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Validation of the use of portable equipment for magnetic characterization of soils, State of Paraná, Brazil

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Abstract

Studies involving the magnetic susceptibility (MS) of rocks are becoming increasingly frequent in geological surveys, mainly in those with petrogenetic approaches and in mineral prospecting. Portable devices have become a good alternative for data acquisition because of their practicality and low cost when compared to laboratory analyses. To assess the efficiency of data acquisition with such devices, 291 soil samples were measured with a Terra Plus KT-5 portable device in the field and with a double frequency Bartington MS2B sensor, with mass correction, in the laboratory. The data obtained allowed the characterization of four distinct populations, ranging from high to very low MS values. Statistical analysis showed good correlation between measurements with mass correction in the laboratory and those made with portable devices, resulting in a correlation coefficient (r) = 0.98. All samples obtained in the field and laboratory were utilized in this correlation. The populations identified by both means are in agreement, with subtle discrepancies, thereby demonstrating the efficiency of portable equipment for acquisition of MS data in geological studies.

KEYWORDS: magnetic susceptibility; soil mapping; soil magnetic susceptibility.

INTRODUCTION

The magnetic susceptibility (MS) of a rock measures its ability to magnetize itself through the action of an induced magnetic field. This attribute is directly related to the characteristics of its ferromagnetic minerals. The abundance, size, and distribution of such minerals in the framework of a given lithotype impact the intensity of MS (Grant and West 1965).

According to Clark (1999), these magnetic properties are conditioned by the partition of Fe between strongly magnetic minerals, such as Fe and Ti oxides, and phases with weaker magnetism, such as silicates and carbonates. This partition also depends on the chemical composition of the rock, on the oxidation state of Fe, and on the petrogenetic conditions involved. Among ferromagnetic minerals, Fe and Ti oxides (e.g., titanomagnetite and ilmenite) are the most important. Their crystalline structures are constituted by a network of oxygen ions (O^{2-}), ferrous iron (Fe^{2+}), ferric iron (Fe^{3+}), and titanium (Ti^{4+}). The relative proportion of these three cations determines the ferromagnetic properties of the mineral. According to Grant and West (1965), among the ferromagnetic minerals, only maghemite (ideal formula γFe_2O_3), franklinite ($(Zn, Fe^{2+}, Mn^{2+})(Fe^{3+}, Mn^{3+})_2O_4$), magnetite ($Fe_3O_4(FeO.Fe_2O_3)$), and pyrrhotite ($(Fe_{1-x}S)$, where x indicates the number of vacancies) provide sufficiently high MS responses to produce detectable anomalies during the prospecting work. Among these, franklinite and magnetite are the minerals that mostly contribute to the magnetization of rocks.

MS data have been used in several geological surveys for multiple purposes, such as petrological investigations, mineral exploration, and environmental surveys (Mooney and Bleiffus 1953, Henkel 1976, Ishihara 1981, Criss and Champion 1984, Lapointe *et al.* 1984, 1986, Magalhães *et al.* 1994, Oudeika *et al.* 2020). MS measurements are either conducted in laboratory facilities or directly made with portable devices on outcrops, drill cores, or hand samples. Laboratory analyses, however, are generally costly and demand longer operating times. Hence, some companies and researchers prefer to use portable instruments, given that they provide faster results at relatively lower costs. For this reason, comparative studies are made necessary to assess the quality of MS data obtained from in situ field measurements (Kapička *et al.* 1997, Lecoanet *et al.* 1999, Nascimento 2006).

To assess the reliability of the MS data obtained by portable equipment, we compared MS results determined using a portable device with data acquired in a laboratory. For this purpose, we analyzed several soil samples collected all over the state of Paraná, Brazil (Fig. 1).

GEOLOGICAL SETTING

Pre-Cambrian terranes outcrop in the southeastern and northeastern areas of the state of Paraná. They comprise granite-gneissic terranes surrounded by folding belts, formed during

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the end of the Neoproterozoic and Lower Paleozoic (Zalán *et al*. 1987, Cordani *et al*. 2009). Overall, high-grade metamorphic rocks are concentrated in the southeastern area of the state, whereas low-grade metamorphic rocks predominate in the northeastern (Fig. 1). These lithotypes form the basis of the Paraná Basin and have a complex crustal architecture (Cordani *et al*. 1984, Zalán *et al*. 1987, Soares 1991). MS investigations in soil samples in this area indicate very low values of MS (with average values of 75×10^{-8} m^3 kg^{-1}; Silva *et al*. 2010).

The sedimentary processes forming the Paraná Basin started during the Upper Ordovician, lasting until the Late Cretaceous (Fig. 1) (Milani *et al*. 2007). It covers an area of 1.5 million km^2, primarily occupying parts of southern Brazil and parts of Paraguay, Argentina, and Uruguay (Bortoluzzi *et al*. 1987). The Paraná Basin comprises the superposition of beds deposited in six main depositional sequences (Milani 1997): Rio Ivaí (Ordovician-Silurian), Paraná (Devonian), Gondwana I (Carboniferous-Lower Triassic), Gondwana II (Meso to Neotriassic), Gondwana III (Lower Jurassic-Lower Cretacic), and Bauru (Lower Cretacic). Overall, each of these sequences records sedimentary processes under different depositional environments, grading from exclusively marine settings to coastal-deltaic and eolian environments (Milani 1997, Milani *et al*. 2007). These super sequences are characterized by a variety of lithotypes, such as conglomerates, diamictites, rhythmites, carbonates, bituminous shales, and carbonates (Almeida and Melo 1981). The MS values in soil samples derived from rocks belonging to the Paraná Basin are relatively low, less than 500×10^{-8} m^3 kg^{-1} (Silva *et al*. 2010).

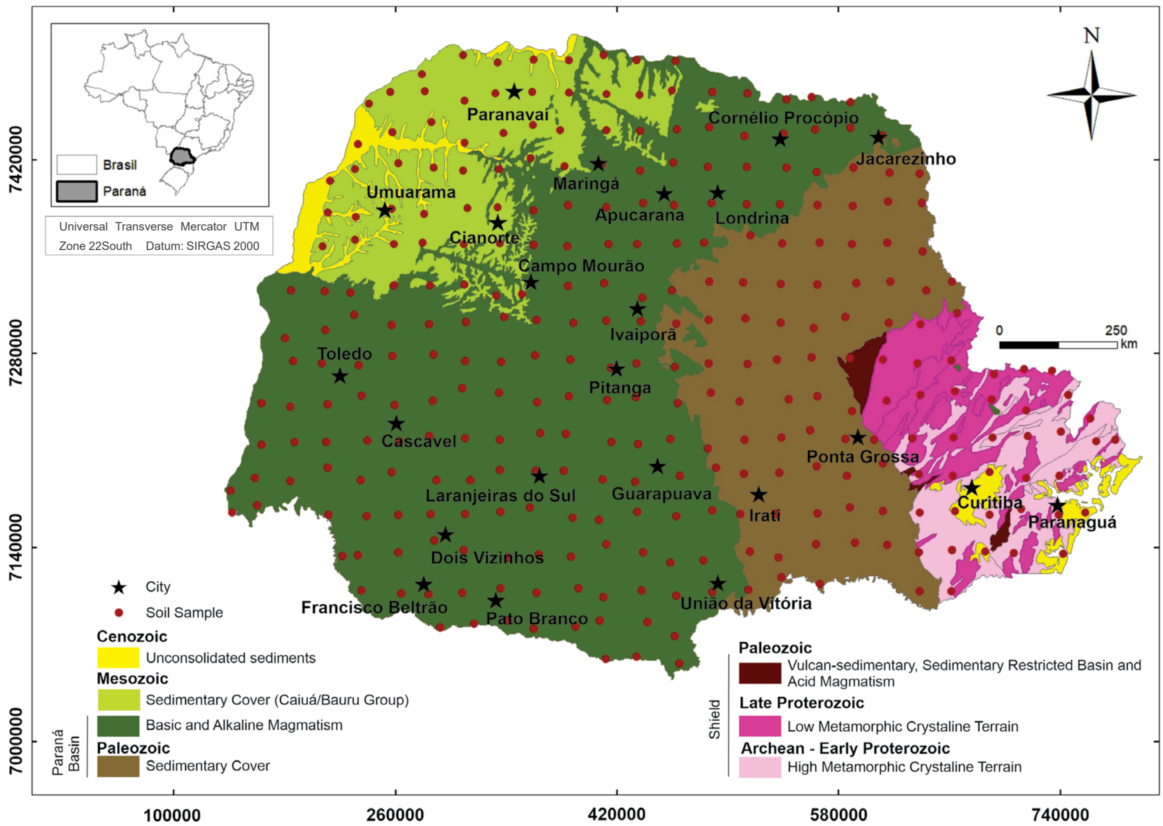
The volcanic rocks of the Paraná Large Igneous Province (LIP) cover the Early Cretaceous sediments of the Paraná Basin (Fig. 1). The lavas cover an area of 1.2 million km^2 (Fedorenko *et al*. 1996), extending throughout the southern and central parts of Brazil, and occupying parts of Paraguay, Argentina, and Uruguay in South America, and parts of Namibia and Angola in Africa. Most extrusive events took place between 135.0 ± 0.6 and 133.2 ± 0.3 Ma, lasting approximately 1.6–3.0 m.y. (Gomes and Vasconcelos 2021). In addition to the lava flows, a large volume of intrusive rocks (dykes, sills, and intrusive complexes) was formed during this event (Bellieni *et al*. 1984). Overall, the Paraná LIP comprises tholeiitic basalts and andesites, with subordinate acidic, volcaniclastic, and alkaline rocks (Melfi *et al*. 1988). Soils derived from the Paraná basalt flows yield significantly high MS (up to 7,790 $\times 10^{-8}$ m^3 kg^{-1}; Silva *et al*. 2010, Ramos *et al*. 2021).

The Caiuá and Bauru groups are sedimentary units that overlie the Paraná lavas (Fig. 1) (Milani *et al*. 2007). The Caiuá Group is made up of fine siliceous sandstones, with a reddish-brown color due to the iron oxide cement. The Bauru Group is also composed of fine sandstones ranging from slightly pink to brown, siltstones, conglomerates, and conglomeratic sandstones. Soil derived from these units yields low MS values (91–219 $\times 10^{-8}$ m^3 kg^{-1}; Silva *et al*. 2010).

MATERIALS AND METHODS

MS analysis

MS data from 291 soil specimens sampled by the Geological Survey of Paraná (Licht and Plawiak 2005) were provided to test the reliability of MS measurements on portable devices. To address this issue, two different approaches were adopted.



Source: modified from ITCG (2008).

Figure 1. Distribution of the 309 sample collection points for determining MS in soils developed from different geological units in the state of Paraná.

First, the MS was measured on a Microkappa Kappameter KT-5 rock susceptibility meter (GEOFYZIKA, Czech Republic) available at the Department of Geology of UFPR, Curitiba, Brazil. The Kappameter KT-5 has a 10 kHz LC oscillator, whose inductivity is detected by a flat measuring coil located on the active face of the instrument. The MS measurement was carried out in two stages. Initially, the measurement was made with the coil in the air, away from the sample, and then with the coil placed on the sample surface. All readings were obtained on flat surfaces, directly on the soil samples, to ensure good contact with the sensor. Three readings of 5 s each, divided between the air-sample sequence, were taken for each sample. A final MS value per sample was estimated by averaging the triplicate measurements. The MS values recorded on the device were transferred via GeoView to the computer, where they were processed using Excel. All measurements were presented in the volumetric electromagnetic unit of the International System of Units ($m^3 kg^{-1}$).

Second, the MS of the soil samples was measured using a Bartington MS2 system (Bartington Instruments Ltd., Oxford, England) at the Soil Chemistry and Mineralogy Laboratory of the Department of Soils of UEM, Maringá, Brazil. The Bartington MS2B meter was coupled with a sensor sensitive to small variations in susceptibility values, and, consequently, in the amount of ferromagnetic minerals (Costa *et al.* 1999). The MS per unit of mass (χ_{BF}) was determined at low (χ_{BF} = 0.47 kHz) and high frequencies (χ_{AF} = 4.7 kHz) and calculated by the Eq. 1:

$$\chi_{BF} = (10 \text{ x } k)/m \text{ (mass of the sample)} \quad (1)$$

Where:

k (reading) = dimensionless.

The frequency that depends on the MS per unit of mass (χ_{BF}, %) was determined by the difference between the low- and high-frequency measurements, according to the Eq. 2:

$$\chi_{FD} \text{ (MS, \%)} = 100 \times [(\chi_{BF} - \chi_{AF})/\chi_{BF}] \text{ (Dearing 1999)} \quad (2)$$

This mineralogical attribute served as a qualitative measure of the presence of single- and multiple-domain magnetic minerals (Dearing 1999).

Statistical analysis

Following analysis, statistical parameters (e.g., minimum and maximum values, median, and mean absolute deviation) were calculated for both MS databases. A linear correlation between the data pairs was measured using the Pearson's linear correlation coefficient (Pearson 1895).

The separation of MS populations was performed based on the inflection points in the probability plots made. Sinclair (1974) detailed how to partition polymodal distribution curves containing two or more populations. The characterization of different MS populations was represented by maps using ArcMap v.10.5.

RESULTS AND DISCUSSION

The data obtained for the soil samples with the KT-5 portable device and the Bartington MS2B meter show significant variations in MS values (Table 1), reflecting the multiple lithotypes of the study area.

The analysis of the inflection points in the graphs of cumulative probability (Figs. 2A and 2B), as well as the combination of these with the frequency histograms (Fig. 3A) allows the identification of different populations (Sinclair 1974):

- Population A: high MS values (50.31–66.26 × 10^{-3} SI);
- Population B: intermediate MS values (30.27–47.17 × 10^{-3} SI);
- Population C: low MS values (5.28–25.21 × 10^{-3} SI);
- Population D: very low MS values (0.00–2.69 × 10^{-3} SI) (Figs. 3B and 3C).

The box plots (Figs. 3B and 3C) summarize the MS measurements obtained from the two different approaches, showing the statistical distribution of these data. Although expressed in different units, the populations derived from the two methods indicate very similar statistical behavior (Figs. 3B and 3C). The KT-5 and the Bartington soil MS data from multiple geological units throughout the state of Paraná show a good correlation (r = 0.98). Similar results were described by Nascimento (2006), who, in methodological tests, compared the MS data obtained by portable equipment with those obtained in the laboratory, in samples of granodiorites. Kapička *et al.* (1997) made MS measurements with a portable equipment in soil samples and compared them with the data obtained in laboratories on the same samples, concluding that the variations between the measurements were less. The results obtained with the KT-5 also show little variation when compared to those obtained in the laboratory, using the Bartington system (Fig. 3A).

Importantly, the four MS populations identified in the cumulative probability plots correlate with the main geological domains of the state of Paraná (Figs. 4A and 4B). The highest MS values (Population A) are found in soils formed by the weathering of the Paraná LIP basalts. This likely reflects the high proportion of ferromagnetic minerals (e.g., ilmenite and

Table 1. Statistical parameters calculated from MS data measured with the KT-5 portable equipment and in the laboratory, using the Bartington system.

Equipment	Min	Max	Mean	SD	First Quartile (Q1)	Median	Third Quartile (Q3)	MAD
KT-5 portable device (× 10^{-3} SI)	0	65.73	12.94	15.76	0.94	5.12	22.95	12.90
Bartington MS2B meter (× $10^{-8} m^3 kg^{-1}$)	1	8338	1680	2057	116.75	577	3010.50	1685.68

SD: standard deviation; MAD: mean absolute deviation.

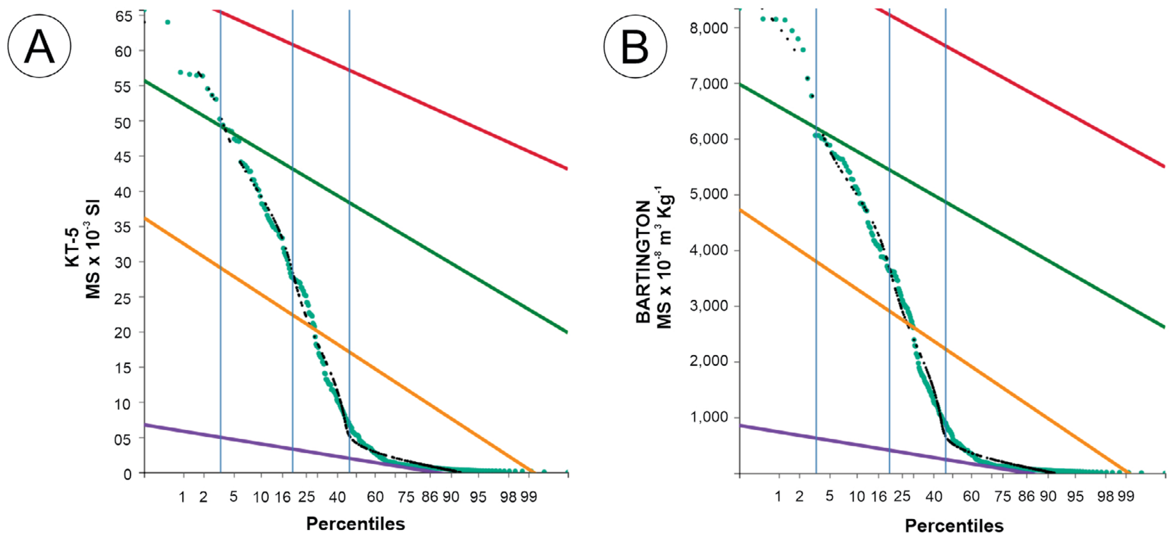


Figure 2. Graphical representation of the cumulative probability estimate of the MS datasets obtained with (A) the KT-5 device and (B) the Bartington meter. At least four populations (colored lines) were identified based on inflection points on the probability curves following the method developed by Sinclair (1974).

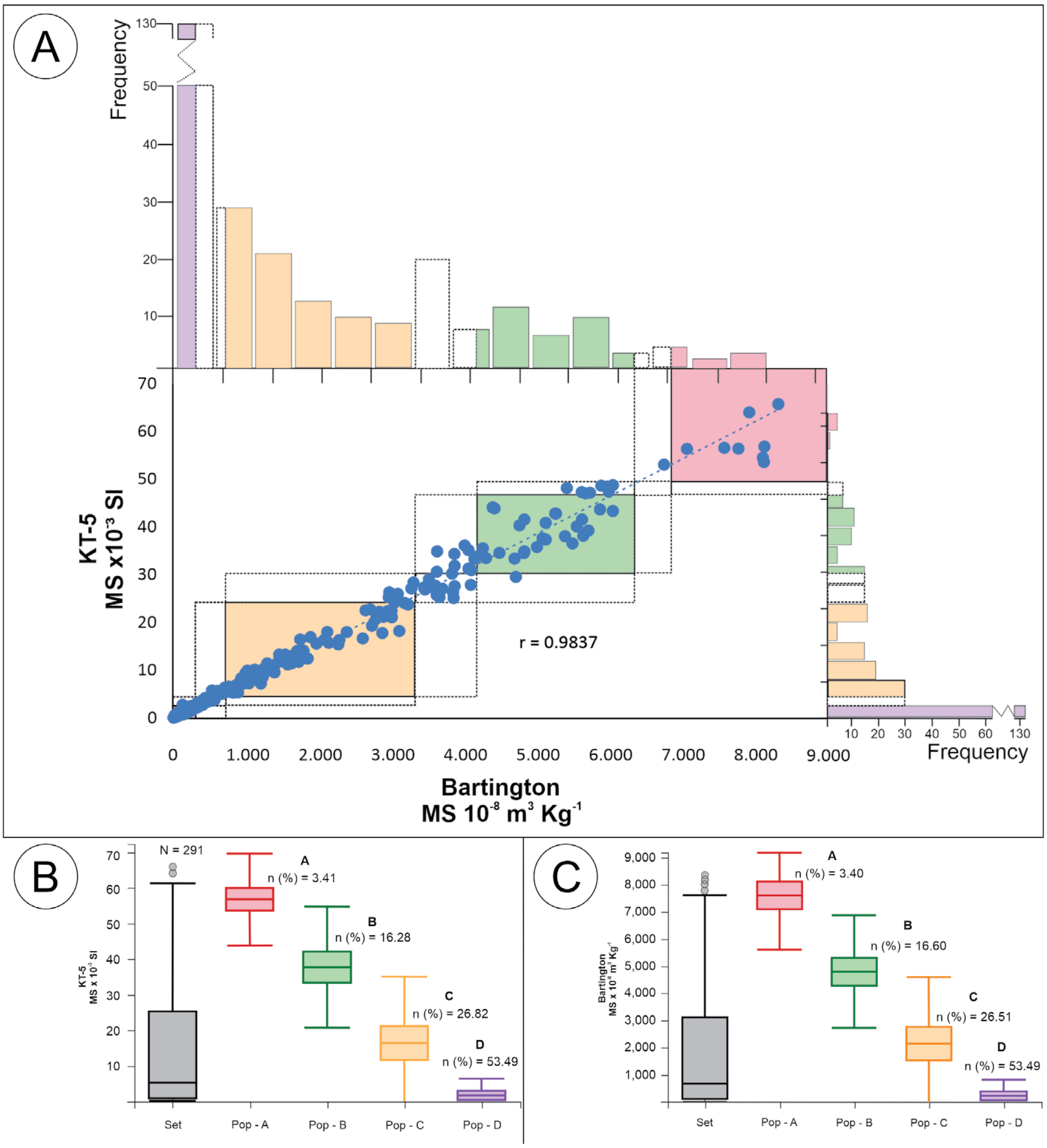


Figure 3. (A) Correlation line and frequency histograms of MS data obtained with the portable equipment KT-5 and Bartington. The data pairs suggest a good correlation (r = 0.9837) between the different datasets. The correlation coefficients are significant at a probability level of 95% ($\alpha = 0.05$). (B) Box plot representing the statistical distribution of MS data obtained by the portable equipment KT-5. (C) Box plot representing the statistical distribution of SM data obtained by the Bartington equipment.

magnetite) in the soils derived from the basalts. High rainfall and high temperatures favor the formation of ferromagnetic minerals in soils derived from basaltic rocks, through processes such as magnetite oxidation, dehydration of lepidocrocite, or via the redox cycle that occur under normal pedogenic conditions (Mullins 1977, Torrent *et al*. 2006, Lu *et al*. 2008). Importantly, the area delimited by Population A appears to correlate with the Type 3 (LSsi-LZr-HTti-LP) lava flows in the upper levels of the PIP geochemical stratigraphy, which contain high Fe_2O_3 (x-y wt%) and TiO_2 (x-y wt%) contents (Gomes et al. 2018, Licht 2018).

Population B, represented by intermediate MS values, is related to basic volcanics classified as Type 1CN geochemical types (Licht 2018).

Population C, represented by relatively low DM MS values, is related to soils formed from the weathering of the PIP volcanic rocks classified as Type 4 and 2 geochemical types, and also comprising acidic volcanics of the 9 and 14 geochemical types (Licht 2018). Importantly, the source of iron of the PIP volcanic geochemical types, may have contributed to the formation of pedogenic maghemite, due to the climatic conditions of the region (Maher *et al.* 2003, Silva et al. 2010).

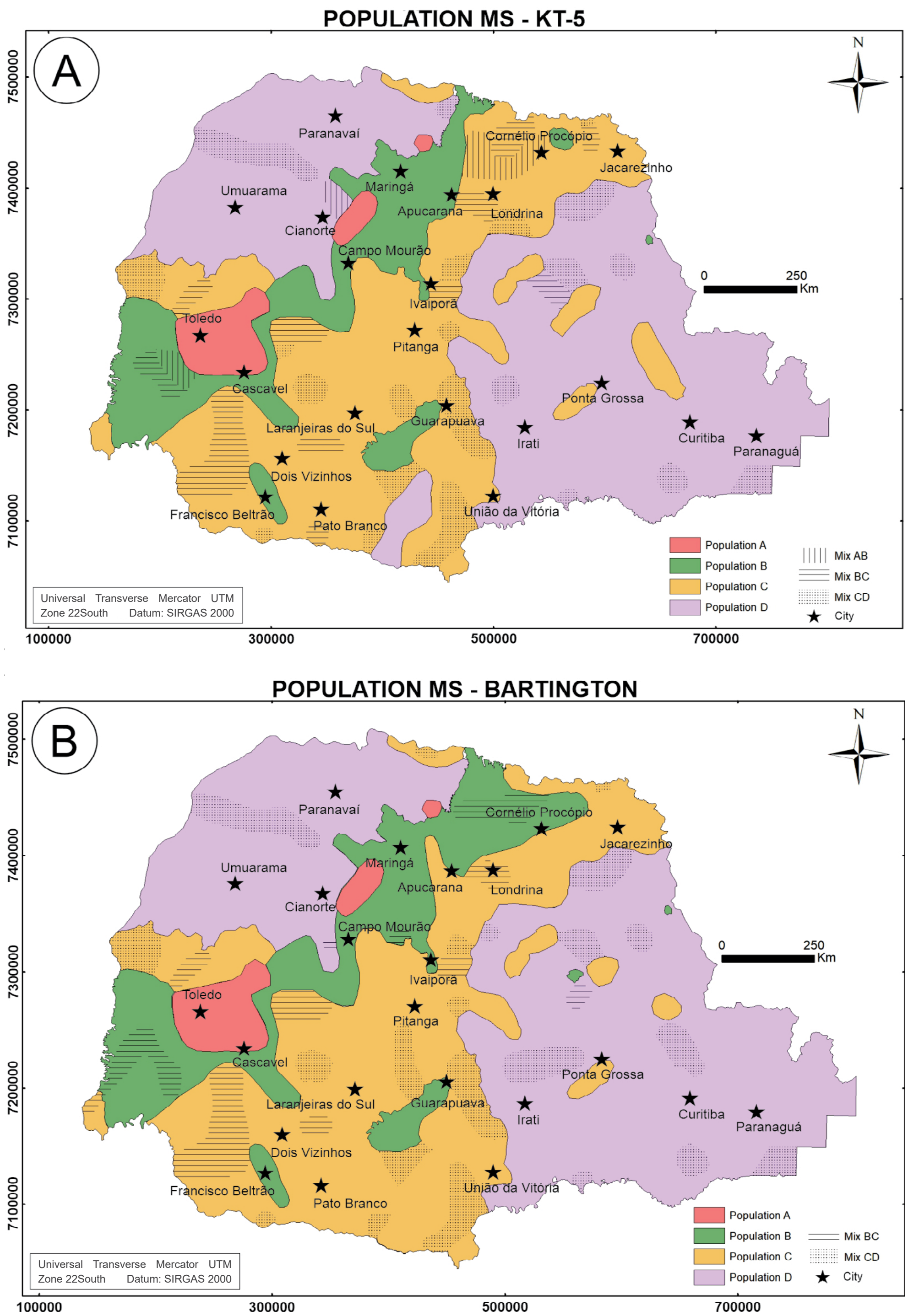


Figure 4. (A) Distribution of populations A, B, C, and D of MS in the state of Paraná, characterized based on data obtained by the portable equipment KT-5. (B) Distribution of populations A, B, C, and D of SM in the state of Paraná, characterized based on data obtained by the Bartington equipment. The hatched zones on both maps symbolize the mixing zones (statistical uncertainty) between two populations.

Population D, characterized by the lowest MS values, is geographically divided in thotwo sectors, and reflects the relative absence of ferromagnetic minerals in soils derived from sedimentary, metassedimentary, metavolcanics, and granitic protoliths. In the eastern sector, it reflects soils formed from the weathering of sandstones Serra Negra and Coastal complexes, of metabasic and metapelitic rocks of the Acungui Group, granites of the Serra da Graciosa Alkaline Granitic Suite, gneisses and marbles from the Setuva Group, volcanics, sedimentary rocks of the Guabirotuba Formation and Castro Group, claystones and siltstones of the Guata and Passa Dois groups, and sandstones from the Botucatu and Piramboia formations. In the northwestern sector the low MS values reflects soils formed over Bauru, and Caiua (e.g. conglomerates and sandstones) groups. Even considering the PIP basic volcanics as an importante source for these sedimentay rocks reflected in centimetric fragments of basalts in the conglomeratic sandstones (Fernandes and Coimbra 2000), the very low MS values suggest very low contents of ferromagnetic minerals, compatible with soils derived from sedimentary lithotypes (Schwertmann and Taylor 1989).

The samples obtainned from soils originating from the alteration of the basalts related to the Serra Geral Group presented a wide variation of MS values, reflecting the presence of this unit in all the identified populations (Figs. 4A and 4B). Gomes *et al.* (2018) and Licht (2018) studied the geochemical variations existing in the basalts of the Serra Geral Group and showed that, although it is the same lithotype, there are evident chemical differentiation between spills. These differences may have influenced the amount of magnetic minerals in each basaltic spill, resulting in this wide range of recorded MS values. However, these variations in MS related to the chemical composition of each basaltic spill in the Serra Geral Group need to be better understood.

CONCLUSIONS

The MS data in soil samples with portable equipment (KT-5) and in the laboratory (Bartton) showed good correlation, validating the use of portable equipment in fieldwork.

Furthermore, it was possible to outline four populations (A, B, C, and D) of MS, identified by high, intermediate, low, and very low values, respectively, related to the main outcropping geological units in the state of Paraná. The different MS populations reflect the different lithologies in the state of Paraná. Population A and B, with the highest values, is constituted by soils whose source area is the basalts of the Paraná LIP. Intermediate values and lower values (Populations C and D) are attributed to soils whose source areas are sedimentary rocks of the Paraná Basin and several lithotypes belonging to the Precambrian shield.

The Serra Geral Group presents a great variation in the values of MS, thus covering all the subpopulations described in this article. The great existing geochemical variation, as described by Gomes *et al.* (2018) and Licht (2018), may indicate that the amount of ferromagnetic minerals also varies from one geochemical type to another, as reflected in the magnetic response of each lava flow. However, this information needs further studies.

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O.L. carried out the collection and preparation of soil samples, obtaining the magnetic susceptibility with the portable equipment, assisted in the elaboration of Figs. 2–4, and improved the manuscript through suggestions and corrections; F.F. participated in obtaining the magnetic susceptibility data with the portable equipment, assisted in the elaboration of Fig. 3, and improved the manuscript through corrections and suggestions; E.V. assisted in the compilation of previous works, regional geology, and in the discussions of the results; A.C. assisted in obtaining the magnetic susceptibility data in the laboratory with mass correction and improved the manuscript with suggestions and corrections.

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