems (Świło et al., 2024). The most intense coastal winds are particularly significant due to the nonlinear relationship between wind speed and wind stress (Caton Harrison et al., 2024). Surface winds are particularly strong during the winter months. The high directional consistency of the wind, along with its close correlation to the underlying terrain, can be interpreted as evidence of katabatic wind activity (Yu et al., 2020). Observations indicate that the directional consistency of Antarctic surface winds exhibits minimal seasonal variation. During the summer, winds are not expected to contain a significant katabatic component due to the enhanced solar heating of the ice slopes. The persistent unidirectional nature of the Antarctic surface winds throughout the year suggests the presence of significant topographic influences beyond those driven by katabatic forcing (Parish & Cassano, 2003). Studies have shown that the strong spatial dependence of surface wind trends in Antarctica is significant enough to suggest the potential for wind energy usage (Simmonds, 2015; Wallenius & Lehtomäki, 2016; Chown et al., 2022). This idea stems from the projected changes in the lower tropospheric westerly winds over the Southern Ocean, which exhibit a strong scenario dependence from 1995-2014 to 2081-2100 (Simmonds, 2015; Yu et al., 2020). Regional average surface wind trends are overwhelmingly positive across all regions and seasons, particularly in the spring and summer months across the continent (Chown et al., 2022). Based on this information, the fact that the highest CRM values were measured in lakes located farthest from the coast suggests that, in addition to the geological location of the lake, dominant meteorological factors such as prevailing winds and temperature on Horseshoe Island also influence these results.

Figure 5 illustrates the prevailing winds and wind intensity across the island and at the time of sampling. This data is primarily associated with northern winds. Close to the coast, extreme winds have an outsized impact on driving ocean currents due to the nonlinear relationship between wind speed and wind stress (Lin et al., 2020; Wu et al., 2016). Wang et al. (2021) also demonstrate how intense coastal winds can significantly promote the production of coastal sea ice. Furthermore, strong coastal winds can disrupt coastal ecosystems, including nesting bird populations (Descamps et al., 2023). The study focuses on key factors such as the spray pressure from marine areas, the formation and/or melting of ice and glacial regions, and the accumulation of snowfall in specific areas. Additionally, the changes observed in temperature data contribute to the accelerated glaciation of the lake surface, leading to the entrapment of all chemical agents within the ice. Figure 6 presents data on sudden fluctuations in air temperature and the increasing freezing potential of the lakes.

Nearly the entire landmass of Antarctica is blanketed by an immense ice sheet, spanning an area more than six times the size of its Greenland counterpart. In some regions, the ice sheet reaches a thickness of 4 km. Summer temperatures rarely exceed −20°C, while winter monthly averages drop below −60°C. Along the Antarctic coastline, temperatures in the summer months (December–February) generally hover near freezing, occasionally reaching slightly above zero, particularly in the northern part of the Antarctic Peninsula (Figure 6). In this figure, the section marked in blue represents the missing data due to a device malfunction.

During winter, monthly average temperatures at coastal stations range from −30°C to −10°C, although they may briefly approach freezing (Hodgson, 2012). The increasing ice melting in Antarctica each day leads to significant changes in the biogeochemical composition of areas and causes rapid expansion of lake regions (Olgun et al., 2024). Therefore, freshwater bodies are the barometers of climate change within polar ecosystems (Conca et al., 2017; Hawkings et al., 2020). Through the natural weathering of rocks, metals, along with other elements and compounds, are introduced into lake ecosystems via meltwater flows and aerosol deposition (Webb et al., 2020). In this study, Clincher, Puller, and Gelin Lakes—lakes fed primarily by glacial and snowmelt—were identified as open lakes with the highest CRM concentrations. Minik Lake, sustained by runoff, exhibited strong interactions, notably high concentrations of B, Ga, and Ti. Skua Lake was found to have the lowest CRM concentrations, attributed to differences in rock type as well as the effects of glacial and snowmelt contributions. Previous studies have detected potential contaminant metals (Pb, Cd, Cu, Zn, and Ni) in Antarctic lacustrine systems (Bhakta et al., 2022; Bhardwaj et al., 2023; Lecomte et al., 2020; Magesh et al., 2021). However, in this study, metals such as Cd, Pb, Li, La, Gd, Ge, Ce, Pd, Pt, and Y were below the detection limits and therefore not measurable. With increasing anthropogenic pressures on these systems (Gasparon & Burgess, 2000), many researchers underscore the need for regular monitoring to evaluate the impact of changing climate conditions. The CRM concentrations observed here, comparable to those in freshwater ecosystems elsewhere, highlight the importance of ongoing monitoring efforts.

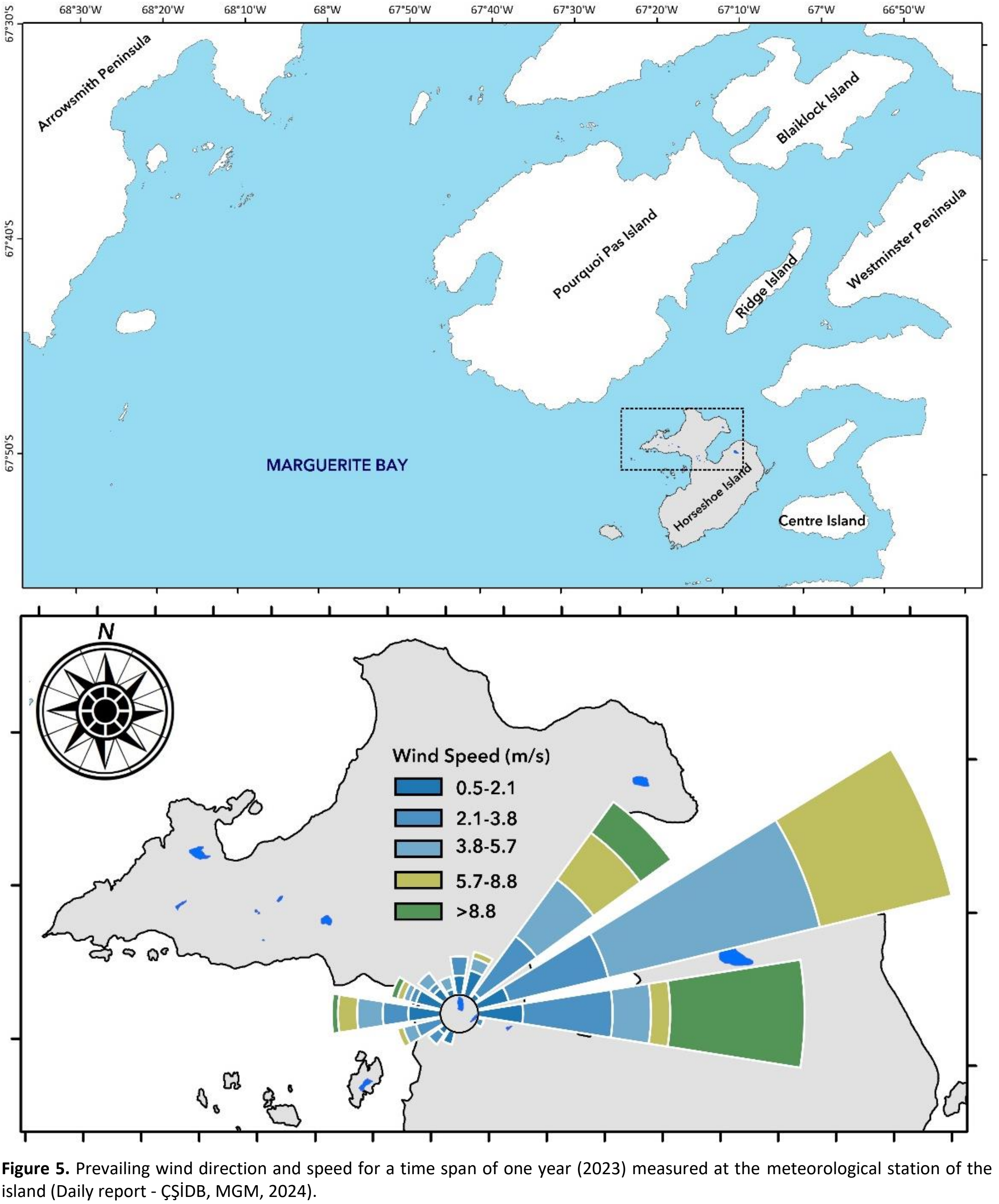

Figure 5. Prevailing wind direction and speed for a time span of one year (2023) measured at the meteorological station of the island (Daily report - ÇŞİDB, MGM, 2024).

Conclusion

The global focus on renewable energy, sustainable infrastructure, and green transportation has spurred research on the sustainable supply and procurement of raw materials. Population growth and the associated rise in demand for essential resources have led to a deprioritization of environmental integrity in favor of resource sufficiency, contributing to rapid environmental degradation and the onset of nearly irreversible ecological challenges facing contemporary society. Mining activities have produced waste that could serve as a potential secondary source of CRMs relevant to current interests. It is within this context that a study was conducted to verify the presence of select CRMs within some of the world's most unique and protected freshwater ecosystems. The findings emphasized the necessity of prioritizing these unique ecosystems' protection from human activities and ensuring stringent monitoring thereafter with larger samples that would allow for more robust statistical analysis.

Contaminants generally enter Antarctica through three primary routes: long-range atmospheric circulation, bio-transport, and local human activities. Antarctica is home to various lacustrine systems, including supra-glacial and sub-glacial lakes, tidal freshwater epi-shelf lakes, perennial ice-capped lakes, lakes on ice shelves, saline and freshwater lakes, and pro-glacial lakes. These diverse lakes exhibit different physical and chemical characteristics, making them ideal natural laboratories for studying biogeochemistry and the origins of life. Additionally, with limited anthropogenic influence, these lakes provide valuable insights into the variability of inorganic and organic compounds in natural environments. Nonetheless, lakes in remote regions of Antarctica are still regarded as pristine, offering a reflection of baseline concentrations of these compounds. The accumulation of metals in lacustrine systems from various sources and their interactions can be assessed through statistical methods. However, standard techniques are insufficient for quantifying the contributions of each metal category and determining the specific pollution sources. This quantification is achieved by breaking down the original dataset into a contribution matrix, based on factor profiles.

This study recommends monitoring the concentrations of CRMs in the aquatic ecosystems of the Antarctic Peninsula, specifically including Horseshoe Island and Lystad Bay, where the research was conducted. The lakes situated on the island, which hosts the Temporary Turkish Scientific Station and aligns with the scientific objectives outlined by the Scientific Committee on Antarctic Research (SCAR)—of which Turkey became an associate member in 2016 and a full member in 2021—can serve as a foundational step for monitoring efforts. Consistent with the objectives of other nations, Türkiye's primary goal is to safeguard the continent through peaceful and scientific endeavors, ensuring that our contributions are commensurate with those of other countries within the Antarctic Treaty System. This study also contributes to the environmental monitoring advocated by the Protocol on Environmental Protection to the Antarctic Treaty. It is anticipated that the data presented here will be valuable not only to researchers in lake ecology, water chemistry, and biodiversity but also to those in geochemistry, granite chemistry, and related fields.

Ethical Statement

This study has been prepared within the scope of Turkey's Polar Research carried out under the auspices of the Presidency of the Republic of Turkey, supported and under the responsibility of the Ministry of Industry and Technology and the coordination of the TÜBİTAK MAM Polar Research Institute.

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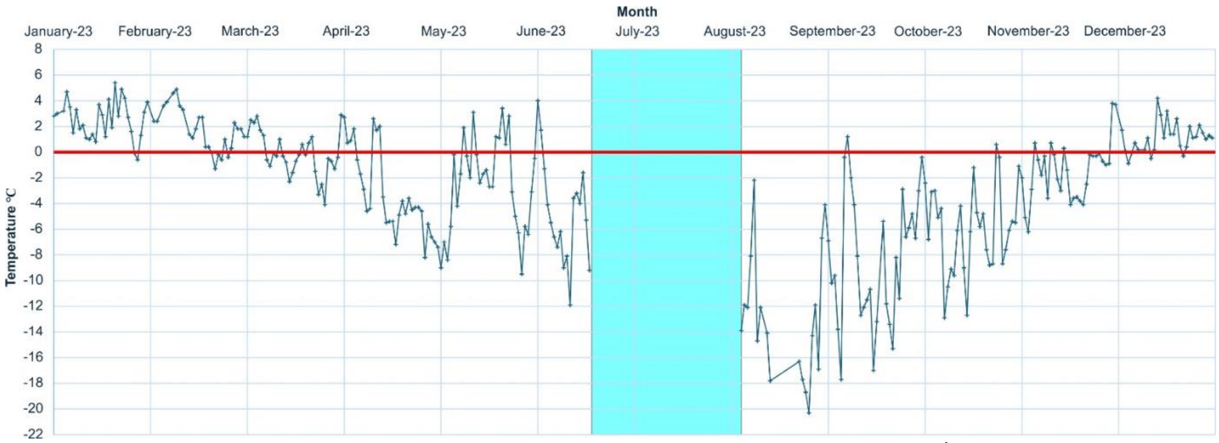

Figure 6. Air temperature trends and their influence on polar lacustrine surface layer freezing (ÇŞİDB, MGM, 2024 - The figure was created with the data recorded during daily visits, note the light blue shaded area indicates malfunctioning of the station during very low temperatures)

Author Contribution

First Author (NS): Conceptualization, Writing - review and editing, Supervision, Project Administration, Funding Acquisition, Investigation; Second Author (NE): Methodology, and Writing -original draft; Third Author (CA): Data Curation, Formal Analysis, Writing -review and editing; Fourth Author (MKE): Visualization, Mapping Methodology, Writing - review and editing; Fifth Author (MCA): Review and editing; Sixth Author (VZS): Review and editing; Seventh Author (MBH): Writing -review and editing; Eighth Author (MD): Investigation, Sampling; Ninth Author (EB): Investigation, Sampling, Expedition leader.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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