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Critical review

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Abstract: The magnetic susceptibility of 51 rock specimens from the Wopmay Orogen, Northwest Territories, was measured using three different hand-held meters to quantify instrument variations. This is a simple but important study for rock-property databases containing measurements taken by different geoscientists. The three instruments (KT-10, MS2E, and SM-30) differ in a) inductive–electromagnetic-signal frequency, b) source-coil size and geometry, and c) applied field strength. Repeat measurements at different locations on a sample provided a measure of signal noise and within-sample susceptibility variations. The MS2E exhibited the largest within-sample–signal standard deviation due to its smaller coil. We then compared instrument response by computing the best-fit least-squares line. The SM-30 and KT-10 produced similar responses, while the MS2E was systematically higher. For use in magnetic modelling, there is no effective difference between the KT-10 and SM-30 susceptibility measurements. More individual measurements are required when using the MS2E.

Résumé : La susceptibilité magnétique de 51 échantillons de roche provenant de l'orogène de Wopmay (Territoires du Nord-Ouest) a été mesurée au moyen de trois magnétomètres portatifs différents afin de quantifier les variations entre les instruments. Bien qu'elle soit simple, cette étude est importante pour les bases de données sur les propriétés des roches lorsque ces bases de données renferment des mesures effectuées par différents géoscientifiques. Les instruments (KT-10, MS2E et SM-30) diffèrent selon : a) la fréquence du signal d'induction électromagnétique, b) la taille et la géométrie de la bobine source et c) l'intensité du champ appliqué. Des mesures répétées à différents endroits sur un échantillon ont permis de mesurer le rapport signal/bruit et les variations de la susceptibilité dans l'échantillon. Le modèle MS2E présentait le plus grand écart type du signal dans un échantillon en raison de sa bobine plus petite. Nous avons ensuite utilisé le calcul de la droite des moindres carrés pour comparer la réponse des instruments. Les modèles SM-30 et KT-10 donnaient des mesures similaires, tandis que celles du modèle MS2E étaient systématiquement plus élevées. Aux fins d'une utilisation pour la modélisation magnétique, il n'y a aucune différence significative entre les mesures de susceptibilité données par les modèles KT-10 et SM-30. Davantage de mesures individuelles sont requises lorsque le modèle MS2E est utilisé.

INTRODUCTION

In situ magnetic-susceptibility measurements are among the most commonly used physical rock-property measurements. Quantifying the variability of magnetic-susceptibility measurements between different meters is necessary discussion when multiple rock-property studies are conducted in the same geographic area. This is especially true when measurements are conducted on similar lithological units and contained in the same database.

A magnetic-susceptibility reading provides a rapid means of estimating the magnetic-mineral content of a rock. As demonstrated by Henkel (1994), a comparison between magnetic-susceptibility and density readings can provide insight into the mineralogy of the magnetic-mineral content. Magnetic susceptibility then provides key information in linking geophysical observations to geological models. Prior knowledge of the magnetic susceptibility of representative rock units provides a critical constraint in any geophysical modelling exercise using aeromagnetic data. All magnetic-anomaly inversion models are compromised by the trade-off that exists between source geometry, source depth, and physical-property contrast. This issue is commonly described by the phrase 'non-unique solution'. Having access to susceptibility data allows the interpreter to impose some limitations on the range of solutions that are mathematically viable. Of course, the quality of these inversions and forward models is significantly influenced by the validity of the susceptibility data that are used in the model definition.

There are a number of magnetic-susceptibility meters available on the market. However, the instrument specifications defined by the respective manufacturers show there are significant differences between individual instruments, which may affect the reported magnetic-susceptibility value. Instrument-design variations include factors such as dimensions and position of the sensor coil and frequency of the current used to activate the coil. In this study, we compare the magnetic-susceptibility values reported by three commonly used meters on hand specimens of rocks from the Wopmay Orogen, Northwest Territories, Canada to establish if there are any systematic differences which could impact magnetic-model outcomes.

DATA

The Wopmay Orogen is a 2.6 to 1.85 Ga Paleoproterozoic Orogenic belt that has been of economic interest because it hosts various mineralized prospects and deposits. A total of 51 rock samples, collected in 2009 and 2010 from the Wopmay Orogen, were selected (Fig. 1). The primary rock types included in the samples are monzonite, diorite, leucogranite, rhyodacite, and mafic dykes. Samples were also obtained from five known mineral occurrences: Sue-Dianne, NICO, Damp, Fab Lake, and Ron Lake.

METHOD

Instruments

Bartington MS2E

The MS2E magnetic-susceptibility meter manufactured by Bartington Instruments Ltd. (undated) is a portable meter that may be used with rechargeable batteries or a main power supply. The Bartington tool comprises two elements: a) the MS2E meter and b) a sensor package that is linked by a cable to the meter. This design approach allows for a variety of sensor configurations. Variations in the geometry and dimensions of the sensor coil allow the user to tailor a measurement to a specific application. Specific sensor and coil geometries are offered for each of the following types of specimens: soil or rock samples, larger diameter

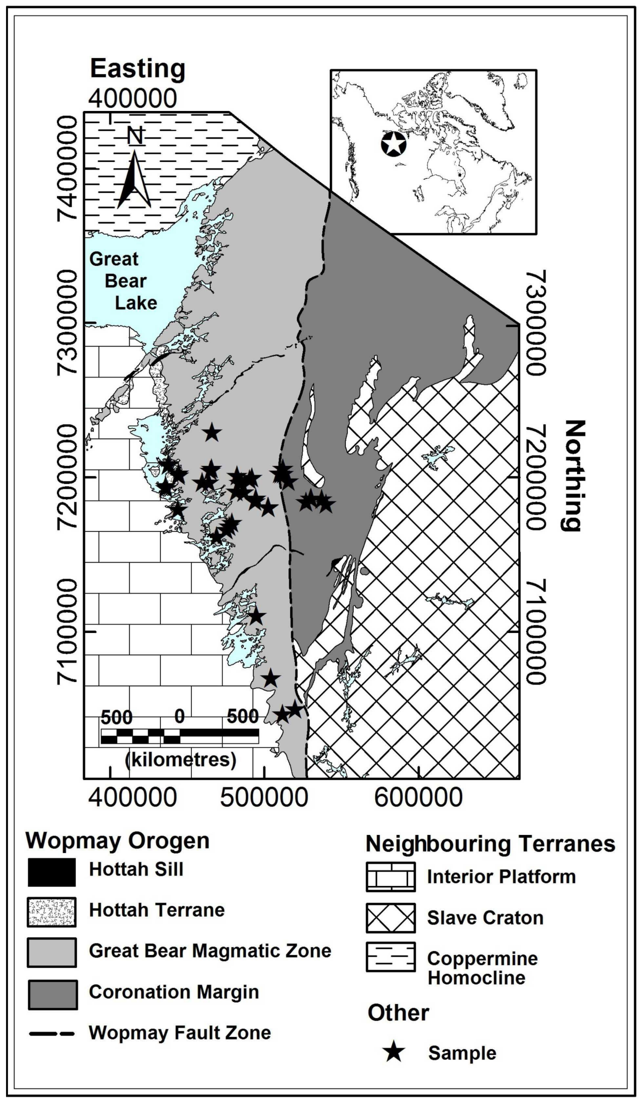

Figure 1. General geology of the Wopmay Orogen (*after* Hoffman and Hall, 1993). Locations of samples are indicated with a black star.

drill cores, soil surfaces, and rock outcrops; the instrument can even be employed down auger holes. In this study we used the MS2E laboratory sensor. The sensor only weighs 0.22 kg, while the meter weighs 1.2 kg. The sensor element, which is located within a ceramic cylinder, is a rectangular coil (3.8 mm x 10.5 mm) that corresponds to a total sensing area of 39.9 mm^2. The small size of the sensor means that it is possible to precisely locate the coil over localized variations within an outcrop. The operating frequency for the coil is 2 kHz. The MS2E incorporates a standard correction for volume, giving it a sensitivity of 1 x 10^{-5} SI units (volume specific) or 1 x 10^{-8} SI units (mass specific). Instrument calibration is provided by reference to a 15 mm x 33 mm Fe_3O_4 disc in alumina and epoxy resin provided by the manufacturer. The measurement does not include corrections for the volume or mass of the sample.

Heritage Geophysics SM-30

The SM-30 magnetic-susceptibility meter by Heritage Geophysics Inc. (2003) is a small, compact hand-held field meter that weighs only 0.180 kg, ideal for outcrop measurements. This instrument has a 50 mm diameter detector coil, corresponding to a sensing area of 1964 mm^2, that is incorporated in the body of the meter. The exact location of the sensor coil in the body of the meter is not exactly known and there is no external measurement trigger (pin) as in the KT-10. The sensor coil has an operating frequency of 9 kHz and a sensitivity of 1 x 10^{-7} SI units. The instrument output does not include any correction for sample volume or mass.

Terraplus KT-10

The KT-10 magnetic-susceptibility meter by Terraplus Inc. (undated) is a hand-held field meter also designed for measurements on outcrops, drill cores, and rock samples. The KT-10 is much bigger than the SM-30, and at 0.30 kg weighs almost twice as much. The inductive coil of the KT-10, which has a diameter of 65 mm corresponding to a total sensor area of 3318 mm^2, is located at the end of the instrument. The KT-10 is designed to be used either with the standard pad that is equivalent in diameter to the inductor coil or with an attachable pin that holds the meter parallel to the rock surface to increase accuracy over uneven samples. This meter utilizes an operating frequency of 10 kHz with a sensitivity of 1 x 10^{-6} SI units. No volume or mass correction is performed by the operational software. Unlike other units, the KT-10 does include a GPS sensor that allows the user to tie a measurement to an observation location.

Measurements

Superficially, measurement of magnetic susceptibility might seem to be a simple procedure; that is, one holds the instrument in contact with a rock surface for a specific period of time while the instrument measures the change in frequency of the input signal caused by the presence of magnetic material. In practice, there are a number of operational complexities that need to be considered.

First, when taking a measurement in the field, it is imperative to choose a flat surface in order to ensure optimum coupling between the inductive coil and the rock surface. The MS2E, having a smaller coil, can acquire more accurate readings than the other two instruments on surfaces having greater curvature. Although the KT-10 has the largest coil diameter, it includes a ‘pin’ option that is intended to help guide the user in finding the best coupling between the rock surface and the coil.

Second, in a natural setting, the mineralogy in the immediate near surface of a rock outcrop may have been modified by weathering. Often that weathering might include alteration of magnetite to less magnetic hematite, or more magnetic maghemite. The depth extent of the weathering rind is dependent on rock type and the location of the observation point. Therefore, measurement on a fresh surface (in the field or in the lab) is ideal if possible.

Third, each susceptibility observation is a summation of all magnetic-mineral contributions that are activated by the inducing coil. The number of magnetic grains examined in a measurement is controlled by various factors: with respect to the instrument, the frequency of the input signal, the number of turns of wire in the sensor coil, and the size of the coil; with respect to the sample, the size and concentration of magnetic grains. Bartington, for example, offers a coil (MS2B) designed for taking measurements on core samples, that can operate at two frequencies: 0.465 kHz and 4.65 kHz. The ratio of these two readings, which is defined as ‘frequency-dependent’ susceptibility, is related to the grain-size distribution of magnetite in the rock sample. Varying the size of the inducing coil means that susceptibility is averaged over different volumes of material. Given multiple measurements of susceptibility on any given rock surface, the observed value will depend on the homogeneity of the rock with respect to the dimension of the sensor coil. That is, the smaller MS2E sensor should detect more detailed variation than the larger KT-10.

Measurements dependent on frequency changes in an inductive-coil circuit are known to drift. Obtaining reliable magnetic-susceptibility readings involves minimization of instrument drift and absolute calibration of the observed frequency change in terms of susceptibility. Each instrument permits different measurement methods, including interpolation and scan mode. An interpolation method was used for the KT-10 and SM-30 measurements, whereby a free-air measurement is taken, followed by a direct measurement on a rock sample or outcrop, and finally a second free-air measurement, where the first and third measurements are compensation steps.

The MS2E measurements were determined using a more extended interpolation mode where a preliminary free-air measurement was followed by up to three sample measurements, before a second free-air reading was taken. In all instances, absolute calibration was made by repeat measurement of a sample with known susceptibility. For the common user, especially in the field, it is usually assumed that the original manufacturer-installed calibration of frequency change versus susceptibility is maintained.

The purpose of this study was to evaluate the relative performance of three different instruments. We achieved this by recording the magnetic-susceptibility value of 51 specimens measured with the three different instruments. Measurements with the KT-10 were made using both the 'pin' and standard pad mode.

We eliminated two possible sources of error by first preparing flat surfaces on each of the samples. These flat surfaces were larger than the largest inductive coil. No attempt was made to look at variations associated with taking measurements on a curved or partially weathered surface. The average thickness of the samples was 13 mm, and the magnetic-susceptibility measurements were taken right at the surface, as the average response drops off to 50% at 1 mm and 10% at 3.5 mm separation from the sample. The second error mitigated was instrument drift and inconsistent measurements due to heterogeneous lithology. The susceptibility of each specimen was measured six times and the location of the sensor coil was moved after each individual measurement. Since the instrument was drift-corrected between measurements, any variation between these six readings represents mineralogical inhomogeneities.

For each sample, we computed an average susceptibility and standard deviation of the six readings. Each magnetic-susceptibility reading represents one value in a population of values. That is, when estimating the representative magnetic susceptibility for a rock unit, it is essential that one obtain more than one reading at each sample location. Taking six readings represents an efficient trade-off between acquiring a large number of observations and adequately representing a population. Having obtained the six readings, there are two possible approaches to calculating the average susceptibility: a) an arithmetic approach in which one uses a simple mean calculation, or b) a geometric approach where the average susceptibility value is computed on the $\log_{10}$ value. A number of publications have shown that when looking at the statistics of magnetic susceptibility, a geometric approach is the more appropriate method (Latham et al., 1989). Susceptibility is directly linked to mineralogical contents, which are known to exhibit a $\log_{10}$ normal distribution.

As stated above, the object of this study was to compare the signal response of three commonly used magnetic-susceptibility meters. Any such comparison of sensor technology defaults into three variables: offset (do the instruments give the same result? Ideally the offset should be near zero); gain (does the offset between the two instruments vary with signal amplitude?); and linearity (does the signal show a linear change of response with signal amplitude?). Estimates of these variables are easily derived from computation of the best-fit least-squares line between equivalent readings taken by two instruments. In this study we computed best-fit lines on $\log_{10}$ transformed values (Fig. 2).

RESULTS

The average magnetic susceptibility of the 51 samples ranged from a low of 2×10^{-5} SI units to a high value of 1.9×10^{-1} SI units. If each of the three meters used in this study was accurately calibrated and was measuring the same magnetic grains, then there should be no difference in the magnetic susceptibility values they report. This is not the case.

The MS2E consistently reported higher magnetic-susceptibility values than the other two instruments (Fig. 2). The difference between the instruments is approximately 2×10^{-4} SI units. Closer inspection of Figure 2b reveals another problem with the MS2E: the slope of the least-squares best-fit line is consistently greater than 1.0, suggesting that there is also a difference in detection response between the instruments. This is actually more apparent than real. The five most strongly magnetized samples measured with the MS2E consistently plot above the least-squares best-fit line. If these five points are eliminated and the best-fit line is recalculated, the slope of the line closely approximates 1.0. This suggests that the MS2E is not properly recording susceptibility for the more strongly magnetic samples.

Comparisons between the SM-30 and the KT-10 indicate that these instruments produce similar results. The highest level of correlation was found to exist between the KT-10 pad and the SM-30 ($R^2 = 0.9976$). This correlation also suggests that the SM-30 readings are systematically slightly lower than the KT-10 pad values, by approximately 5×10^{-5} SI units. The slope of the least-squares best-fit line between the SM-30 and the KT-10 is less than 1.0 (Fig. 2b). For strongly magnetic rocks, these two instruments would produce slightly different susceptibility values, with the SM-30 giving higher values: they would differ by less than 2%. As should be expected, the comparison between the two styles of measurement using the KT-10 provides a correlation with a slope that most closely approaches 1.0; it is actually 0.9995. The fact that the best-fit slope does not pass through the origin, and the R^2 value is less than 1.0, can only be attributed to noise in the individual measurements.

Taking six readings on a sample allows us to examine the variability in susceptibility values due to lithology. Again the results obtained with the MS2E are quite different from the results obtained with the KT-10 and SM-30 instruments, which yield a similar response. The MS2E exhibited a much larger within-sample variation of magnetic signal than either the KT-10 or the SM-30, as anticipated due to a smaller sampling area with the MS2E. Broadly, there appears to be an increase in signal variance with increasing susceptibility value (Fig. 3). This trend is not surprising, since a more weakly magnetic sample will not have any strongly

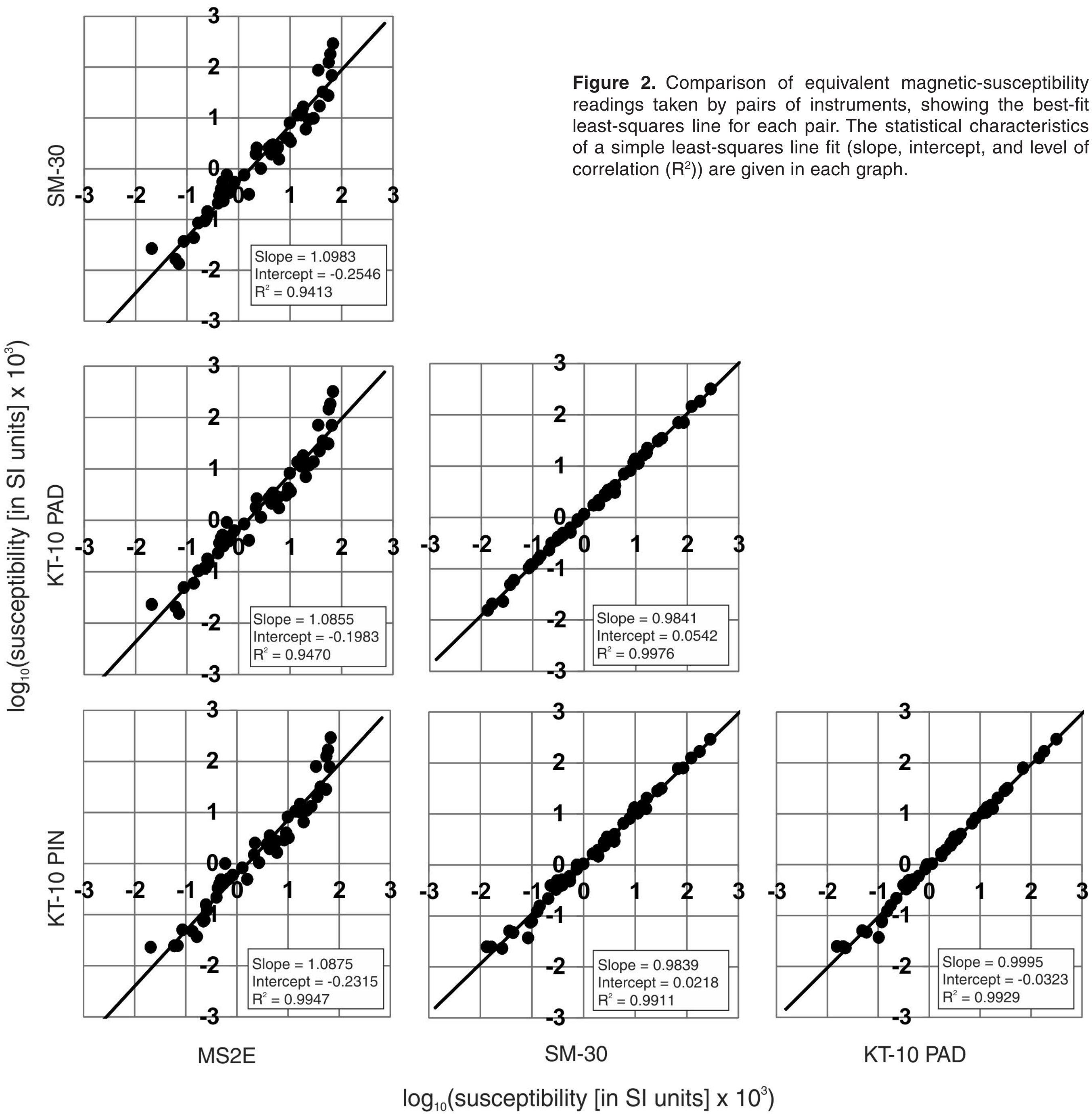

Figure 2. Comparison of equivalent magnetic-susceptibility readings taken by pairs of instruments, showing the best-fit least-squares line for each pair. The statistical characteristics of a simple least-squares line fit (slope, intercept, and level of correlation (R^2)) are given in each graph.

magnetic regions. The sensor coil used in the MS2E samples an area two orders of magnitude smaller than areas sampled by the KT-10 and SM-30. If the MS2E is measuring a heterogeneous coarse-grained rock, it is quite possible that the small size of the sensor package could detect local 'nuggets' with enhanced magnetite concentration. The SM-30 and the KT-10 both show little variance in repeat susceptibility readings, especially for more magnetic samples (Fig. 3). This is expected, since each of these tools has a larger measurement coil. What was surprising is that measurements made by all three of these meters showed a noticeable increase in signal variance for the most weakly magnetic samples (Fig. 3). The SM-30 showed the least variation, followed by the KT-10 pad configuration, with the KT-10 pin configuration showing the largest variance (Fig. 3). The only viable explanation for this observation is that both the SM-30 and (especially) the KT-10 have limited detection capability for susceptibilities below 10^{-4} SI units. Furthermore, using the pin activation on a flat-surface sample appears to increase signal noise.

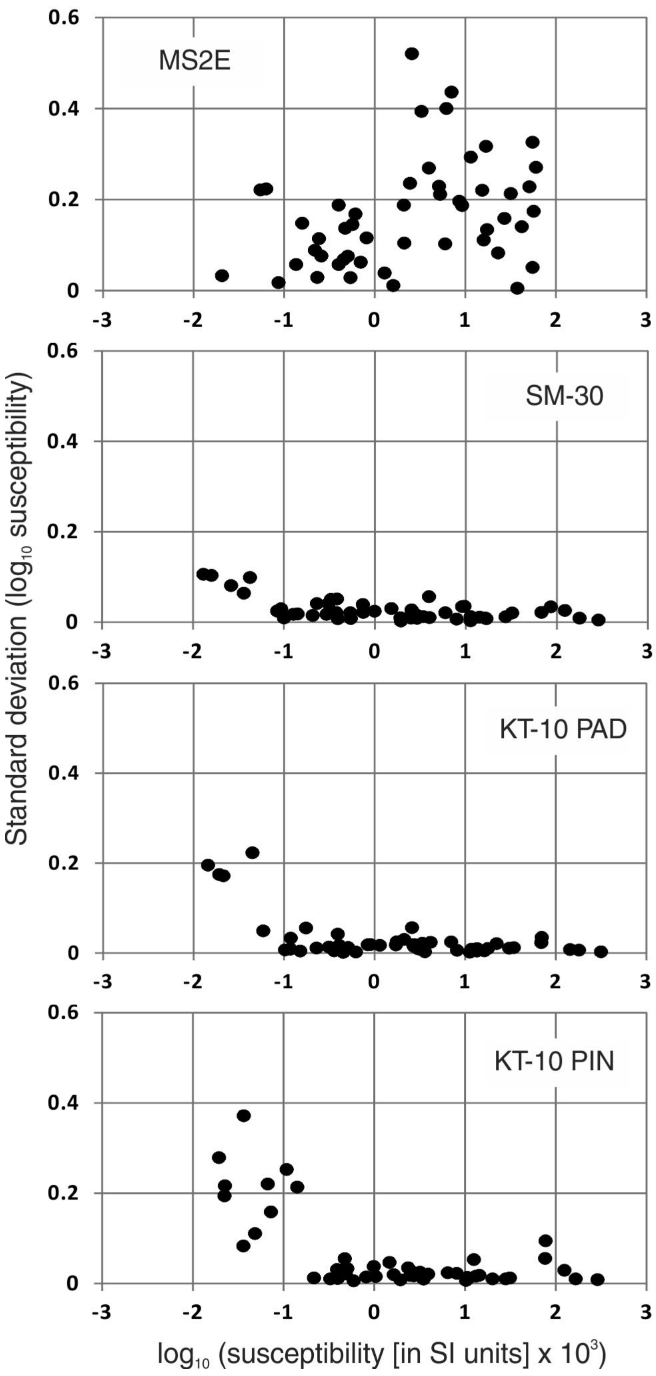

Figure 3. Comparison of standard deviation of magnetic-susceptibility measurements taken with different instruments.

CONCLUSIONS

This comparative study suggests that there are no meaningful differences in the susceptibility values obtained with the KT-10 and SM-30 instruments. When considered in terms of the errors associated with field measurements on irregular, probably weathered surfaces, the difference in susceptibility values has no significance in terms of magnetic-anomaly modelling or geological mapping. Both of these instruments use a similar higher-frequency signal in their inductive coil. Both of the instruments also use coils with similar areas.

The MS2E reported magnetic-susceptibility values that were consistently higher than those reported by the KT-10 and the SM-30. This difference may be explained by the lower-frequency signal used by its sensor. Magnetic susceptibility measured with an inductive circuit exhibits frequency dependency. It is quite possible that the MS2E is recording the presence of a coarser-grained magnetic-mineral fraction. Laboratory susceptibility meters which offer a range of signal-frequency values are available to take advantage of this factor. For example, the SM100 meter produced by ZH Instruments offers five frequency levels and six power settings.

The three instruments respond quite differently to inhomogeneous rocks. Depending on the usage of the instrument, this could be detrimental or advantageous. When used as a general field tool, it would require the operator to take more readings at a location in order to minimize impact of local mineralogical effects. The larger coils of the SM-30 and the KT-10 average susceptibility values over a broader area, so fewer observations at a point would be required. In contrast, the small coil size of the MS2E and drill-core–diameter input of the KT-10 make these meters best suited for taking susceptibility measurements on curved surfaces such as drill core. In this case, a significant portion of the larger coils of the SM-30 and the KT-10 are not in effective contact with the rock surface. When attempting to compare susceptibility results obtained by different groups using different instruments, the interpreter should ensure that they are only compiling results obtained with sensors using the same operating frequency.

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