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# Mineral magnetic properties of surface soils from the Broknes and Grovnes Peninsula, Larsemann Hills, East Antarctica

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**Abstract**

This study presents soils' mineral magnetic, particle size, and organic content data from Larsemann Hills, East Antarctica. The analysis of isothermal remanent magnetization and the high specific magnetic susceptibility values –mean (± S.D.) values of 117.7 (± 175.0) $\times 10^{-8} m^3 kg^{-1}$ for Broknes Peninsula and of 330.9 (± 217.4) $\times 10^{-8} m^3 kg^{-1}$ for Grovnes Peninsula– indicate high concentrations of low-coercivity magnetic minerals. The magnetic minerals are coarse-grained in the multidomain and pseudo-single domain range, and the significant correlation between some magnetic parameters suggests the dominant control of multidomain grains. The remanent acquisition coercivity $H_{1/2}$ shows mean (± S.D.) values of 38.2 (± 4.9) for Broknes and 38.3 (± 3.7) mT for Grovnes soils suggesting magnetite dominance. The soils lie in the sand and loamy sand textural classes, and the concentration of organic matter is very low. Values of percentage frequency-dependent susceptibility indicate insignificant proportions of superparamagnetic grains, and therefore no significant evidence for pedogenic magnetic minerals was observed in these soils. The magnetic signal of Larsemann Hills soils was primarily terrigenous with no contributions from bacterial magnetite, authigenic greigite and anthropogenic magnetic minerals.

**Keywords:** soils; weathering; environmental magnetism; pedogenesis; particle size.

## 1. Introduction

Soil studies in Antarctica started in the early 20th century. Since then, several workers have studied and classified the Antarctic soils and pedogenic processes (Campbell and Claridge, 1987; Bockheim and Ugolini, 1990; McLeod et al., 2008; Navas et al., 2008; Bockheim 2015a, 2015b). The pristine soils of Antarctica are of particular interest from a climatological point of view since they are practically undisturbed and sensitive to changing climatic conditions. Antarctica has a tiny portion of ice-free regions, only about 0.44% of its total area (Roudier et al., 2022). Antarctica possesses the coldest climate in the world and receives very little precipitation. The soils of Antarctica are poorly developed because of the extreme climatic conditions (Campbell and Claridge, 1987; Bockheim, 2015a). The soil formation, even though slow, has been progressing steadily. The dominant factor in the Antarctic soil formation is physical weathering, with weak chemical weathering playing a role in the coastal regions (Jordanova, 2017). Even in such harsh conditions, the soils of Antarctica are known to play natural hosts to different forms of life, such as nematodes, tardigrades, rotifers, and soil microbes (Convey et al., 2014).

Iron oxides such as magnetite/titanomagnetite are ubiquitous in soils and primary carriers of soil magnetism. Environmental magnetism techniques allow the measurement of the magnetic properties, such as the magnetic mineral concentration and the magnetic grain size, of these Fe-bearing minerals that vary under different environmental regimes. Magnetism techniques are fast, sensitive, non-destructive, and easy to carry out. Magnetic techniques have been extensively used to investigate the pedogenic processes in tropical (Amrutha et al., 2021; Sandeep et al., 2012) and temperate (Blundell et al., 2009; Chaparro et al., 2020) soils. They allow us to constrain the processes of soil formation and the climatic and environmental conditions existing during pedogenesis. In Antarctica, mineral magnetic techniques have been utilized, and limited studies have been made. Limited number of studies on the soils of Antarctic soil are available (Chaparro et al., 2007; Gargiulo et al., 2021; Jordanova, 2017; Warrier et al., 2014b). In the studies by Chaparro et al. (2007) and Gargiulo et al. (2021), the authors investigated anthropogenic pollution in the soils of Marambio Station (Antarctic Peninsula) using environmental magnetic methods. Although the authors studied the magnetic properties of unpolluted soils in the station's surroundings, they did not conduct detailed investigations on the soil's pedogenic processes in the region. Jordanova (2017) studied the magnetic properties of the soils of the Antarctic Peninsula (AP). However, the study is limited to the AP. Warrier et al. (2014b) investigated the magnetism of the catchment soils in Schirmacher Oasis, East Antarctica. Such study was limited to only seven samples from Sandy Lake's catchment in the region.

Larsemann Hills (LH) is one of the major ice-free regions in East Antarctica, encompassing an area of approximately 50 $km^2$. The region is marked with several lakes, and the soil materials are mainly sandy with negligible amounts of silt and clay (Wang et al., 2022). Previously, researchers have studied LH soils to detect the presence of contaminants. The presence of these contaminants in the soils of Larsemann Hills was found to result from anthropogenic activities. For example, Shi et al. (2018) reported the presence of heavy metals in LH soils, primarily resulting from the weathering of the parent rocks. However, elevated levels of Pb were found in the soils inside the station areas, resulting from anthropogenic activities. More recently, Wang et al. (2022) analyzed the LH soils for the presence of a distribution of persistent organic pollutants (POPs). Contaminants were found to be concentrated near the station areas, suggesting an anthropogenic source. Bhakta et al. (2022) analyzed the trace elements from the soil samples and their risks to the local biota; the source of contamination was found to be natural. Wang et al. (2023) measured the mercury content of LH soils and found a close relationship with the soil's organic carbon content. Applying environmental magnetic techniques could also help identify soils contaminated by anthropogenic minerals. Anthropogenic magnetic grains fall into the multidomain and pseudo-single-domain grain size ranges (Lu and Bai, 2008; Yunginger et al., 2018). These grains could be attributed to industrial activity or vehicular and fuel generator exhaust emissions (Warrier et al., 2014a). To the best of our knowledge, no attempts have been made to investigate the mineral magnetic properties of the LH soils and determine the intensity of the pedogenic processes. In the present study, we examine soil samples from the Grovnes and Broknes Peninsulas in Larsemann Hills, East Antarctica, to gain knowledge concerning the mineral magnetic characteristics of the soils and processes influencing pedogenesis. This study represents one of the first attempts towards establishing a comprehensive environmental magnetism record of the soils of Larsemann Hills.

## 2. Materials and Methods

### 2.1 Study area

The Larsemann Hills is an ice-free oasis located along the Ingrid Christensen Coast of Princess Elizabeth Land (Fig. 1). It lies along 69° 23′ S and 76° 53′ E. The area comprises two large peninsulas, Stornes and Broknes, and a smaller peninsula, Mirror Peninsula, along with several dispersed offshore islands (Gasparon et al., 2002). It occupies about 50 $km^2$ and has more than 150 lakes. The region is also marked by well-established meltwater streams and second-order drainage networks (Gillieson, 1990). The Larsemann Hills are distinguished by slightly undulant topography, consisting of low rounded hills interlayered by lakes of variable sizes and U-shaped glaciated valleys (Asthana et al., 2013). Morainic deposits are rarely seen in the LH, but erractic blocks can be seen. The most significant geomorphic process going on in the LH is aeolian and salt weathering (Gillieson, 1990). Precipitation in the LH occurs in snow and reaches a maximum of up to 250 mm water equivalent. Average monthly temperatures during summer remain slightly above 0°C and between -15°C and -18°C during winter months (ANARE, 2000; Hodgson et al., 2001). Three scientific research bases are located within the Larsemann Hills viz., Progress Station (Russia), Zhongshan Station (China), and Law Base (Australian summer base) located in the Broknes Peninsula while the Bharati Station (India), is in the Grovnes Island.

The Larsemann Hills is principally dominated by upper amphibolite to granulite grade paragneisses interloped frequently by pegmatitic and granitic bodies. The region is a metasedimentary sequence section stretching to the Bolingen Islands to the south and the western Rauer Group to the north (Carson et al., 1995). The major lithological units of the region are predominantly low-pressure granulite facies, metasedimentary gneisses, and partial melt bodies. The area is dominated by metapelitic cordierite and Fe-Ti oxide-rich gneisses (Stüwe et al., 1989).

The soils in Antarctica are developed in a permafrost zone and could be classified as cryosols (Kukharchyk et al., 2022). The soils in the wet valleys of Larsemann Hills are neutral to slightly acidic and devoid of carbonates (Mergelov, 2014). The principal soil development processes in the Larsemann Hills are physical disintegration and biochemical weathering (Bockheim, 2015b). The unconsolidated remnants of the bedrock weathering are predominantly sandy with minimal concentrations of silt and clay. The thickness of the active layer ranges between 20 and 90 cm (Mergelov, 2014). There is no permanent snow cover in the region. The snow that is received is redistributed by the wind and piles up as snowfields (Kukharchyk et al., 2022). The well-drained soils show rich colours, resulting from iron liberation due to chemical weathering. The predominant soil types in the region are lithic haplothels, followed by typic haplothels and typic haploturbels (Bockheim, 2015b).

### 2.2 Sample collection

Sixty-five surface soil samples were collected from the Broknes Peninsula (n = 46) and Grovnes Peninsula (n = 19), Larsemann Hills, during the 33$^{rd}$ Indian Scientific Expedition to Antarctica. Before collecting the soil samples, the top layer of the coarser rock particles was gently removed by using a plastic spatula. The soil samples were collected in HDPE bags and stored at 4º C before being shipped to National Centre for Polar and Ocean Research (NCPOR), Goa (India), for further analysis.

## 2.3 Methodology

### 2.3.1. Environmental magnetic measurements

The magnetic measurement of the soil samples was performed at the Environmental Magnetism Laboratory at Mangalore University (India). The mass-specific magnetic susceptibility ($\chi_{lf}$) measurements were carried out with a Bartington dual-frequency magnetic susceptibility meter. The susceptibility was measured at a low frequency ($\chi_{lf}$) (0.465 kHz, $\chi_{0.465}$) and a high frequency ($\chi_{hf}$) (4.65 kHz, $\chi_{4.65}$). The percentage frequency-dependent susceptibility ($\chi_{fd}$%) was calculated from the difference between the low-frequency and high-frequency measurements, i.e. $\chi_{fd}\% = [(\chi_{0.465} - \chi_{4.65})/ \chi_{0.465}] \times 100$. Anhysteretic remanent magnetization (ARM) was applied to the samples with a Molspin AF demagnetizer. The peak field was 100 mT with a DC bias field of 0.04 mT. The ARM was determined with a Molspin fluxgate magnetometer. The anhysteretic susceptibility ($\chi_{ARM}$) was determined as well. Isothermal remanent magnetization (IRM) was applied to the samples with a Molspin pulse magnetizer. The IRM was acquired at increasing fields from 20 – 1000 mT. The IRM at 1000 mT was considered the saturation isothermal remanent magnetization (SIRM). The remanence obtained at each acquisition was also determined with a Molspin fluxgate magnetometer.

### 2.3.2. Particle size analysis

The particle size analysis and the organic content estimation of the twenty-seven soil samples representing the Broknes (n = 19) and Grovnes (n = 8) Peninsulas were performed at the environmental engineering research laboratory at the Manipal Institute of Technology (India). Approximately five grams of samples were first transferred to pre-weighed beakers, treated with 30% hydrogen peroxide ($H_2O_2$), and kept overnight to calculate the soil's organic matter. The samples were weighed after treatment with $H_2O_2$, and this weight was subtracted from the initial weight to estimate the amount of organic matter present in them. The samples were treated with acetic acid and kept overnight to remove the inorganic carbon content. The weights of the samples were noted down after each step. After removing organic carbon and carbonates, Calgon solution was added to the samples to deflocculate the clay particles adhering to the sand grains. The samples were then sieved through a +63 μm sieve, and the sieved fractions were transferred to pre-weighed beakers. The beakers were oven dried and weighed, and the percentage sand content was calculated. The remaining fraction after sieving was transferred to 1-litre measuring cylinders and then pipetted out. The pipetted-out fractions were oven dried and weighed, and the silt and clay content percentages were calculated following the Folk's classification (Folk, 1954).

## 3. Results and discussion

### 3.1. Magnetic properties of the surface soils

#### 3.1.1. Concentration

The parameters $\chi_{lf}$, $\chi_{ARM}$, and SIRM reflect the concentration of the magnetic minerals. $\chi_{lf}$ accounts for all magnetic minerals present in a sample (Evans and Heller, 2003; Thompson and Oldfield, 1986). $\chi_{lf}$ values range between $14.6\times10^{-8}m^3kg^{-1}$ and $971.3\times10^{-8}m^3kg^{-1}$ for Broknes Peninsula with an average (± S.D.) value of 117.7 (± 175.0) $\times10^{-8}m^3kg^{-1}$ (Fig. 2). The values for Grovnes Peninsula vary between $49.8\times10^{-8}m^3kg^{-1}$ and $844.5\times10^{-8}m^3kg^{-1}$ with an average (± S.D.) value of 330.9 (± 217.4) $\times10^{-8}m^3kg^{-1}$. Almost all the samples show high magnetic susceptibility values, revealing the predominance of magnetically strong minerals in the soils of Larsemann Hills. $\chi_{ARM}$ indicates the proportion of stable single-domain (SSD) grains (Maher, 1988). The samples from Broknes Peninsula show an average (± S.D.) value of 0.10 (± 0.15) $\times10^{-5}$ $m^3kg^{-1}$ with a maximum value of $0.65\times10^{-5}$

$m^3kg^{-1}$, while the samples from Grovnes show an average (± S.D.) value 0.16 (± 0.10) $\times 10^{-5} m^3kg^{-1}$ with a 0.36 as the maximum value (Fig. 2). $\chi_{ARM}$ has a statistically significant correlation with $\chi_{lf}$ (Supplementary Tables S1 and S2) for the soils from both Broknes ($R = 0.96$, $p < 0.05$, $n = 19$) and Grovnes ($R = 0.93$, $p < 0.05$, $n = 8$) peninsulas suggesting the influence of SSD grains on the magnetic signal of the soils from these regions. SIRM reflects the overall proportion of the remanence carrying magnetic grains (Oldfield, 1991), that is, ferromagnetic minerals. The SIRM ranges from $39.2\times10^{-5}$ $Am^2kg^{-1}$ to $4935.1\times10^{-5}$ $Am^2kg^{-1}$ for the Broknes samples (Fig. 2). The samples from Grovnes have SIRM values between $195.48\times10^{-5}$ $Am^2kg^{-1}$ and $3013.99\times10^{-5}$ $Am^2kg^{-1}$. The concentration-dependent parameters show comparatively high values for most of the samples, with the samples from Grovnes Peninsula showing slightly higher values on average than those from Broknes Peninsula. The statistically significant correlations observed between $\chi_{lf}$ and SIRM for both Broknes ($R = 0.95$, $p < 0.05$, $n = 19$, Supplementary Table S1) and Grovnes ($R = 0.98$, $p < 0.05$, $n = 8$, Supplementary Table S2) peninsulas suggest the dominance of magnetically strong ferrimagnetic grains in the samples.

**3.1.2. Mineralogy**

Magnetic mineralogy can be inferred from the parameter S-ratio (= $IRM_{-300mT}$/SIRM). S-ratio indicates the relative proportions of the low coercivity minerals (e.g., magnetite) and the high coercivity minerals (e.g., hematite) present in the samples (Evans and Heller, 2003). Since magnetite saturates under low fields, typically < 300 mT, high S-ratio values indicate the higher concentrations of low coercivity minerals in the samples. S-ratio values vary from 0.90 to 0.99, reflecting the predominance of magnetically soft ferrimagnetic minerals. The IRM acquisition curves show that most of the samples from both peninsulas saturate at fields below 300 mT (Fig. 3a), reinforcing the predominance of low-coercivity minerals such as magnetite and titanomagnetite. The parameter $H_{1/2}$ can be used to determine magnetic mineralogy, where the $H_{1/2}$ values between 10 and 77 mT correspond to the magnetite range (Chaparro and Sinito, 2004; Peters and Dekkers, 2003). The $H_{1/2}$ values for the Broknes samples show mean (± S.D.) values of 38.2 (± 4.9) mT, while that of the Grovnes of 38.3 (± 3.7) mT (Fig. 2), suggesting that the magnetic carrier is magnetite. The statistically significant correlation between $\chi_{lf}$ and SIRM (Fig. 3b) and $\chi_{lf}$ and $\chi_{ARM}$ (Fig. 5a) for all the samples indicates substantial concentrations of magnetically strong ferrimagnets such as magnetite/ titanomagnetite in our samples.

**3.1.3. Magnetic Grain Size**

The ratio $\chi_{ARM}$/SIRM documents the magnetic granulometry. High values in this ratio suggest finer magnetic grain sizes, and lower values indicate coarser grain sizes (Oldfield, 1991; Walden et al., 1999). The Broknes samples show an average (± S.D.) $\chi_{ARM}$/SIRM value of 10.24 (± 5.59) $\times 10^{-5}$ mA$^{-1}$ with a maximum value of $34.80\times10^{-5}$ mA$^{-1}$, while the Grovnes samples show an average (± S.D.) value of 12.86 (± 2.12) $\times10^{-5}$ mA$^{-1}$ and a maximum of $16.28\times10^{-5}$ mA$^{-1}$ (Fig. 2). Values exceeding $200\times10^{-5}$ mA$^{-1}$ are suggestive of the occurrence of bacterial magnetite (Foster et al., 2008). The values remain consistently low for the Broknes and Grovnes Peninsulas samples, suggesting coarser magnetic grain sizes. The ratio $S_{20}$ (= $IRM_{20mT}$/SIRM) is discriminative of the MD-sized ferrimagnetic grains. Higher $S_{20}$ values indicate a more significant concentration of MD grains. The $S_{20}$ values are high for all the samples suggesting significant MD grain content. The parameter $\chi_{fd}$ (= $\chi_{0.465}$ - $\chi_{4.65}$) reflects the intensity of pedogenesis, and $\chi_{fd}$% denotes semi-quantitatively the concentration of ultrafine superparamagnetic (SP) grains in the samples (Oldfield, 1991; Walden et al., 1999). $\chi_{fd}$ is sensitive to magnetic grains in the superparamagnetic (SP) size range with a diameter of 0 to 0.3 μm. This grain size range is unlikely to include primary magnetic minerals (Dearing et al., 1996a). Therefore, $\chi_{fd}$ is considered sensitive to the SP grains formed due to pedogenic processes. Furthermore, the samples with high concentrations of coarse-grained MD ferrimagnets will have high $\chi_{lf}$ and zero $\chi_{fd}$. Samples with higher proportions of SP grains will have $\chi_{fd}\% > 6\%$. SP grains dominate the assemblage in samples with $\chi_{fd}\% > 10\%$ (Dearing et al., 1996a). $\chi_{fd}\%$ values less than 2% imply the lack of superparamagnetic grains (Fig. 2). Values between 2 and 10% suggest an admixture of superparamagnetic and coarser grains, and $\chi_{fd}\%$ values > 10% suggest the dominance of superparamagnetic grains (Dearing et al., 1997). The $\chi_{fd}\%$ values of LH soils remain lower than 2% for most samples, and only two samples show values > 2% suggesting negligible concentrations of SP particles (Fig. 2). The plot of $\chi_{fd}\%$ vs $\chi_{ARM}$/SIRM (Fig. 4) indicates that the soil samples from Broknes and Grovnes peninsulas are dominated by an envelope of MD and PSD-sized ferrimagnetic grains. The samples also plot in the zone of no SP grains with $\chi_{fd}\%$ values less than 2%. Only two samples have values > 2% implying insignificant proportions of superparamagnetic grains in the magnetic minerals of the LH samples.

**3.2. Origin of iron oxide minerals in the soils**

Magnetite and maghemite, along with titanomagnetite, are the two most seen iron oxide minerals in soils. They are primarily derived from lithogenic sources and pedogenic processes. The magnetic minerals in the soils may also be influenced by the transformation of iron oxides under high temperatures associated with harvest burning or fires (Maher, 1986; Dearing et al., 1996b), authigenic formation of greigite (Fassbinder and Stanjek, 1994; Roberts, 1995), the formation of bacterial magnetite (Fassbinder et al., 1990) and contributions from anthropogenic sources (Maher, 1986; Blundell et al., 2009; Gargiulo et al., 2021). The contributions from magnetotactic bacteria can be constrained by the inter-parametric ratios $\chi_{ARM}$/SIRM and $\chi_{ARM}/\chi_{lf}$. Values exceeding $200\times10^{-5}$ mA$^{-1}$ for $\chi_{ARM}$/SIRM (Foster et al., 2008) and > 40 for $\chi_{ARM}/\chi_{lf}$ (Oldfield, 1994) reflect the occurrence of bacterial magnetite. Magnetotactic bacteria produce the bacterial magnetite. These bacteria produce SD magnetite crystals, which assist them in steering along the geomagnetic field lines in search of anaerobic conditions (Bazylinski and Williams, 2007). In LH soils, the maximum values were $34.8\times10^{-5}$ $mA^{-1}$ for $\chi_{ARM}$/SIRM (Fig. 2) and 2.68 for $\chi_{ARM}/\chi_{lf}$, signifying the absence of any bacterial magnetite in these samples. Greigite is a ferrimagnetic iron sulfide forming under anaerobic, reducing environments (Berner, 1984; Roberts, 1995). SIRM/$\chi_{lf}$ values > $30\times10^{3}$ $Am^{-1}$ is reflective greigite formation (Snowball, 1991). Samples show maximum SIRM/$\chi_{lf}$ values of $12.9\times10^{3}$ $Am^{-1}$ (Fig. 2), indicating the absence of any greigite in the samples. The high-temperature thermal transformation of iron oxide minerals due to harvest burning/occurrence of natural fires is improbable due to the climatic conditions of the study area. Antarctica records extremely cold temperatures and has scarce vegetation for any fires. Industrial activities and emissions from vehicles mainly supply anthropogenic magnetic minerals (Warrier et al., 2014a). In urban soils, the anthropogenic magnetic minerals fall in the MD and PSD grain size range, and $\chi_{lf}$ negatively correlates with $\chi_{fd}$ (Lu and Bai, 2008). Contributions from vehicular emissions and electric power generators are minimal in the study area. Previous studies indicate no significant contributions from anthropogenic activities in the soils of Larsemann Hills, and the metal concentrations are regulated by natural processes (Gasparon and Matschullat, 2006a; 2006b). However, Shi et al., (2018) reported elevated concentrations of Pb within a research base. Enrichment of other metals were accounted for by natural variability. From the above observations, there are no substantial contributions from bacterial magnetite, authigenic greigite and anthropogenic magnetic grains in the magnetic signal of the soils from Larsemann Hills. Moreover, the principal rock types in the study area are orthogneisses, paragneisses, and metapelites consisting of minerals such as biotite, sillimanite, spinel, and magnetite (Carson and Grew, 2007). Hence, it can be established that the magnetic grains present along the soils of Larsemann Hills are principally lithogenic.

**4. Particle size distribution and organic content of the soils**

The sand distribution in the samples from the Broknes Peninsula ranges from 81.5 to 96.82% with an average (± S.D.) of 93.08 (± 4.28) %. The silt content ranges from 0 – 13.65% with an average (± S.D.) of 3.04 (± 3.75) %, while the clay content varies from 0.60 – 6.81% with an average (± S.D.) of 3.88 (± 1.78) %. It is evident from these results that the Broknes samples are predominantly sandy with minor fractions of silt and clay. The organic content of the soils from the Broknes peninsula is very low, ranging from 0.10 to 0.87% with an average (± S.D.) of 0.39 (± 0.21) %. No significant correlation between the magnetic data, particle size data and the organic matter is observed for the soils from the Broknes Peninsula (Supplementary Table S1).

In the samples from the Grovnes Peninsula, the sand percentage varies from 77.73 – 96.32% with an average (± S.D.) of 90.64 (± 6.54) %. The silt content ranges from 0.70 to 16.24% with an average (± S.D.) of 5.76 (± 5.99) %, and the clay content ranges from 0.20 – 6.23% with an average (± S.D.) of 3.60 (± 1.78) %. The organic matter content varies between 0.18 and 0.80% with an average (± S.D.) of 0.49 (± 0.22) %. Like the Broknes soils, the soils from the Grovnes Peninsula also have very little organic content. Except for three magnetic parameters and particle size variables (Supplementary Table S2), no significant correlations were found between magnetic parameters, particle size and the organic matter data.

In the soil textural diagram, the Broknes and Grovnes Peninsula samples occupy the sand and loamy sand textural classes (Supplementary Figure S1). The soils of Larsemann Hills were previously studied by Bockheim, (2015b), who reported low concentrations of silt and clay in the soils. The high sand percentage indicates a glaciofluvial environment erosion by glaciers, and glacial meltwater is the dominant mode of weathering. The dominant force behind the formation of soils in Larsemann Hills is the physical action on the rocks leading to their disintegration by the erosive nature of glaciers. The scarcity of precipitation and low temperatures result in low degrees of chemical weathering. Mergelov (2014) reported an average $SiO_2/Al_2O_3$ ratio of 5.8 in the soils of Larsemann Hills, indicating a low degree of chemical weathering. The principal soil development process in the Larsemann Hills is physical disintegration, and the soils were texturally classified as sand to loamy sand (Bockheim, 2015b).

## 5. Comparison with soils from other Antarctic regions

Geographic location has a significant role in the weathering process leading to soil formation. For example, soil formation in tropical regions is primarily controlled by chemical weathering (Sandeep et al., 2012), while physical weathering dominates in polar regions (Bockheim, 2015a, 2015b; Lin et al., 2021; Navas et al., 2008; Ugolini and Bockheim, 2008; Zvěřina et al., 2012). Soils formed by the mechanical disintegration of the parent material generally have a coarser grain size (Bockheim, 2015a). Coastal Antarctica records milder climatic conditions than the interior portion of the Antarctic continent; as a result, chemical weathering also plays a role in pedogenesis in this region (Simas et al., 2008; Haus et al., 2016). The soils of the ice-free territories of coastal Antarctica are also affected by a large population of seabirds. Vast amounts of seabird manure result in the phosphatization of soil, giving rise to ornithogenic soils (Bockheim, 2015b). They are primarily seen in coastal regions with active penguin rookeries. Previous studies on the soils of Larsemann Hills show low degrees of chemical weathering (Shi et al., 2018), indicating the dominance of physical weathering processes on soil formation.

Rock magnetic techniques allow us to differentiate the magnetic minerals formed under differing climatic regimes and pedogenic processes based on their grain sizes. The scatter plot of $\chi_{ARM}$ vs $\chi_{lf}$ (King et al., 1982) (Fig. 5a) indicates the magnetic particle size. The soils from Larsemann Hills have been compared with soils from Schirmacher Oasis (Warrier et al., 2014b) and Antarctic Peninsula (Chaparro et al., 2007). The soil samples from

Broknes and Grovnes peninsulas show higher magnetic concentration values on average compared to the soils from Antarctic Peninsula and comparable values with the Schirmacher Oasis soils. Also, the soil samples from Broknes and Grovnes Penninsula show coarser magnetic sizes than the soils from Antarctic Peninsula. Magnetic grain sizes range from 1 μm to > 20 μm for Broknes samples (MD+PSD) and > 20 μm (MD) for Grovnes soil samples, indicating significant proportions of MD grains. This is also observed by the magnetic particle size plot of the anhysteretic ratio $\chi_{ARM}/\chi_{lf}$ (Fig. 5b). The soft component of IRM, $IRM_{20mT}$ is especially responsive to the ferrimagnetic grains in the MD size range. A highly significant correlation is noticed for $\chi_{lf}$ and $IRM_{20mT}$ for Broknes ($R = 0.97$, $p < 0.05$, $n = 19$) and Grovnes ($R = 0.96$, $p < 0.05$, $n = 8$), implying that the majority of the remanence is carried by magnetically soft MD-sized ferrimagnetic grains.

The Kruskal-Wallis test (Conover, 1999), a non-parametric one-way evaluation of variance, was performed to evaluate medians of variables between the Broknes and Grovnes Peninsula soils. Supplementary Table S3 shows that parameters $\chi_{lf}$, $\chi_{fd}$, $\chi_{ARM}$, SIRM, $\chi_{ARM}$/SIRM, SIRM/$\chi_{lf}$ and $S_{20}$ are significantly different at the 0.05 level for the two peninsulas. The parameters $\chi_{lf}$, $\chi_{fd}$, $\chi_{ARM}$, and SIRM represent the magnetic concentration, while $\chi_{ARM}$/SIRM, SIRM/$\chi_{lf}$ and $S_{20}$ depend on the magnetic grain size. The magnetic parameters and inter-parametric ratios show that the magnetic concentration is slightly higher on average for the soil samples from the Grovnes Peninsula compared to those from the Broknes Peninsula. Moreover, differences can also be observed in the magnetic parameter distributions of the two regions (Fig. 6). This is because samples from Broknes Peninsula show two distinct magnetic grain size assemblages and magnetic mineral concentrations. One set of samples shows higher magnetic susceptibility values with coarser magnetic grain sizes, while the other set has comparatively finer magnetic grains with lower susceptibility values. This fact could be due to the differences in lithology. The area with the coarser magnetic grains (Fig. 6b) and higher magnetic concentrations (Fig. 6a) in the Broknes Peninsula is dominated by Lake Ferris metapelites, which consist of dark garnet, sillimanite, biotite metapelite with spinel and magnetite (Carson and Grew, 2007). While the area having finer magnetic grains and lower magnetic concentrations is dominated by Broknes paragneiss consisting of garnet-bearing quartz feldspathic paragneiss with variable sillimanite, spinel and magnetite (Carson and Grew, 2007).

The plots of $\chi_{ARM}$ vs $\chi_{lf}$ and $\chi_{ARM}/\chi_{lf}$ (Figs. 5a, 5b) and $S_{20}$ vs $\chi_{ARM}$/SIRM (Fig. 7) allow to differentiate soils of different regions based on magnetic grain size. Soil data from Broknes and Grovnes peninsulas are plotted in Figure 7 alongside synthetic magnetites (Dankers, 1978; Maher, 1988) and soil data from Schirmacher Oasis (Warrier et al., 2014b). The soil samples from Larsemann Hills plot along the envelope of synthetic magnetite (Dankers, 1978) having coarser magnetic grain sizes and significant proportions of MD grains. The Schirmacher Oasis soils also show coarse magnetic grain sizes. In these polar regions, physical weathering dominates, producing magnetic minerals with coarser grain sizes (Warrier et al., 2021a; 2021b; 2021c).

Warm and wet conditions are required for the pedogenic formation of magnetic minerals and prolonged surface exposure to sunlight. Such conditions are not observed in the study area, where the conditions are cold and dry, and the surface remains under ice cover for a significant part of the year. Previous studies from Schirmacher Oasis (Warrier et al., 2021a; 2021b; 2021c) reported that even though pedogenesis activity occurs in the region, its intensity is insufficient to form SP-sized magnetic grains. Moreover, the pedogenic magnetic grains are generally fine-grained in the SP or SSD size range. The soil samples from Broknes and Grovnes peninsulas are coarse-grained, falling in the MD and PSD size range with little or no inputs from SP grains. The $\chi_{fd}$ values also stay low, indicating no significant pedogenic activity in the soils of Larsemann Hills. The results imply that the magnetic properties of LH soils are primarily generated by lithogenic input with no significant contributions from the pedogenic formation of magnetic minerals.

## 6. Conclusions

The present study provides insight into the magnetic properties and particle size distribution of Larsemann Hills, East Antarctica soils. From the analyses, it is observed that:

- The magnetic minerals in the soils of Larsemann Hills are principally lithogenic with no significant inputs from bacterial magnetite, authigenic greigite and anthropogenic magnetic minerals.
- The magnetic minerals of the soils of Larsemann Hills are coarse-grained, falling in the MD size range.
- S-ratio values for all the samples remain > 0.90, reflecting the predominance of ferrimagnetic minerals. The parameter $H_{1/2}$ shows average values of 38.2 and 38.3 mT for Broknes and Grovnes samples, respectively, which are in the range for magnetite. These observations suggest that magnetically soft ferrimagnetic grains such as magnetite generate the magnetic signal of the soils of Larsemann Hills.
- The soils are predominantly sandy, with an average sand content of 93.08% in Broknes soils and 96.32% in Grovnes soils with low concentrations of organic matter. No significant correlation has been observed between the magnetic properties and organic content.
- No evidence for any significant pedogenic activity has been observed for soils of the Broknes and Grovnes peninsulas.

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## Figure Captions

**Fig.1.** Location map of the Larsemann Hills showing the Broknes and Grovnes peninsulas with the map of Antarctica (inset). The sampling sites are marked as red circles on the map.

**Fig. 2.** Box plots (box delineates the interquartile range of 25–75%, horizontal lines indicate the mean (black) and median (yellow), and the minimum and maximum values are shown using whiskers) showing the magnetic parameters and inter-parametric ratios of soils from the Broknes Peninsula and Grovnes Peninsula.

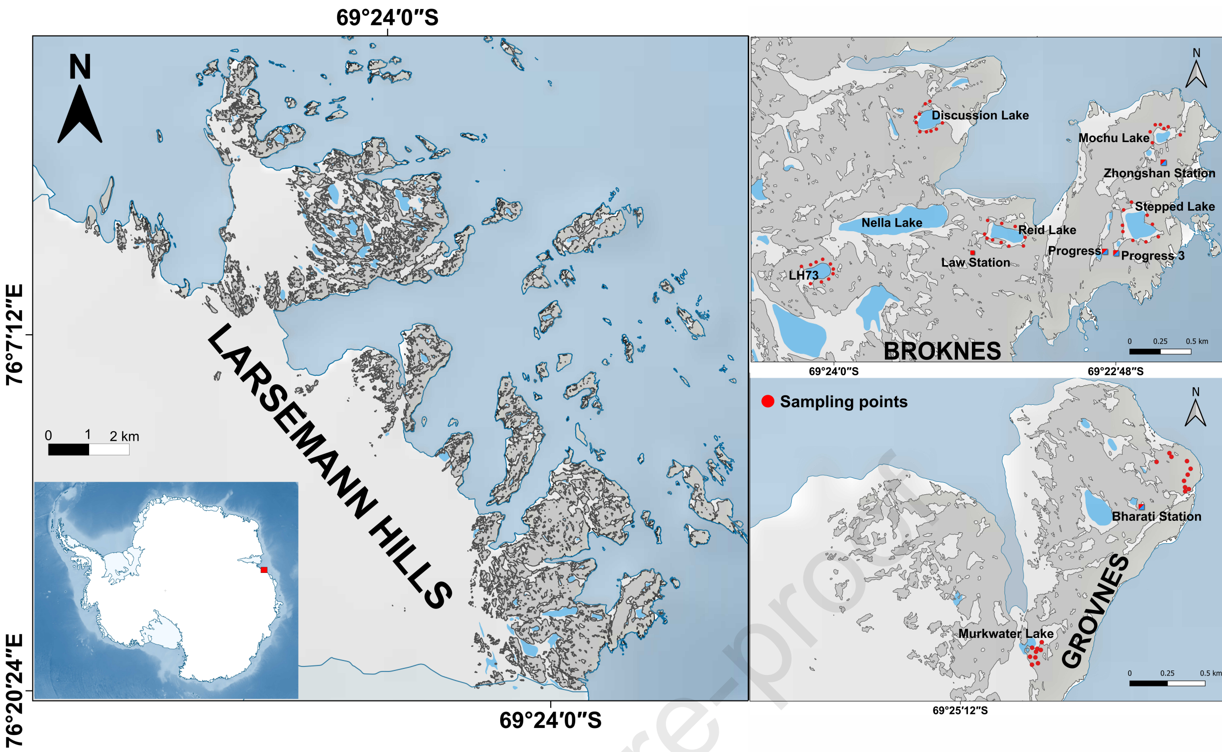
**Fig. 3.** (a) IRM acquisition curves, and (b) biplot of $\chi_{lf}$ *vs* SIRM for the soil samples from Broknes and Grovnes peninsulas.

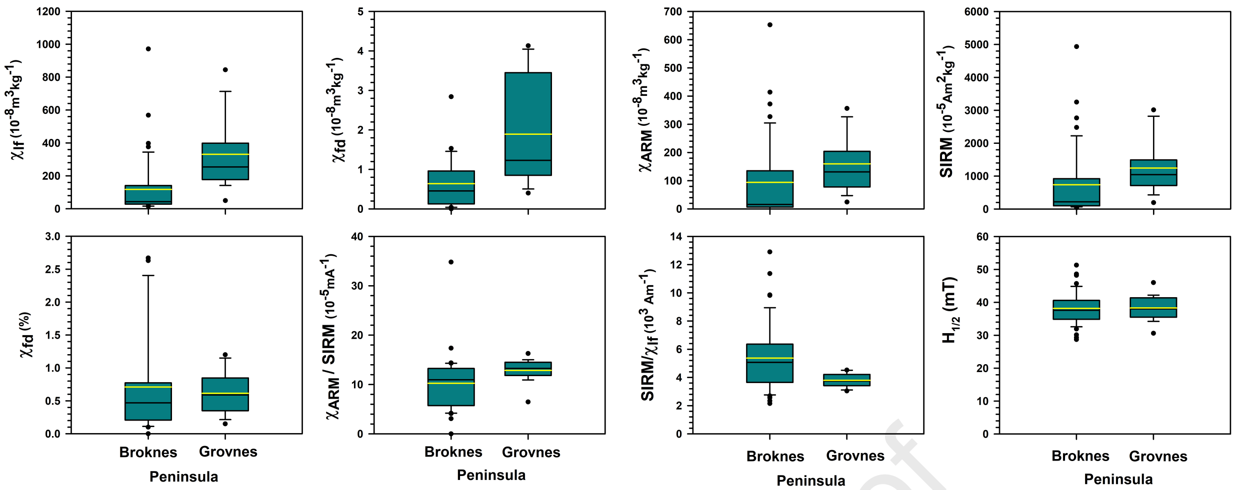
**Fig. 4.** Semi-quantitative biplot of $\chi_{fd}$% *vs* $\chi_{ARM}$/SIRM (Dearing et al., 1997) parameters for the Broknes and Grovnes Peninsula soil samples.

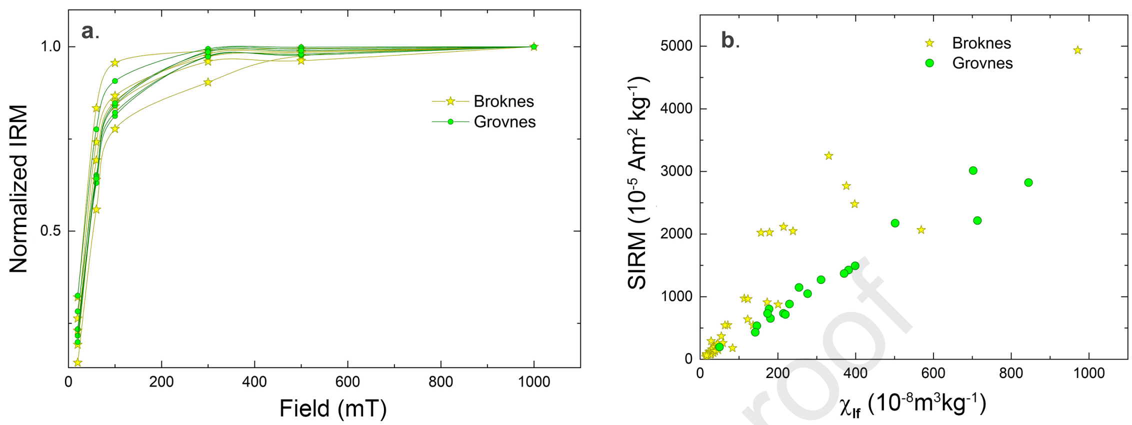
**Fig. 5.** (a) $\chi_{lf}$ *vs* $\chi_{ARM}$ biplot (King et al., 1982), and (b) Box plots (box delineates the interquartile range of 25–75%, horizontal lines indicate the mean (black) and median (red), and the minimum and maximum values are shown using whiskers) of $\chi_{ARM}/\chi_{lf}$ for soil samples from the Broknes Peninsula, Grovnes Peninsula, Schirmacher Oasis (Warrier et al., 2014b), and Marambio Island, Antarctic Peninsula (Chaparro et al., 2007).

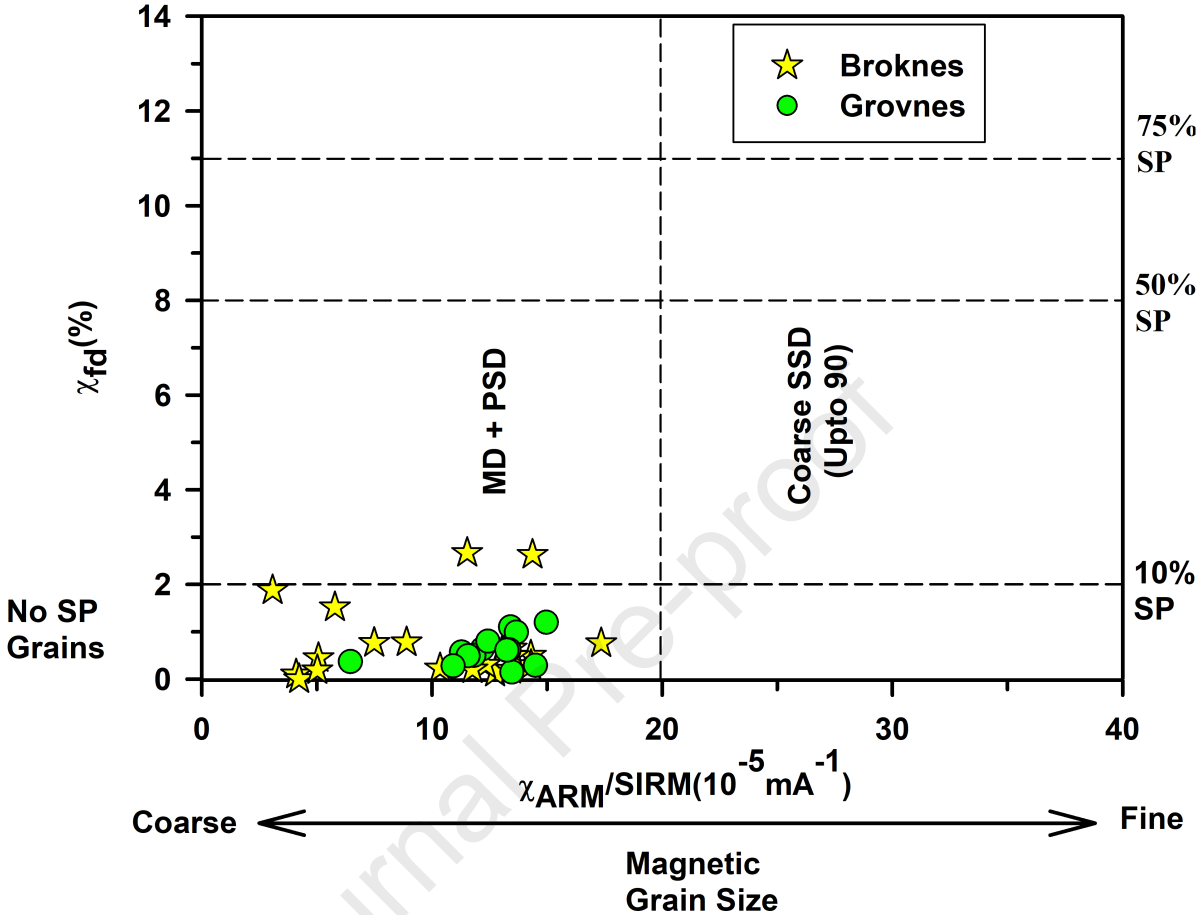
**Fig. 6.** Color-mapped graph of magnetic parameters for Broknes and Grovnes Peninsula soils. (a) $\chi_{lf}$ (magnetic concentration dependent parameter), and (b). $\chi_{ARM}/\chi_{lf}$ (magnetic grain-size dependent parameter).

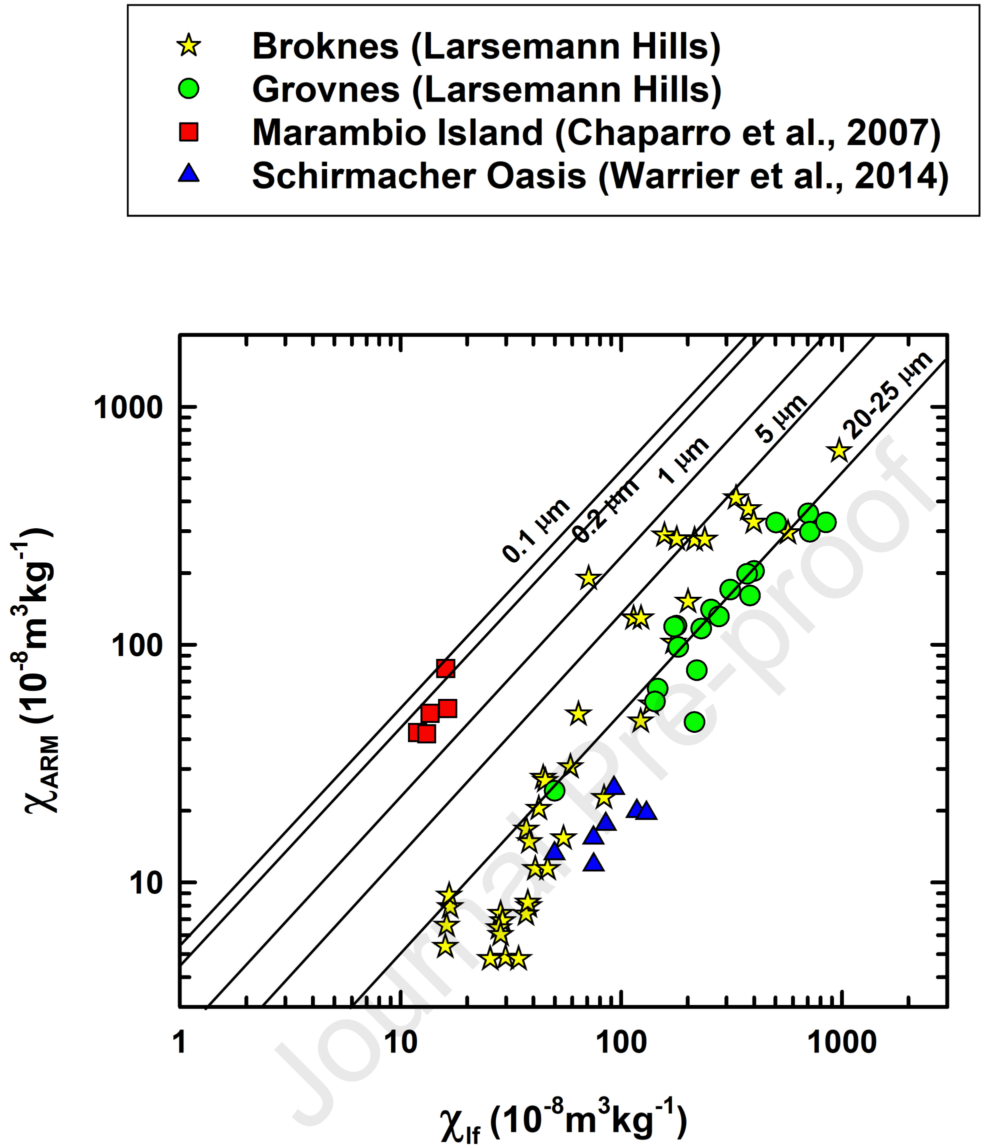
**Fig. 7.** Biplot of $S_{20}$ vs $\chi_{ARM}$/SIRM of soils from the Broknes and Grovnes peninsulas. This data is plotted alongside synthetic magnetites (Dankers, 1978; Maher, 1988) and soil data from Schirmacher Oasis (Warrier et al., 2014b). Numbers indicate size in microns.

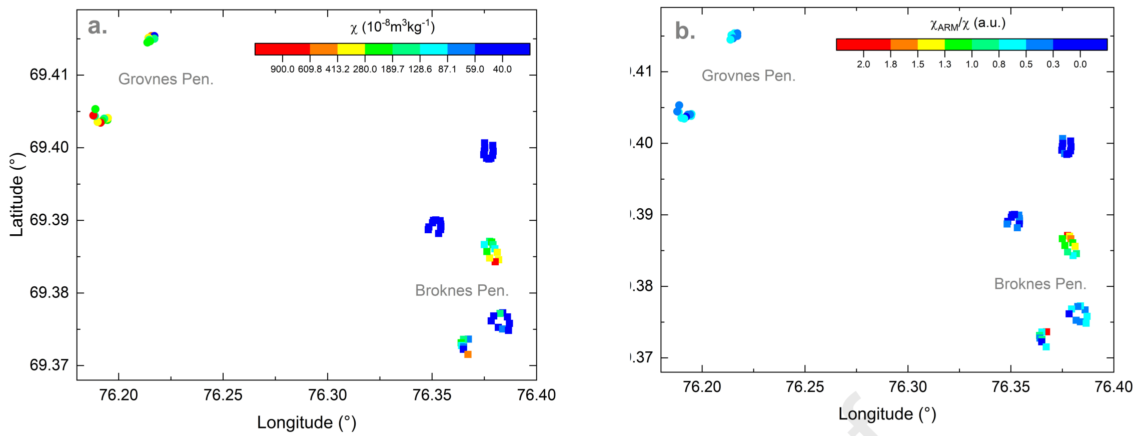

69°24′0″S
N
LARSEMANN HILLS
76°7′12″E
76°20′24″E
0 1 2 km
69°24′0″S
Discussion Lake
Mochu Lake
Zhongshan Station
Nella Lake
Stepped Lake
Reid Lake
Progress
Progress 3
Law Station
LH73
BROKNES
0 0.25 0.5 km
69°24′0″S
69°22′48″S
76°22′48″E
Sampling points
Bharati Station
76°12′0″E
Murkwater Lake
GROVNES
0 0.25 0.5 km
69°25′12″S

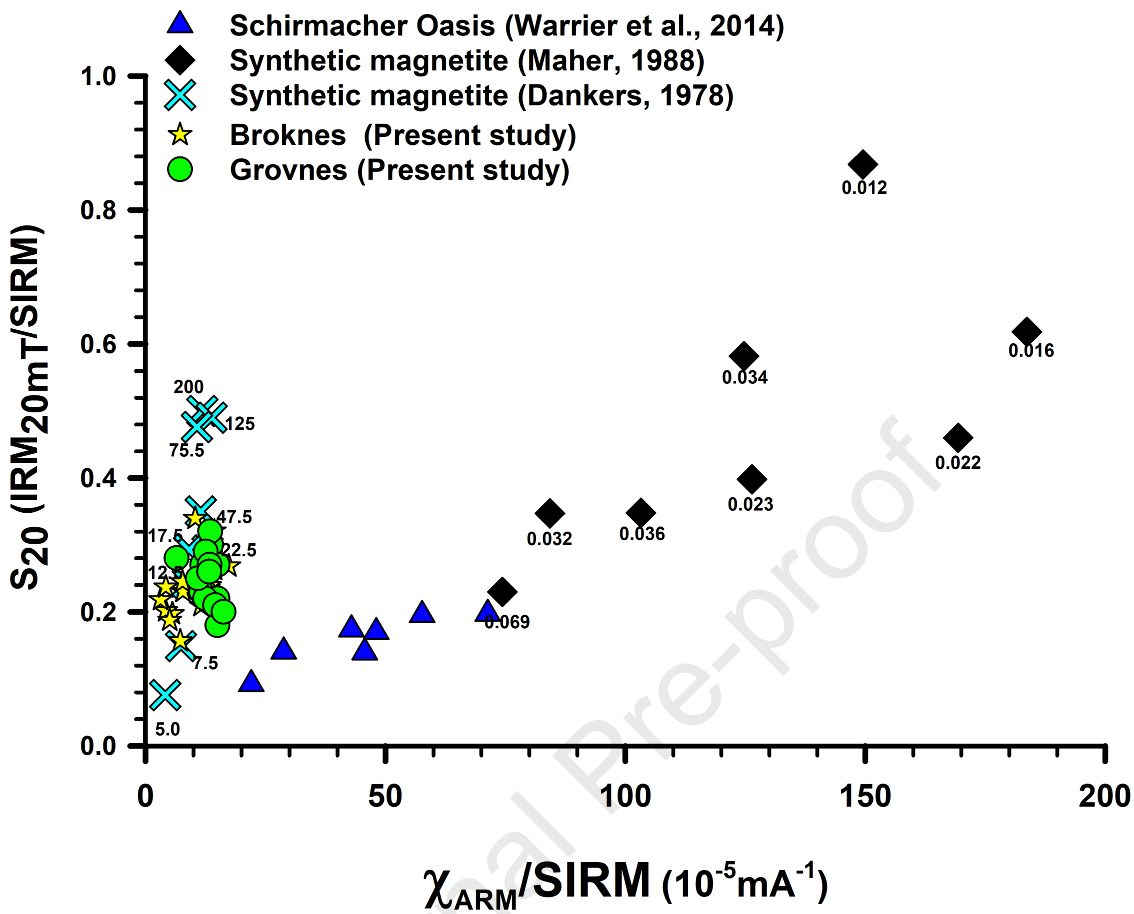

χlf (10-8m3kg-1)
χfd (10-8m3kg-1)
χARM (10-8m3kg-1)
SIRM (10-5Am2kg-1)
χfd (%)
χARM / SIRM (10-5mA-1)
SIRM/χlf (103 Am-1)
H1/2 (mT)
Broknes
Grovnes
Peninsula


a.
Normalized IRM
Field (mT)
Broknes
Grovnes
b.
SIRM ($10^{-5}$ Am$^2$ kg$^{-1}$)
$\chi_{lf}$ ($10^{-8}$m$^3$kg$^{-1}$)
Broknes
Grovnes


Broknes
Grovnes
75%
SP
50%
SP
10%
SP
No SP
Grains
MD + PSD
Coarse SSD
(Upto 90)
$\chi_{fd}$(%)
$\chi_{ARM}$/SIRM($10^{-5}$ mA$^{-1}$)
Coarse
Fine
Magnetic
Grain Size


Broknes (Larsemann Hills)
Grovnes (Larsemann Hills)
Marambio Island (Chaparro et al., 2007)
Schirmacher Oasis (Warrier et al., 2014)
0.1 µm
0.2 µm
1 µm
5 µm
20-25 µm
1000
100
10
1
10
100
1000
$\chi_{ARM}$ ($10^{-8}m^3kg^{-1}$)
$\chi_{lf}$ ($10^{-8}m^3kg^{-1}$)


a.
χ (10-8m3kg-1)
900.0 609.8 413.2 280.0 189.7 128.6 87.1 59.0 40.0
Grovnes Pen.
Broknes Pen.
Latitude (°)
Longitude (°)
b.
χARM/χ (a.u.)
2.0 1.8 1.5 1.3 1.0 0.8 0.5 0.3 0.0
Grovnes Pen.
Broknes Pen.
Longitude (°)



Schirmacher Oasis (Warrier et al., 2014)
Synthetic magnetite (Maher, 1988)
Synthetic magnetite (Dankers, 1978)
Broknes (Present study)
Grovnes (Present study)
$S_{20}$ ($IRM_{20mT}$/SIRM)
$\chi_{ARM}$/SIRM ($10^{-5}mA^{-1}$)
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
0.012
0.016
0.034
0.022
0.023
0.032
0.036
0.069
200
125
75.5
47.5
17.5
22.5
12.5
7.5
5.0

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: