

Petrophysical attributes of the Seixo Amarelo-Gonçalo Li-bearing aplite-pegmatites (Guarda-Belmonte area, central Portugal)

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Abstract

Lithium-bearing pegmatites of the Seixo Amarelo-Gonçalo area are hosted within two-mica granites of the Guarda-Belmonte area in central Portugal. The pegmatites, often concealed beneath cover material, occur at sizes difficult to detect via airborne geophysical methods but may be detectable at the prospect scale using high-resolution methods such as geoelectrical surveys. However, to maximize contributions from these methods, an understanding of the rock physical properties, e.g., electrical resistivity of pegmatites and their host rocks, is required. In this study, we present results from petrophysical data acquired from laboratory measurements of drill core samples, including volume magnetic susceptibility, electrical resistivity, and chargeability for a suite of pegmatites and their host granite from the Gonçalo Li mine. Though there was large overlap in all petrophysical characteristics between the pegmatites and granites, overall, granites indicated higher magnetic susceptibility than pegmatites, the degree of which increases with alteration associated with pegmatite halo formation and crystallization of Fe-rich minerals (e.g., zinnwaldite, tourmaline). Lepidolite-bearing pegmatites have lower magnetic susceptibility compared to their barren counterparts or those containing zinnwaldite. Unexpectedly, based on laboratory measurements, the electrical resistivity values of granites are higher than those of pegmatites, and highest in granites containing tourmaline, followed by the general two-mica granite of the area and lastly by zinnwaldite-bearing granites in alteration halos. In pegmatites, resistivity values were highest in pegmatites containing zinnwaldite, followed by barren pegmatites, with lepidolite-bearing pegmatites having the lowest resistivity values. The lone dolerite sample, representing late veins that crosscut the deposit, has the lowest resistivity value.

Results from chargeability measurements presented as phase angle proved inconsistent owing to overall weak polarization potential and also samples dominated by coarse-grained minerals for studied lithologies, which yielded scattered data. The petrophysical work presented here serves as a supplement for future geophysical investigations in pegmatite exploration in the region and elsewhere with similar geological settings.

1. Introduction

Granitic pegmatites represent the most important hard rock Li resource in addition to hosting a suite of other strategic or critical raw materials (CRM, e.g., Be, Cs, Nb, Ta, Sn) necessary for 'green technologies' (e.g., high Ni-Li-ion batteries for the electric vehicle industry) or industrial minerals for other applications (e.g., ceramic feldspar). Resultantly, exploration for Li-bearing pegmatites has increased significantly in recent years, necessitating innovative exploration techniques to keep pace with demand. A variety of tools have been developed to guide exploration efforts in the detection of pegmatites. These include vectoring techniques such as use of indicator minerals (e.g., London, 1986) or mineral trace element chemistry (e.g., Linnen et al., 2015; Müller et al., 2021; Keyser et al., 2023), use of alteration halos in host rocks (Errandonea-Martin et al., 2022; Barros et al., 2020; Keyser et al., 2024; Sirbescu et al., 2025), remote sensing techniques (e.g., Cardoso-Fernandes et al., 2020) or holistic toolsets consisting of multiple methods applicable to different geological settings (Müller et al., 2025). However, while

determining the petrophysical properties of various orebodies in relation to their host rocks remains crucial to their detection under cover, geophysical methods for use on pegmatites have largely been unsuccessful due to small physical property contrasts with host rocks and their relatively non-magnetic, low density and nonconductive nature (Trueman and Černý, 1982).

Various studies have had varying degrees of success using geophysical methods for pegmatite detection. For example, Trueman and Černý (1982) were able to distinguish the wall zone from the core zone of the Tanco pegmatite (Canada) using gravity measurements, where the wall zone, consisting of feldspar (potassic and albitic), quartz and muscovite, displayed lower anomalies compared to the Li-rich core. Qu et al. (2023) performed petrophysical characterization of a large sample suite of schist, pegmatite and granite from the Altay Orogenic belt in China and were able to conduct forward modelling of the audio magnetotelluric data using resistivity values measure in the lab. The results helped them to establish the genetic relationship between deep granitic bodies and structurally higher pegmatite veins using inversion of audio magnetotelluric data. Roncato et al. (2025) were similarly able to distinguish Li-rich pegmatites from their overlying schist host rock using combined geophysical methods. However, the intrinsic variability between different pegmatite bodies and geological settings limits the establishment of consistent petrophysical attributes as proxies for pegmatites and their host rocks.

As part of a large project seeking to establish effective exploration techniques for buried pegmatites hosting Li, high-purity quartz and other CRM (GREENPEG; Müller et al., 2025), Haase and Pohl (2022) determined the petrophysical characteristics of pegmatite and their host rock from various localities in Europe in an effort to establish a database to facilitate pegmatite exploration in Europe. In furtherance of such efforts, the 'Exploration and Geomodelling' work package of the Dinamine project, we present petrophysical data on a suite of Li aplite-pegmatites and their host granite from the Gonçalves Li mine in central eastern Portugal. Pegmatites of this region are part of a larger pegmatite province within the Central Iberian zone that are associated with the waning stages of the Variscan Orogeny. This study provides petrophysical data that will be used in subsequent geophysical surveys with application towards pegmatite exploration in Portugal and comparable pegmatite fields elsewhere.

2. Geological Background

The Seixo Amarelo-Gonçalo pegmatite field is located within the Central Iberian Zone (CIZ) of the Iberian Massif, ~ 100 km south of the Galicia-Trás-os-Montes Zone (GTMZ) and ~ 20 km southwest of Guarda in central eastern Portugal (Fig. 1). The field covers an area of approximately 100 km² within a terrain consisting predominantly of peraluminous S-type granites that intruded a Cambrian schist-metagraywacke complex late in the Variscan Orogeny during ductile deformation (e.g., Dias et al., 1998; Valle Aguado et al., 2017; Pereira et al., 2018), generating mica schist-hornfels contact aureoles in the process. The granites represent multiple phases of intrusion and consist of syn-to-late (D3), late- and late-to-post orogenic variants (e.g., Sant'Ovaia et al., 2010; Nieva et al., 2011). The main pegmatite-hosting granite in the Seixo Amarelo-Gonçalo area is a syn-to-late orogenic porphyritic biotite granite

(e.g., the Guarda granite), whereas post-orogenic porphyritic monzonite occurs further to the south of the field in the Belmonte area.

Numerous NE-SW striking, sub-horizontal aplite-pegmatite veins and sills (veins hereafter) are observed in the Seixo Amarelo-Gonçalo region crosscutting the biotite granite host rocks and generating metasomatic halos in the host rock in the process (Ramos, 2007). The veins measure from a few cm up to 15 m in thickness, but are generally < 4 m thick, and include amblygonite- and lepidolite-subtypes, the former typically occurring at lower structural levels than the latter. Whereas pegmatites of the amblygonite-subtype typically only contain a single aplite-pegmatite layer, those of the lepidolite-subtype can be complex and contain numerous (6–7) textural and compositional layers, from aplite along footwall and hanging wall contacts to coarse-grained pegmatite zones displaying complex structures (Ramos, 1998; Nieva and Ramos, 2009). Genetically, the aplite-pegmatite veins have been linked to a fine-to-medium-grained biotite granite through fractional crystallization (Nieva and Ramos, 2009, 2010)

The aplite-pegmatites are diverse in terms of their mineralogy and in accordance with their degree of fractionation. The amblygonite-subtype aplite-pegmatite veins contain quartz, perthite and microcline, albite, muscovite, tourmaline, topaz, beryl, zircon, apatite, amblygonite, monazite, cassiterite and columbite-group minerals. The lepidolite-subtype veins, in addition to the above, also contain lepidolite, petalite, microlite, torbernite, autunite, pyrite and chalcopyrite (Ramos, 1998; Nieva and Ramos, 2010). The lepidolite-subtype pegmatites are considered more highly evolved than the amblygonite-subtype.

3. Petrophysical properties of pegmatites from a global perspective

Variations in physical properties of rocks and sediments, besides other parameters, influence the measured resistivity and chargeability (IP effect) response of subsurface material, as these parameters affect the electrical current flow through rocks, resulting in variations in the distribution of electric potential within them. Therefore, studying the micro-scale geoelectrical and magnetic properties of rocks helps to better understand the macro-scale response of field-collected geophysical data such as electrical resistivity and magnetic data (Tavakoli et al., 2021). Petrophysical laboratory measurements of pegmatites from the Wolfsberg deposit in Austria showed magnetic susceptibility as a useful property for distinguishing mica schist-hosted pegmatites (MHP; median magnetic susceptibility of 0.0004 SI) and amphibolite-hosted pegmatites (AHP; median magnetic susceptibility of 0.0008 SI) from their host rock. The contrast was large enough to model and distinguish pegmatites and host rock from magnetic surveys (Hasse and Bohl, 2022). However, it was concluded that the overall setting and geometry of the pegmatites are determining factors during exploration. The pegmatites of the Wolfsberg deposit have an average thickness of 2 m, with an approximate maximum thickness of 5 m, which complicates their detection at large depths, e.g., ≥ 5 m. Large negative magnetic susceptibilities are often described by dominance of the diamagnetic minerals, for example, quartz (e.g., Machek et al., 2023).

Borehole resistivity logging demonstrated a higher electrical resistivity for MHP and AHP pegmatites (3,000 Ω m and 4,000 Ω m, respectively) compared to their mica schist (1,000 Ω m) and amphibolite (2,000

Ωm) host rocks, respectively (Haase and Pohl, 2022). The same authors suggested that such contrasts in resistivity should allow for pegmatite detection if the pegmatites are at least several meters thick and not deeper than 100 m below the surface. Szetu (1956) performed geological and electrical resistivity surveys to distinguish pegmatites from granites in the Lacorne Township of northwestern Quebec. The sheet-like pegmatite bodies were found lying concordant with the host muscovite granite sheet. The results showed that pegmatite dikes in the studied area had, with minor fluctuations, a similar order of magnitude of electrical resistivity to their host granite. However, values were much higher for granites compared to quartz-mica schist. It was thus concluded that if a noticeable pegmatite dike is located within a schist layer, it will appear as a persistent narrow zone of comparatively higher resistivity in an area of low resistivity. Previous research has primarily focused on the geological and geochemical aspects, lacking indirect geophysical evidence regarding the genetic link between the pegmatite veins and the deep-seated granitic basement. However, differences in rock composition and mineral content and differences in number of the measured samples must be considered when making direct comparison between the results from different studies.

4. Methodology and Measurement Procedure

4.1. Sample suite

The open pit exposure at the Gonçalves pegmatite mine provides insight into the nature of pegmatite veins and their relationship to the host rock, a biotite granite, and other lithologies such as dolerite dikes. The wall exposure shows two major sub-horizontal pegmatite veins measuring roughly 2–3 m in thickness (Fig. 2A). One of the veins is offset by ca. 10 m subvertical fault. A set of near-vertical dolerite dikes crosscut the pegmatite veins. Emplacement of the pegmatites formed alteration halos in the host granite, typically composed of Fe-rich minerals such as zinnwaldite, a Li- and Fe-rich variety of biotite, or black tourmaline (Fig. 2B). The main pegmatites are the lithium type, which display complex zoning with aplitic banding and coarser domains (Fig. 2C). However, abundant thinner (10–20 cm) pegmatite veins occur throughout the deposit with a similar flat-lying habit as the larger veins. Vertically crosscutting the deposit is a set of roughly 1-m thick dolerite dikes (Fig. 2D).

From the deposit, thirty-one drill cores were made available for petrophysical measurements, from which fifty granite samples, sixty-one pegmatite samples and one sample from a dolerite dike were analyzed. Figure 3 shows an example of such sampled drill core where a ~ 3 m lepidolite-bearing pegmatite has generated a ~ 50 cm alteration halo in the host granite. Further sample details are provided in Supplementary Material.

4.2. Laboratory measurement

All samples were analysed at the petrophysical laboratory at the Department of Civil, Environmental and Natural Resources Engineering at the Luleå University of Technology (LTU). A brief description of the instruments and their setup is provided in this section.

4.2.1. Magnetic susceptibility

Magnetic susceptibility was measured using a AGICO KLY-3 Kappabridges (AGICO, 2003). Instrument calibration was performed prior to measurements and every two hours thereafter. Samples were cut to a size of $\approx 1 \text{ cm}^3$ to fit the sample holder within the instrument chamber. The accuracy of the calibration is $\pm 3\%$ and the sensitivity for bulk measurements is 3×10^{-8} (SI). The instrument was operated at a field intensity of 300 Am^{-1} . Since many samples were not oriented, the anisotropy of the magnetic susceptibility was not measured, though this can help to better understand and link small-scale structural lineaments and foliations to large-scale tectonic structures such as shear-zones, which were not observed at the site. Measurements for each sample were repeated three times to account for potential errors induced by instrument or operator.

4.2.2. Electrical resistivity and chargeability

Complex resistivity can be calculated based on measurements of spectral induced polarization (SIP). In this study, SIP measurements were conducted on a total of 172 selected samples from the Gonçalo Li deposit. In total, 112 samples demonstrated acceptable results from electrical resistivity and 59 samples indicated acceptable results from IP effect (i.e., chargeability). Electrical resistivity was characterized by determining the impedance (Ω) of samples, which was then converted to resistivity (Ωm), knowing the samples dimensions. The phase angle of the samples were measured as milli-radian (mrad) determined at three frequency ranges (details below) via injecting an alternating current. The SIP instrument was manufactured at Luleå University of Technology (LTU) and consists of a signal generator, reference resistors with known resistances (details below), a sample holder comprising current and potential electrodes and a data logger. A brief description of the instrument components is given below.

Signal generator

A logarithmic sinusoid-form sweep signal – a signal for which frequency increased logarithmically with time – is induced. The frequency of the signal was determined at three frequency ranges: 0.1–3 Hz, 1–300 Hz and 100–10,000 Hz.

Reference resistor

From the signal generator, the current passes through a reference resistor that is set to either 2 k Ω , 10 k Ω , 100 k Ω or 1 M Ω , based on the order of magnitude of the resistance of the core sample being measured. The sample impedance is then measured against this reference resistance. To reduce uncertainty with the estimated complex resistivity and to acquire more accurate results, it is preferable that the resistance over the sample and reference resistor is of the same order, as it would imply that the measured voltages are within a comparable amplitude.

Sample holder

The sample holder is composed of a PVC tube with a current (C) electrode on one end and a potential (P) electrode on the other into which the core sample is placed. The current is then transmitted via a copper plate into the sample. The potential difference (ΔV) across the sample is then measured using the copper wire potential electrodes (P). Two thin sponge layers are placed between the current electrode and sample on one end and between the potential electrode and sample on the other. Prior to measurement, the mounted electrodes and sponges are dipped into a saturated copper sulphate solution (CuSO_4) to ensure good current conduction and to minimize contact resistance. Alternatively, an NaCl solution can be used, however, this can create unwanted corrosion in the copper wires.

Receiver unit (data logger)

A SMARTem24 data logger from ElectroMagnetic Imaging Technology was used for transient electromagnetic measurements. The logger contains sixteen channel amplifiers, filters, a data logger, a laptop programmed with recording and processing software. For this study, we used only two channels: CH_1 (V_r), which records voltage across a reference resistor, and CH_2 (V_s), which measures the voltage over the sample. The signal-to-noise ratio must be sufficiently high over the entire frequency range to manage recording the small phase shifts that cause even low IP effects.

Data processing was performed in MATLAB to convert the measurement outputs and plot resistivity and phase angle across the measured frequency. Data plots showing smooth trends and no negative phase values are indicative of acceptable results, whereas scattered data with several negative phase values are indicative of unacceptable results.

5. Results

The results from the petrophysical measurements are presented in the following sections as box and whisker diagrams in Figs. 4–7 and in Table A1. Although data for outliers are included within the diagrams, the outlier values are not discussed.

The sample suite can be categorized by three general lithologies: granites, pegmatites and a lone dolerite sample. The range of measured values amongst the sample set was large. For magnetic susceptibility, granites generally indicated much higher values compared to other lithologies, ranging from -3.84 – 40.6 ($\times 10^{-6}$ SI) with a median value of 9.57 ($\times 10^{-6}$ SI) (Fig. 4A), followed by the dolerite sample (0.11×10^{-6} SI), and then by pegmatites, which ranged from -11.53 – 1.19 ($\times 10^{-6}$ SI), with a median value of -5.14 ($\times 10^{-6}$ SI), although several outliers within the data ranged from roughly 3 up to 63 ($\times 10^{-6}$ SI). The dolerite was the least resistive ($144 \text{ } \Omega\text{m}$) followed by pegmatites (Fig. 4B), which ranged from 31 – $75,611 \text{ } \Omega\text{m}$ (median of $5,116 \text{ } \Omega\text{m}$). Granites showed the highest electrical resistivity, with values ranging from 679 to $19,061 \text{ } \Omega\text{m}$ (median of $5,371 \text{ } \Omega\text{m}$).

Within the individual lithological categories, several sub-categories could be identified based on, e.g. specific mineralogy. For example, besides the common two-mica granite observed in the area,

zinnwaldite and tourmaline were observed as alteration products in some two-mica granite samples, typically within metasomatic halos. In general, the two-mica granite shows a magnetic susceptibility ranging from -3.84 to 40 ($\times 10^{-6}$ SI) (median of 5.69 SI; Fig. 5A), whereas granite containing zinnwaldite shows a range of -2.79 to 41 ($\times 10^{-6}$ SI), median value 16 ($\times 10^{-6}$ SI). Granite samples containing black tourmaline had a magnetic susceptibility range of 9.57 – 30.8 ($\times 10^{-6}$ SI) (median of 20 ($\times 10^{-6}$ SI)), and a lone granite sample containing abundant epidote had a susceptibility value of 29.6 ($\times 10^{-6}$ SI). In terms of resistivity values, granite samples containing zinnwaldite had the lowest resistivity values (679 – $4,886$ Ωm ; median of $3,744$ Ωm ; Fig. 5B), whereas normal two mica granite had resistivity values of 725 – $72,158$ Ωm (median of $5,851$ Ωm), and granites containing tourmaline had the highest resistivity values of $7,209$ – $12,087$ Ωm (median of $11,020$ Ωm).

Pegmatites similarly show a large range of magnetic susceptibility values owing to mineralogical variation. The pegmatite categories include lepidolite-bearing pegmatites, barren pegmatites, and pegmatites containing zinnwaldite. Lepidolite-bearing pegmatites ranged in magnetic susceptibility from -8.2 to -1.8 ($\times 10^{-6}$ SI) (Fig. 6A), with a median value of -5 ($\times 10^{-6}$ SI). However, within this sample set, outliers occurred up to 17 ($\times 10^{-6}$ SI). Barren pegmatites show higher magnetic susceptibility values of -9.23 – 3.24 ($\times 10^{-6}$ SI), with a median value of -6.4 ($\times 10^{-6}$ SI), whereas zinnwaldite-bearing pegmatites ranged in magnetic susceptibility from 1.19 – 27.4 ($\times 10^{-6}$ SI), with a median of 11 ($\times 10^{-6}$ SI). All pegmatite categories showed large ranges of resistivity values from 31.1 – $75,611$ Ωm (Fig. 6B). However, lepidolite-bearing pegmatites had the lowest overall median resistivity value of $2,897$ Ωm followed by barren pegmatites (median of $8,634$ Ωm), while zinnwaldite-bearing pegmatites showed the highest median resistivity of $8,221$ Ωm .

The chargeability for all lithological categories showed scattered characteristics or otherwise near zero anomalies, i.e., no IP response. Figure 7 shows an example of the measured IP presented as phase angle (mrad) versus measured frequency (Hz) for two samples: a barren pegmatite and a lepidolite-bearing pegmatite. The mean and median values for the lepidolite pegmatite show consistent phase angle values, whereas those for the barren pegmatite show two separated trends at roughly $3,000$ and $-3,000$ mrad, effectively cancelling each other out. The resulting IP response from both lithologies is ca. 0 mrad, i.e., indicating no significant chargeability. The near-zero IP response for the dominant lithologies at this site is expected, due to the absence of mineralization with considerable chargeability, compared to the background geology.

6. Discussion

The petrophysical characteristics of the studied lithologies provided important insights into the magnetic and geoelectrical properties of pegmatites, granites and dolerites in the region. This information can serve as a priori information in modeling and in interpretation of data acquired in future pegmatite exploration campaigns in the Seixo Amarelo -Gonalo area and in similar geological settings. Apart from the general magnetic and geoelectrical response of the studied lithologies, which contribute

to a better understanding of observed anomalies from the different field surveys, there are several other parameters that contribute to the measured response of the lithologies that should be taken into consideration.

The Koenigsberger ratio (Q), which is defined as the ratio between remanent and induced magnetization and indicates the relative importance of remanent magnetization in the quantitative interpretation of magnetic anomalies. As a result, remanent magnetization may constitute a significant proportion of the magnetization of a rock and thus it is important to consider. However, the contribution of remanent magnetization to observed magnetic anomalies is often neglected in due to its rather complex laboratory experiment process and thus high costs. Understanding remanent magnetization is more significant for rocks with higher Q values (Tavakoli et al., 2012). Granites and pegmatites often yield low Q values as they are mainly composed of diamagnetic minerals. As such, an absence of remanent magnetization data will not largely affect the overall understanding of their magnetic properties. Another important parameter when interpreting petrophysical data is the quantity and dimensions of measured samples, as a small sample population and sample size from a given lithology may result in unrepresentative values (e.g., Tavakoli et al., 2012; Mohammed and Corbett, 2003). Moreover, variations in some of the physical properties (e.g., rock magnetic properties) can be large, and fluctuations in measured values occurring at orders of magnitude over distances of decimeters are common, which further impresses the need for a larger number of measurements systematically distributed across a given sampling zone (Dentith et al., 2020). Both pegmatites and granites usually contain non-polarizable minerals of neither membrane nor electrode polarization source, which explains their near-zero IP response. However, the alteration of granitic rocks can produce clay minerals such as kaolinite that may result in, small but elevated chargeability (Piolat et al., 2025). Interpretations of the laboratory IP data can benefit from knowledge of samples matrix properties: connected porosity and cation exchange capacity (CEC). Fresh samples are often characterized by low porosities with small CEC. Both porosity and CEC of the granite increase with increased alteration and weathering (Piolat et al., 2025), which could explain the insignificant increased IP effect for some of the samples. Assigning numerical values acquired from petrophysical measurements to categorize geological classifications often ignores the geological, geochemical and rock mechanical properties of the rock such as grain size, mineralogy, porosity and more, which, according to Dentith et al. (2020), can be addressed by incorporating information based on the mineral systems concept and its link to the regional geological framework (Wyborn et al., 1994).

7. Conclusion

The magnetic susceptibility measured on core samples show that granites have a positive and stronger magnetic susceptibility 9.57×10^{-6} SI relative to pegmatites -5.14×10^{-6} SI, which can be explained by presence of Fe-bearing minerals in granites (e.g., biotite) and a greater abundance of diamagnetic minerals such as quartz in pegmatites. Defining subcategories based on the presence or absence of specific minerals helped to better understand fluctuations in the results. Zinnwaldite, tourmaline and rarely epidote were observed as alteration products, which were formed during metasomatic halo

generation and increased the magnetic susceptibility in granites relative to their unaltered variants. Subcategories were also defined for pegmatites containing different minerals, with zinnwaldite-bearing pegmatites showing the highest median magnetic susceptibility values 11×10^{-6} SI), which is slightly higher than the measured median value for all granites. However, pegmatites displayed slightly lower resistivity values (5,116 Ωm) compared to granites (ca. 5,371 Ωm). The zinnwaldite-bearing pegmatites and barren pegmatites had respective resistivities lower and higher than the average.

Studying the magnetic and electrical properties of the rocks proved useful in differentiating pegmatites from their host granitic rocks, particularly in terms of magnetic susceptibility. The result also shows the importance of incorporating sub-classification within each rock category, which sometimes helps to explain the mismatch between laboratory and field data. Considering that petrophysical measurements are complex, expensive, time-consuming and require access to enough samples with information such as logging, geochemical analysis, depth, orientation etc., they become neglected in many geophysical studies. Therefore, including information from mineral system analysis, if available, can be beneficial for interpretations of petrophysical data by clarifying the above outlined uncertainties. Despite the outlined uncertainties, a petrophysical knowledgebase for, in particular, “geophysically invisible” lithologies e.g. pegmatite and granites can provide significant information for better understanding of the geophysical anomalies and thereby identifying their occurrences more accurately which decreases the uncertainty in interpretation of geophysical data. Complementary mineralogical studies on the studied samples and geoelectrical and magnetic surveys at the study site can thus help to improve the geological understanding and thereby pegmatite occurrences at the site. Therefore, information provided in this study provides valuable insights to better understand anomalies from geophysical surveys in the study area and similar environments.

Declarations

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Declaration of Competing Interest

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.

Authors contributions

Saman Tavakoli compiled the core samples and was responsible for laboratory measurements. He was also responsible for preparation of the manuscript. William Keyser contributed to writing the manuscript, analysis, interpretations and linking petrophysical and geological and mineralogical dimensions. Castelo Joao contributed in petrophysical measurement and data analysis. José Oliveira and Paulo Moutela provided core samples and contributed with geological discussions and interpretations of results. Thorkild Maack Rasmussen helped with laboratory measurements, data analysis and interpretations of the results.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon request, and after agreement with the owner of data, MCS.

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Figures

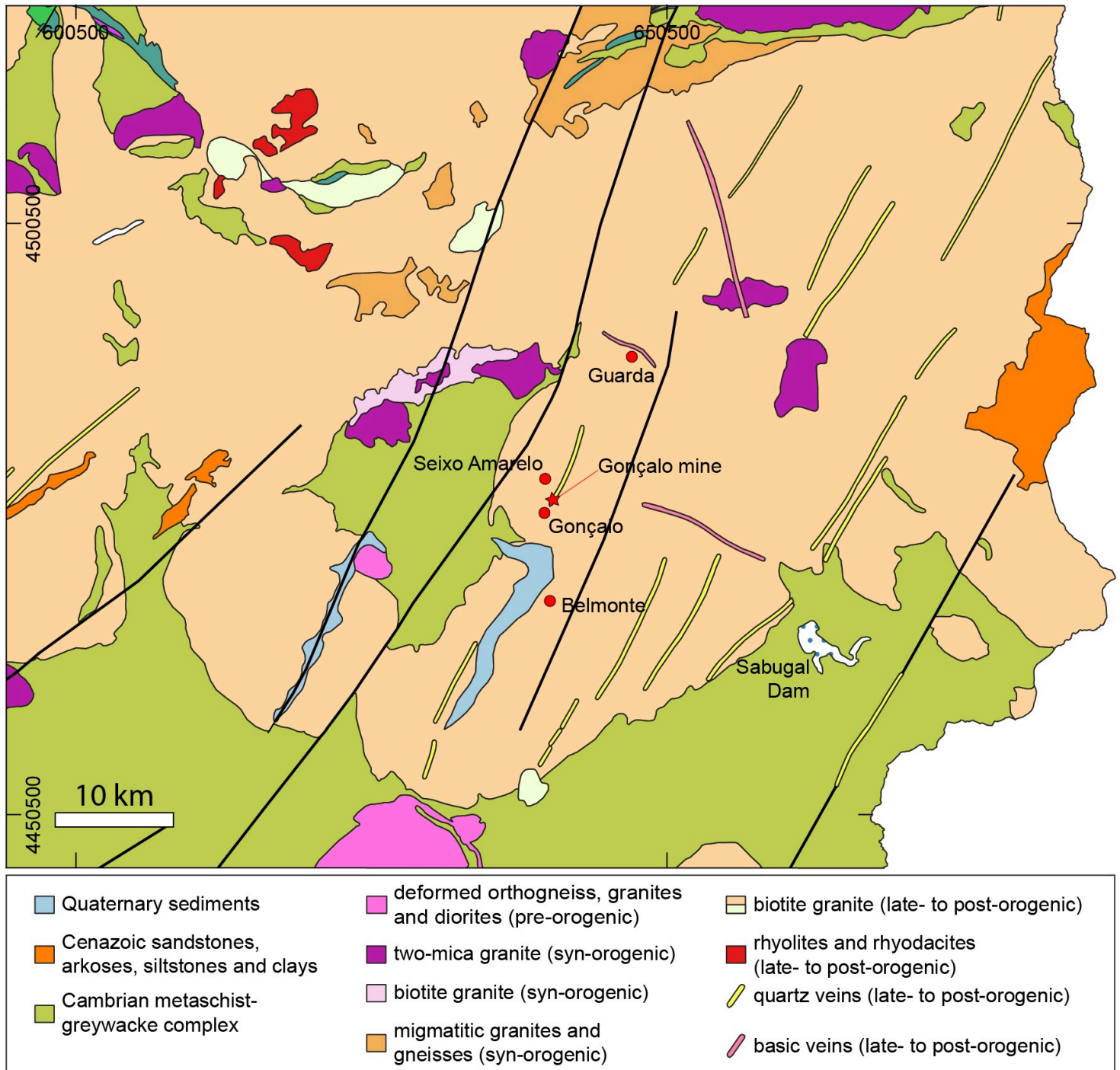


Figure 1

The Guarda-Belmonte area represented in a geological map of the central east Portugal showing the location of the Gonçalo pegmatite mine as well as various pegmatite veins in the area. Modified after LNEG-LGM (2010) Carta Geológica de Portugal á escala 1:1,000,000.

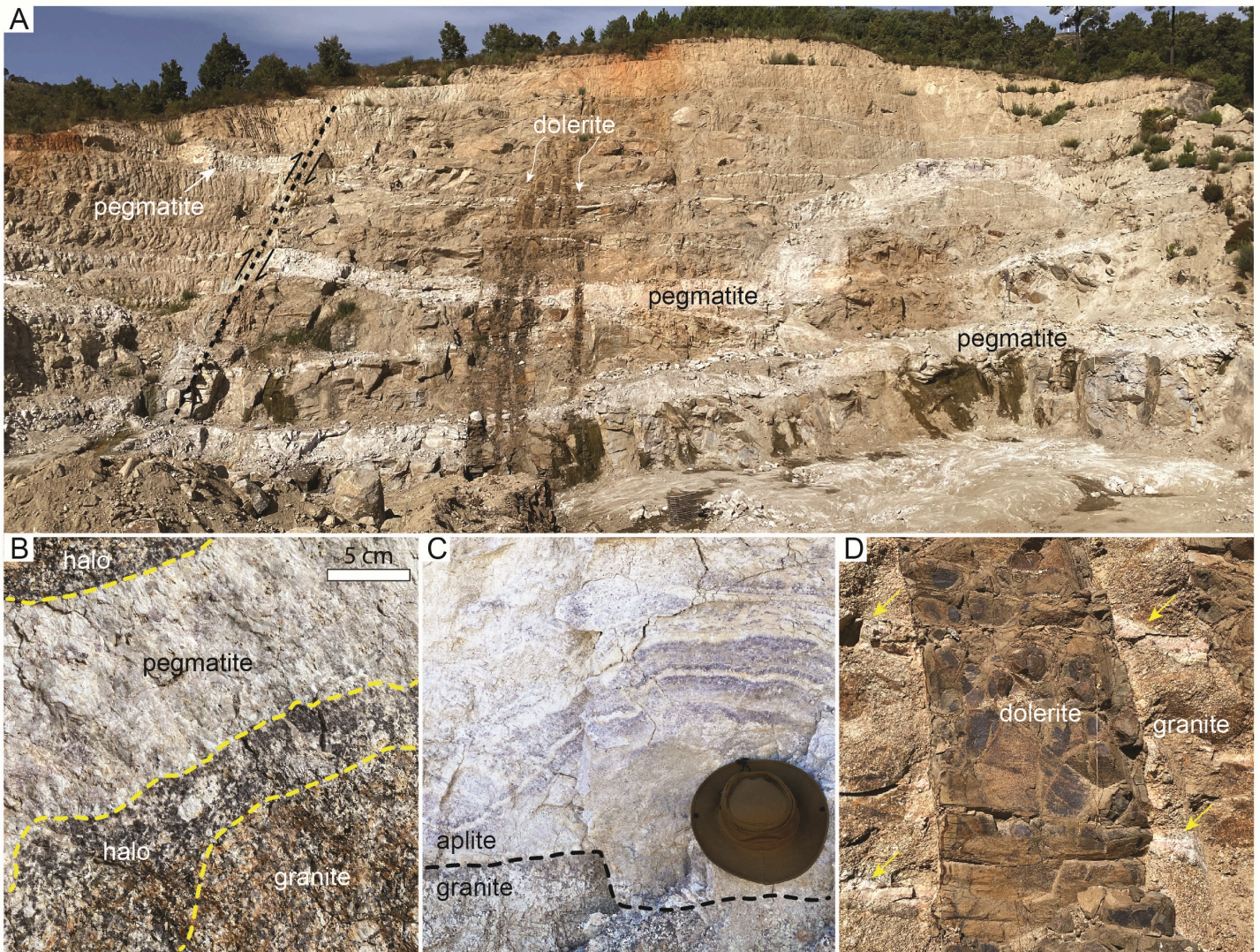


Figure 2

Field photos of different lithologies from the Gonçalo pegmatite mine. A) Open pit face showing two 2-3 m sub-horizontal aplite-pegmatite veins and numerous smaller (<20 cm) veins. Note the fault that offsets the vein system, and the younger dolerite dikes that crosscut all veins. B) The host biotite granite crosscut by a 10 cm pegmatite vein generating a zinnwaldite-rich halo in the granite. C) Photograph of a 2-m thick lepidolite-rich aplite vein (30-cm wide hat for reference). D) A roughly 70 cm wide vertical dolerite dike crosscutting and slightly offsetting some of the thinner pegmatite veins (yellow arrows).

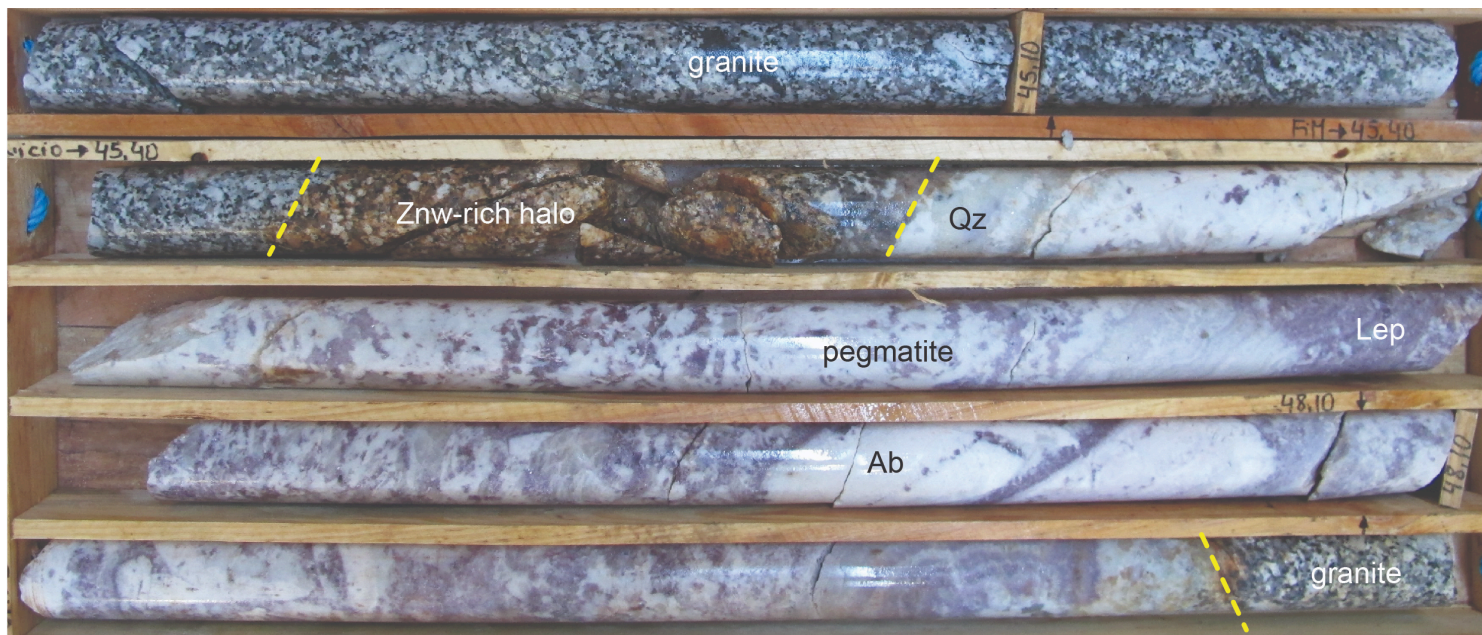


Figure 3

Drill core intersection of a ~3 m pegmatite hosted in granite. Note the ~50 cm zinnwaldite-rich alteration halo in the hanging wall of the pegmatite. Mineral abbreviations: Ab-albite; Lep-lepidolite; Qz-quartz; Znw-zinnwaldite.

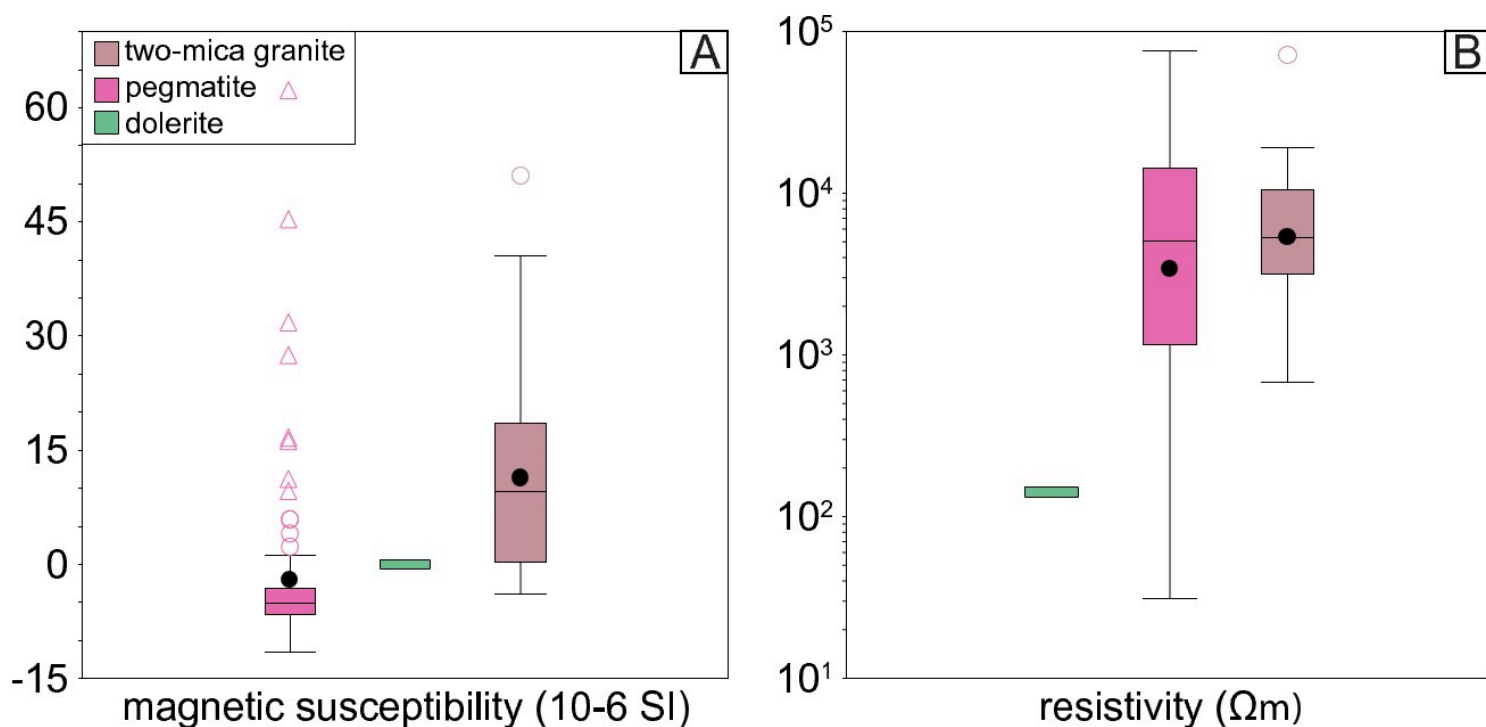


Figure 4

Box-and-whisker diagrams showing (A) magnetic susceptibility and (B) resistivity data for the three generalized rock categories. The box represents 50% of the data from Q1–Q3, whereas the whiskers represent extreme values that are not yet outliers. Hollow circles represent outliers. Hollow triangles

represent significant outliers. Black circles represent averages. Black lines within boxes represent medians.

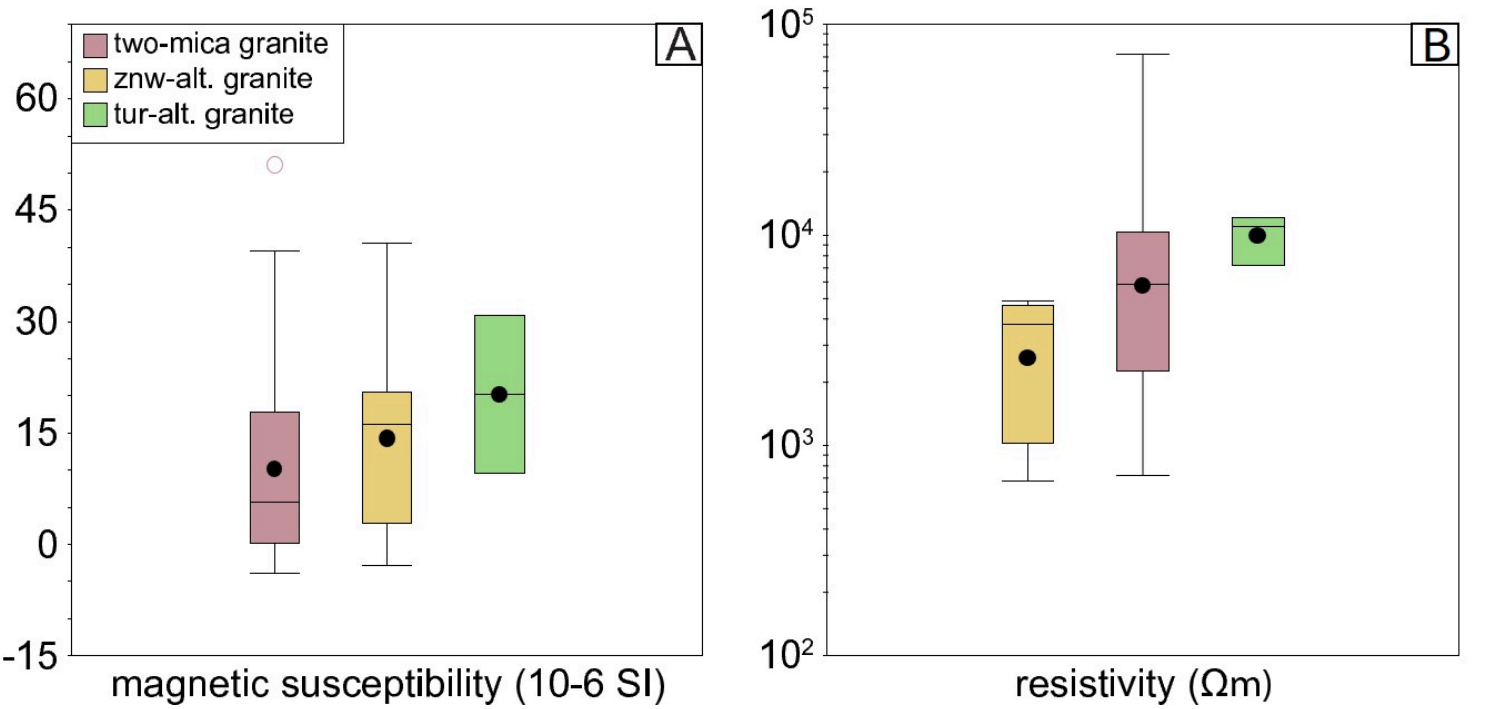


Figure 5

Box-and-whisker diagrams showing (A) magnetic susceptibility and (B) resistivity data for granite categories. The box represents 50% of the data from Q1–Q3, whereas the whiskers represent extreme values that are not yet outliers. Hollow circles represent outliers. Hollow triangles represent significant outliers. Black lines within boxes represent medians.

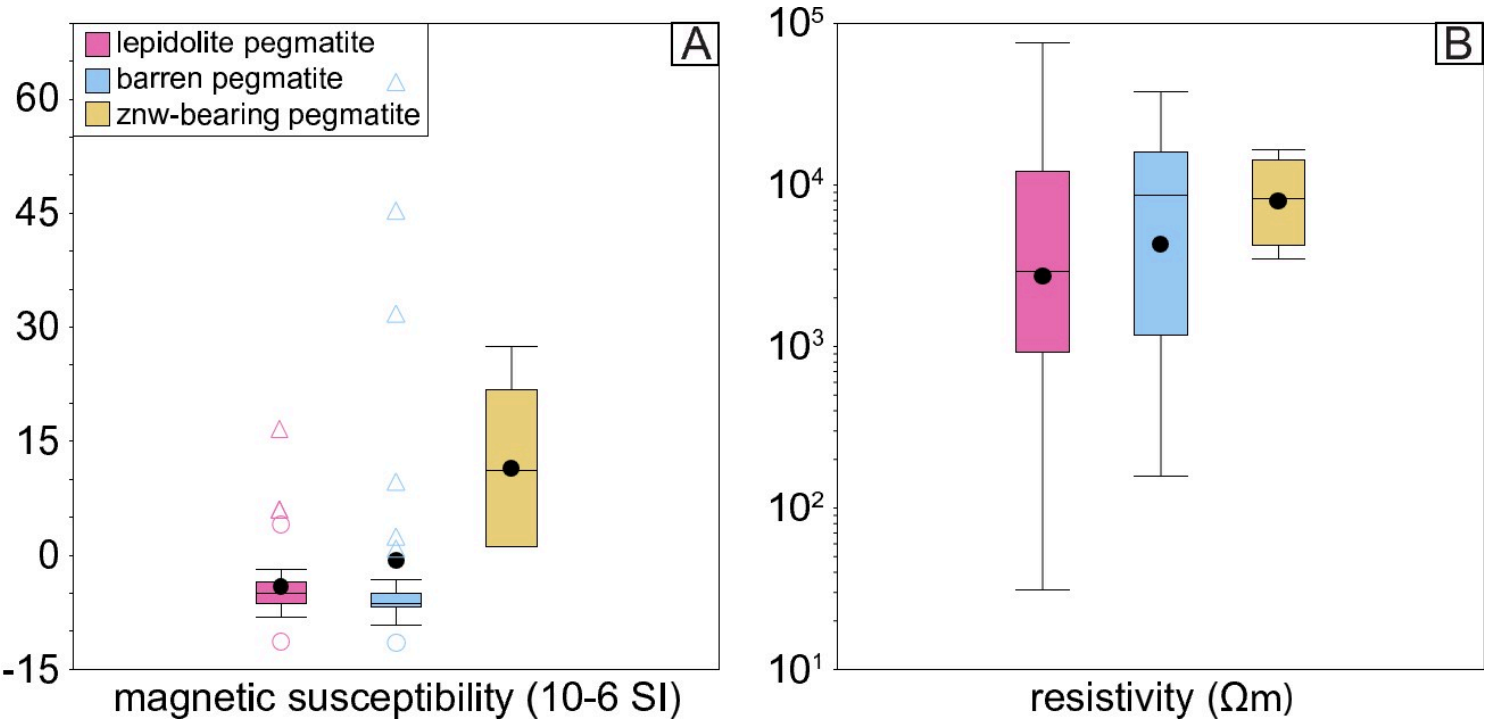


Figure 6

Box-and-whisker diagrams showing (A) magnetic susceptibility and (B) resistivity data for pegmatite categories. The box represents 50% of the data from Q1–Q3, whereas the whiskers represent extreme values that are not yet outliers. Hollow circles represent outliers. Hollow triangles represent significant outliers. Black circles represent averages. Black lines within boxes represent medians.

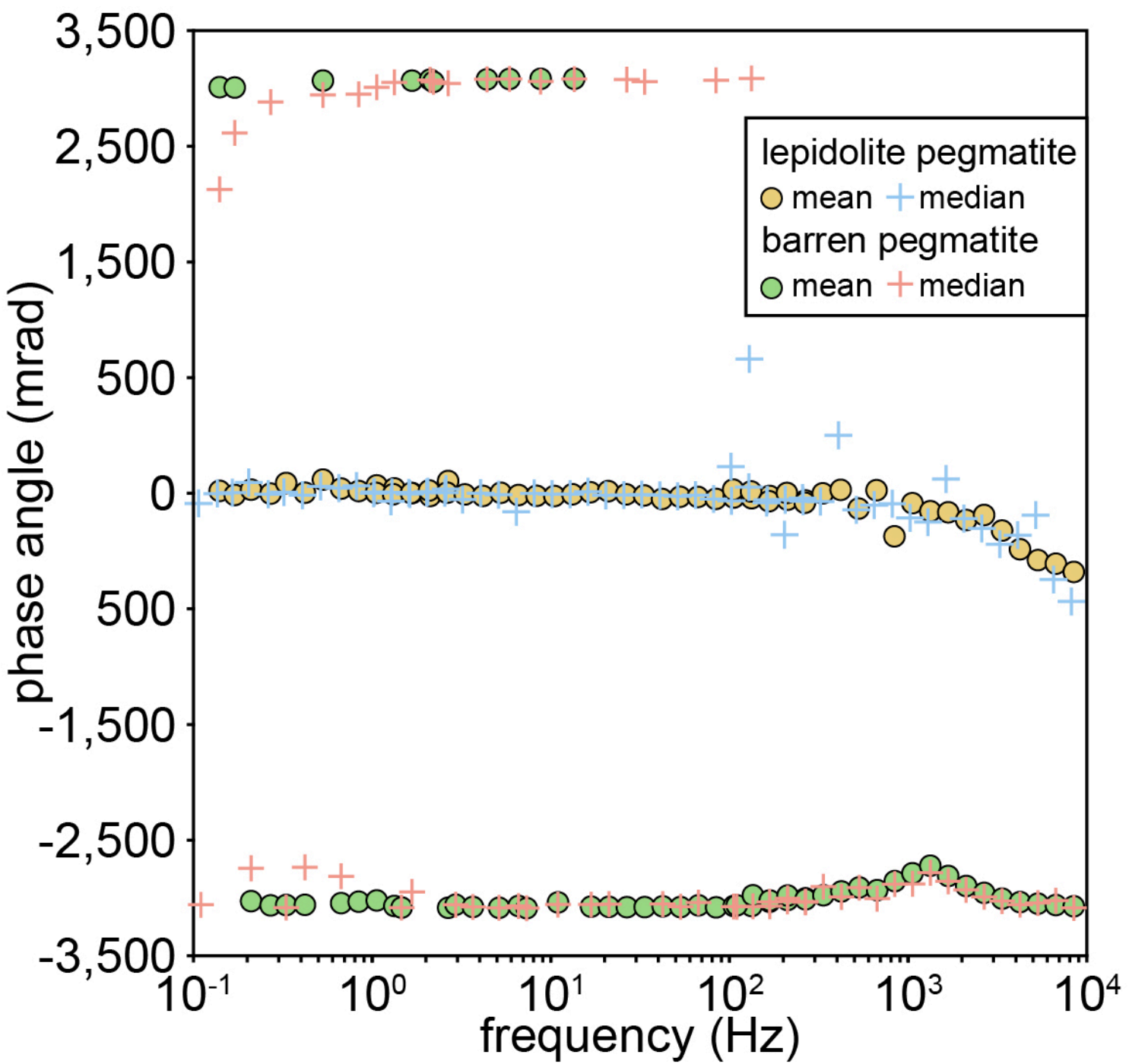


Figure 7

Induced-polarization response (chargeability) presented as phase angle (mrad) versus measuring frequency for two samples, lepidolite pegmatite and barren pegmatite, showing consist mean and

median trend for the former and a split trend for the latter.

Supplementary Files

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- [SupplementaryMaterial.xlsx](#)