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Feature

A comparison of magnetic susceptibility meters using samples from the Thompson Nickel Belt, Canada

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Overview

Comparisons of field portable magnetic susceptibility (MS) meters have been carried out by a number of geophysicists. Bleeker (2012) compared the KT-10 and the SM-30. He concluded that the KT-10 was most suitable for his purposes, as the KT-10 has a mode that provides the average and standard deviation of multiple readings on an outcrop. Bleeker (2012) found that the MS readings were useful for studying dyke swarms and differentiating between different dyke swarms. Lee and Morris (2013) compared three instruments and found that the KT10 and SM-30 gave similar readings, with the Bartington MS2E giving readings that were about 9% greater.

This article builds on this previous work and summarises the results of a study carried out for an MSc project (Deng, 2014). Measurements were taken on 71 samples of drill core, recovered from the Thompson Nickel Belt in Canada, using six types of magnetic susceptibility meters, two of which were also capable of measuring conductivities greater than about 1 S/m. Some of the meters used were quite versatile in that they could measure in different modes, for example, they could take individual (more accurate) measurements, or continuous measurements as the meter is moved along a core box or over an outcrop. In this study, we were interested in accuracy and reproducibility, so we chose the more accurate mode. Table 1 shows the meters used, the mode selected, and some other specifications of the meters (N/A implies information not available). Note that the Bartington MS2C and MS2K are only sensors; they cannot be used without a MS3 meter.

Measurements

Seventy-one samples were chosen to cover a broad range of susceptibilities from very small values to values up to about 200 $\times 10^{-3}$ SI. On each sample a specific location was marked with a permanent marker to ensure that all the measurements were made at the same location. Nevertheless, different meters will sample different volumes of the rock depending on their coil size. Susceptibility meters generally show some variability due to instrument drift and geological variation. Lee and Morris (2013) recommend six readings per sample and Rainsford and Muir (2010) recommend up to ten measurements on an outcrop. In this study we took five measurements per sample as a reasonable compromise between collecting good data and spending too long on the data acquisition process.

The first test, of reproducibility or drift, was undertaken by taking repeat measurements on a number of different samples with different susceptibilities. As one example, we show the measurements taken over a man-made sample that can be purchased from Terraplus for calibrating their instrument (Figure 1). This sample was too large to be placed in the coils used with the MS2C, but was measured using all the other instruments. The factory-calibrated value for the sample is 36 x 10^{-3} SI, however most instruments give a value a few percent less than this, except the MS2K, which gave values about 10% greater. Values for the MS2K are relatively erratic, while the others are fairly reproducible, with the RT-1 showing a slight downward drift, the KT-10 and SM-30 showing a very slight upward drift and the GDD showing an increase in scatter in the later measurements. It took about 10 minutes for each instrument to acquire 35 measurements. These calibration measurements were repeated a number of times over two months and very similar values were obtained.

Drift experiments were also undertaken on strongly and weakly susceptible geological samples, with slightly different results being obtained. This indicates that the degree of drift might vary

Table 1. Meters used in this study, mode selected and other specifications

	Fugro RT-1	Terraplus KT-10 S/C	GDD MPP-EMS2+	Bartington MS2K	Bartington MS2C	ZH Instruments SM30
Physical quantities	MS	MS and conductivity	MS and conductivity	MS	MS	MS
Number of modes	2	3	4	2	2	6
Mode selected	Scan	Measure	Manual	Manual	Manual	Mode B
Sensing area (mm^2)	N/A	3318	N/A	491	4072	1964
Operating frequency (kHz)	0.75	10	N/A	0.93	0.565	8
Resolution	10^{-4}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-7}
Comments					Designed for cylindrical core	

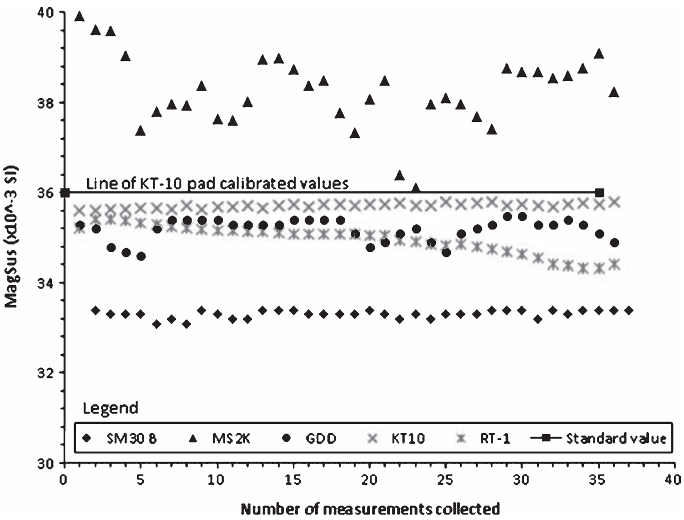

Figure 1. *Repeat measurements on a calibration sample with five instruments. The factory calibration value is 36 x 10-3 SI. Four of the instruments generally give a reading below this value, with each instrument showing different degrees of drift and scatter in the values.*

with the strength of the magnetic susceptibility, or it might be a function of the homogeneity of the sample. In general, the instruments with smaller coils seemed to show greater drift (GDD and MS2K). The results are summarised on rows 3 and 4 of Table 2.

Analysis

We compared the values measured by one instrument with the values measured by other instruments for all 71 samples. As an example, in Figure 2 we compare the KT-10 with the other five instruments. In this analysis we used the median of the five measurements taken by each meter on each sample. When we used the mean we found that the fit was poorer and the scatter greater. From this we concluded that for magnetic susceptibility values the median is a better way to estimate the central value of a distribution than the mean. Lee and Morris (2013) suggested a logarithmic average, but we did not test this option. Each plot in the correlation analysis shows a line of best fit. In a perfect world each instrument would give the same reading on the same sample, and the line of best fit would have a slope of one, an intercept of zero and an R^2=1. The slight differences in slope might be due to operating frequency, instrument design or the factory calibration of the instrument. Using curves similar to those on Figure 2, it should be possible to compare/convert the values measured with one instrument with/to those measured with another instrument.

When looking at all the plots we noticed that, in general, there was greater scatter in the bottom left quadrant compared to the top right quadrant. This suggested that measurements for smaller values are less reliable than measurements for larger values; however, it is not clear which of the two instruments is less reliable. In order to gauge the reliability of each instrument as a function of the measured value, we calculated the standard deviation σ of each measurement. When the standard deviation is divided by the mean m, this gives the co-efficient of variation CV = σ/m. If CV is less than 0.1 (10% error), then the reading is reliable, if it is greater, then the reading is unreliable.

In general, we found that for large MS, the CV was small, but for smaller values of MS, the CVs sometimes increased. We concluded that the instrument was not able to give reliable readings below a value where the CV was greater than 0.1. This was the lower limit of susceptibility that the instrument is capable of measuring. Figure 3 shows the plot of the $\log_{10}$ of the CV as a function of the $\log_{10}$ of the measured susceptibility (with the x10^{-3} ignored). For large values of MS, the CV is small, but as the MS decreases there is trend towards increasing CV such that when the MS is less than 0.1×10^{-3} SI the readings are not reliable. Hence for the RT-1, we estimate the lower limit of sensitivity of the instrument as 0.1×10^{-3} SI. Similar plots have been interpreted for the other instruments and the lower limits of resolution of the instruments as interpreted from the CVs are shown on the first row of Table 2. In cases

Table 2. Summary of results and some features of the six magnetic susceptibility meters used in this study

	RT-1	KT-10	GDD	MS2K	MS2C	SM30
Lower limit of accuracy (SI) CV>0.1 or lower limit	0.1×10^{-3}	0.007×10^{-3}	0.15×10^{-3}	0.005×10^{-3}	0.02×10^{-3}	0.02×10^{-3}
Largest value measured (SI)	280×10^{-3}	186×10^{-3}	360×10^{-3}	230×10^{-3}	220×10^{-3}	200×10^{-3}
Example drift – strongly susc (×10^{-3} SI)	0.0014	0.0082	−0.0396	−0.0053	−0.0008	0.0058
Example drift – weakly susc (×10^{-3} SI)	−0.0004	0.00004	0.0011	0.0001	−0.00006	−0.0014
Portability in the field	✓	✓	✓	x	x	✓
Usability on large irregular sample size	✓	✓	✓	✓	x	✓
Usability on core of diameter >72 mm	✓	✓	✓	✓	x	✓
Usability on core of diameter ≤72 mm	✓	✓	✓	✓	✓	✓
Ability for the instrument to account for split core in software	x	x	✓	x	x	x
Mode used in this research	Scan	Measure	Manual	Manual	Manual	Basic mode B
Most Erratic mode	Step	Scanner	N/A	N/A	N/A	Scanning
Reading on diamagnetic sample (should be negative)	Zero	Positive	Zero	Negative	Negative	Small negative
Cost when purchased in 2011	AU$2850	CA$2150 or CA$4450 for S/C	CA$6300	US$2925 + 2520 (for MS3)	US$2925 + 2520 (for MS3)	US$1995

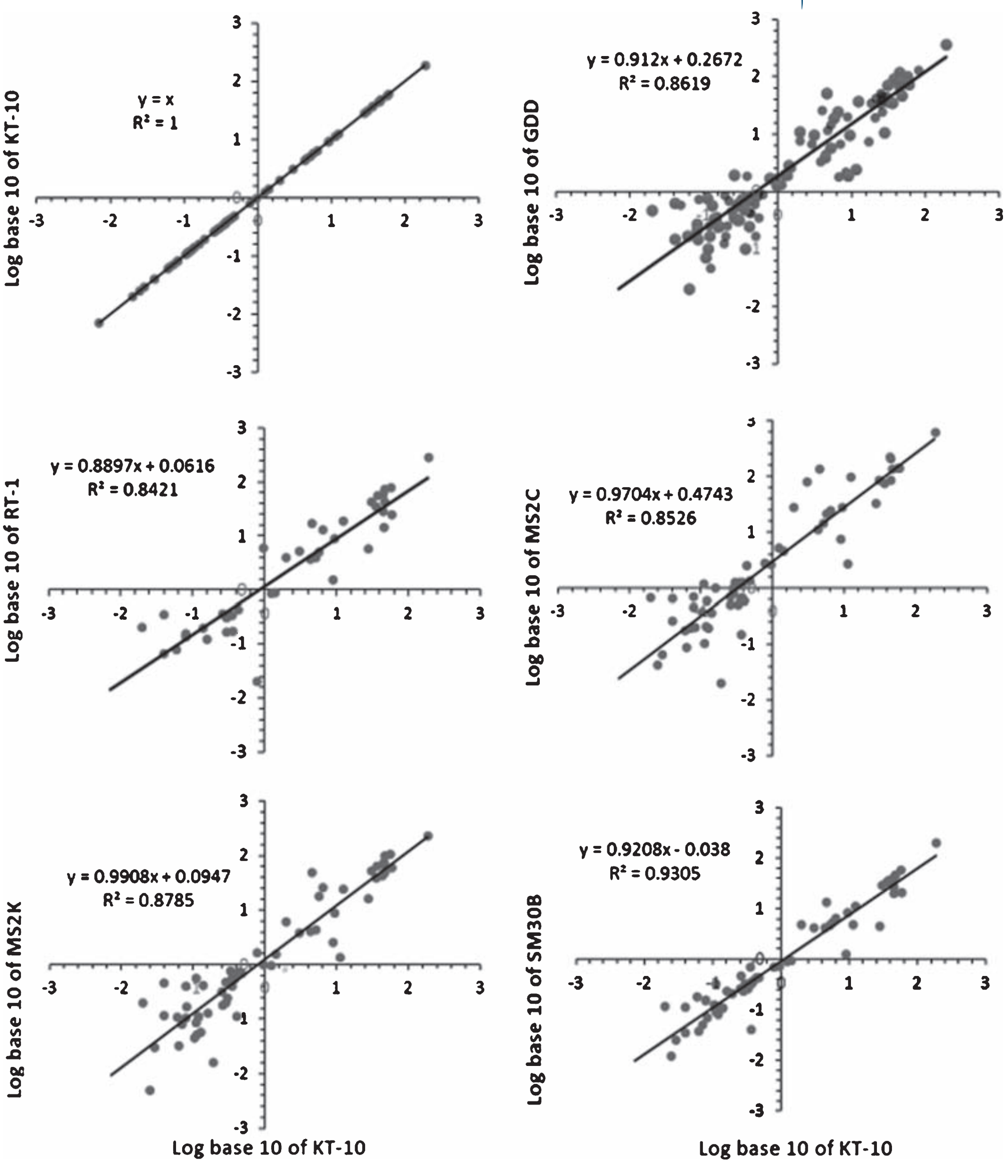

Figure 2. *Comparison of the susceptibilities measured on 71 samples using the KT-10 (horizontal axis) and the other five instruments (vertical axis). Ideally, the plot should be a straight line with slope one, intercept zero and R^2=1.*

when the CV was never larger than 0.1, we selected the lower limit of the instrument as the smallest value measured by the instrument.

The upper limit of an instrument is difficult to determine. Lee and Morris (2013) found that the linearity of the correlations plots (similar to those shown on Figure 2) broke down when one of the instruments was near its upper limit. However we did not see any sign of this in our study, so we conservatively estimated an upper limit as the largest susceptibility that we measured. There are no iron formations or highly susceptible rocks in the study area, so this will be a low value and we acknowledge that is not realistic. These values are also tabulated in the second row of Table 2.

A further feature that might be required of magnetic susceptibility meters is the ability to measure the susceptibility of diamagnetic materials that have small negative susceptibilities. Twenty measurements were taken with each instrument on a sample of quartzite (Figure 4). The RT-1 and GDD instruments gave readings of zero. The KT-10 gave erratic positive readings, the SM30 gave very small negative readings, and the MS2K and MS2C gave larger negative readings, with the latter being larger and more erratic.

Which instrument should I use for my project?

The most appropriate instrument to use on a particular project will depend on the purpose of the project. For example, if an instrument is to be used in a study of highly susceptible iron formations then accuracy at large values is required, and this study will not provide appropriate guidance. In other cases, the speed or ease of undertaking measurements might determine which instrument to use, or the ease with which the data can be downloaded from the instrument might be an important. These logistical factors are discussed in greater length by Deng (2014). In ideal circumstances measurements should be taken on fresh (unweathered) and flat sample surfaces. However, some instruments can correct for the diameter of the core, or have the correction factors built into the software of the instrument (Deng, 2014). The MS2C sensor assumes the core is cylindrical. Information in Table 2 will guide individuals interested in particular instrument features, i.e. lower limits of sensitivity,

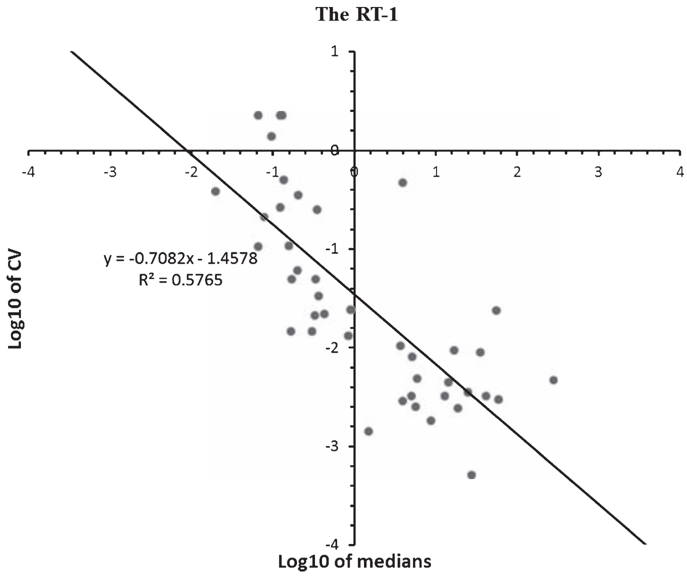

Figure 3. *The co-efficient of variation (standard deviation/mean) as a function of the measured magnetic susceptibility (log-log plot).*

drift rate, ability to handle cylindrical core, cost etc. In addition to the information on the table, we have the following observations about each instrument.

The **RT-1** Instrument is the easiest to use. It can take readings within a few seconds of being switched on and can download the readings via Bluetooth. This instrument gave poorer results for small and negative susceptibilities. The instrument has a scan mode for finding the most susceptible samples.

The Bartington Instruments' **MS3** sensor requires 20 to 45 minutes to set-up, but once set up measurements can be taken quickly and easily. It can be used with a variety of sensors for different types of samples. The **MS2C** is restricted to narrow cylindrical core, and the **MS2K** is designed for flat surfaces. The instruments and computers required to connect to the **MS3** require mains power, so they are not easy to use in the field, but could be used in a core shed. We found that the **MS2C** generally returns stable values.

The **GDD-EMS2+** requires 40 minutes to warm up after it is switched on. The instrument comes with a pocket computer that processes, logs and displays the data in a convenient manner. This instrument showed some temporal drift, but was stable over the two month period during which data were collected. The main advantage of this instrument is that it can simultaneously measure conductivity, provided that the conductivity is greater than 0.5 S/m. The GDD instrument can take continuous measurements and graph the results on the pocket computer.

The **KT-10** requires the sensor to be moved away from the samples for an in-air calibration. The buttons must also be pressed in a certain time frame or an error message will be displayed. This procedure requires some practice. The KT-10 showed minimal drift, but did not measure a negative susceptibility on our sample of diamagnetic quartz. Bleeker (2012) found the KT-10's scan mode more convenient than the SM-30. The S/C version of the KT-10 can also measure conductivity for values greater than 1 S/m. Since this study was undertaken, Terraplus has released a new model called KT-20, which also measures MS and conductivity. This new instrument has a resolution of 0.1 S/m for conductivity and may have different characteristics from the KT-10 we tested.

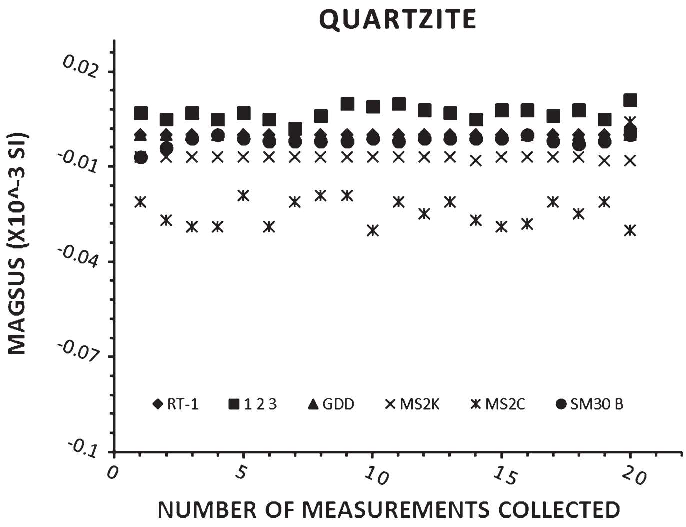

Figure 4. *Repeated measurements of the susceptibility on diamagnetic quartzite. The results should be small and negative. The GDD readings and RT-1 readings (the latter are obscured) are zero.*

The **SM-30** is a little complicated to operate, so the manual should be read carefully and the correct procedures followed to avoid mixing modes and overwriting measurements. Like the KT-10, the SM-30 showed minimal drift. One of its greatest advantages is that it is comparable in size to a large cigarette packet and can be carried in a pocket.

After having purchased an instrument the manufacturer should be contacted to ensure that the instrument includes the latest version of the appropriate software. We found this was necessary in one case and after the software was upgraded better results were obtained. Readings can be erratic; we found that it was a good idea to take at least five reading and to take the median of these as the measurement.

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